Desalination discharge in shallow coastal waters

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**DESALINATION DISCHARGE IN
SHALLOW COASTAL WATERS**

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2010

DESALINATION DISCHARGE IN SHALLOW COASTAL WATERS

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School of Civil and Environmental Engineering

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Summary

For the design of a desalination plant, the intake and outfall structures need to be properly addressed. From an environmental viewpoint, it is important to design a brine outfall so that the discharge plume can be mixed rapidly with the ambient coastal waters. Previous studies have suggested a 60° inclined jet to be the optimal discharge scheme in terms of the mixing efficiency. However, the maximum rise height associated with 60° is relatively large, which might not be suitable for disposal in shallow coastal waters.

In this study, we investigate the behavior of submerged round brine discharges injecting at smaller angles, i.e., 0° , 30° and 45° , to stationary receiving water in the laboratory. Advanced laser diagnostic method of combined Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) is adopted to measure the velocity and concentration fields, respectively. The simultaneous measurement also resolves the correlation of the turbulent fluctuations of the two quantities, i.e., the Reynolds flux, which is vital in the analysis of the mass transport and mixing processes. The experimental results obtained provide regulatory references on the gross geometrical characteristics of the smaller-angle discharges, e.g., the location of the centerline peak, the return point where the dense jet returns to the source level, etc. The mixing behavior of the discharge is also quantified through the analysis of the axial and cross-sectional velocity and concentration distributions. Both geometrical and mixing properties are found to proportionally correlate with the densimetric Froude number, Fr as well as, in some cases, the nozzle diameter, D , and the resulting proportionality coefficients are derived from the experimental data.

Another important concern associated with the discharge in a shallower ambient is the potential influence of the close proximity of the seabed on the brine plume, i.e., the Coanda effect. We study the proximity effect by explicitly adjusting the distance of the nozzle from the boundary z_0 as well as implicitly varying the initial discharge velocity, which in turn varies the dynamic length scale L_M . Through the comparison of the results between two experimental

series with distinct z_0/D but overlapping z_0/L_M , the latter is identified as the deciding factor for the boundary influence. For 30° cases, it is found that the bed influence became significant when z_0/L_M is less than approximately 0.2, while for 0° and 45° , the boundary effect is considerably weaker and indiscernible for z_0/L_M down to the smallest tested value of 0.12 and 0.05, respectively. As such, the proportionality coefficients for 30° case are categorized into two subsets, namely free dense jets with and without boundary effects. Comparisons with available coefficients reported in the literature are satisfactory.

For the horizontal dense jet, the cross-sectional profiles of the turbulence intensity, Reynolds shear stress and Reynolds flux are further investigated. The results reveal the transition of the flow from a dense-jet regime to a wall-dense-jet regime. In the dense-jet regime, the profiles at different downstream locations collapse after normalization, and the turbulent mass and momentum transport are found to be weaker than in the unbounded vertical buoyant jet. In the transitional regime, the turbulence characteristics grow stronger but self-similarity has not been reached for the measured range of the flow up to 18D. The associated turbulent viscosity, ν_t , turbulent diffusivity, D_t , as well as the turbulent Schmidt number, Sc_t , have been derived from the experimental data.

Aside from the experimental study on the near field mixing, a mathematical model simulating the long-term salinity build-up on the far field around the brine outfall is also developed in this study. A simplified scenario of flat seabed and steady longshore current is assumed for the first attempt. Transient and steady-state analytical solutions are derived and applied to assess hypothetical shoreline and offshore discharges. The effect of the advection-to-diffusion ratio μ on the modeling results is also discussed. The mathematical model is then extended to incorporate the effects of the oscillatory tidal currents which are commonly encountered in the coastal environment. The tidal currents are represented by a small constant component, V (normally referred to as residual or drift current), plus a periodic part, $U_0 \sin \omega t$. Anisotropic eddy dispersivities in the longshore and offshore directions are also considered. The convergence to the quasi-steady state for the salinity excess due to the continuous salinity input has been studied. Model predictions for representative velocity ratios of ν ($= V/U_0$) are obtained. A comparison of the results between constant, time-dependent and tidally-averaged dispersivities has also been conducted. For both mean and oscillatory currents, the placement of the outfall further offshore has proven to reduce the shoreline impact as expected.

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List of Symbols

B	Local Specific Buoyancy Flux
B_0	Initial Specific Buoyancy Flux
b_c	Concentration Spread Width using the e^{-1} Notation
b_u	Velocity Spread Width using the e^{-1} Notation
C	Local Mean Concentration
C_0	Volumetric Solute Concentration of the Inject Source
C_c	Local Centerline Maximum Mean Concentration
	Concentration Distribution due to Continuous Source Input
C_i	Concentration Distribution due to Instantaneous Source Input
C_{num}	Various Proportionality Constants related to the Dense Jet Discharge Characteristics
C^*	$= C / (C_0 Q / V h_0^2)$ $= C / (C_0 Q / 4\pi h_0 \sqrt{D_x D_y})$
c	Local Instantaneous Concentration
c_i	Instantaneous Concentration for the i -th Sample
c'	Local Turbulent Concentration Fluctuation
D	Nozzle Diameter
D_m	Molecular Diffusivity
D_t	Turbulent Diffusivity
D_x	Effective Dispersivity Averaged over the Tidal Cycle in the x Direction
D_y	Effective Dispersivity Averaged over the Tidal Cycle in the y Direction
$D(t)$	Time-varying Dispersivity
$\overline{D}$	Tidally-averaged Dispersivity
d_{pixel}	Pixel Pitch
$E(f)$	Spectral Energy Density at a Particular f
f	Frequency
f_l	Lower Limit of the Measuring Frequency
f_{sub}	with Different Subscripts denoting Specific Functions based on Dimensional Analysis

f_u	Upper Limit of the Measuring Frequency
Fr	$= U_0/\sqrt{g_0' D}$, Initial Densimetric Froude Number
g	Gravitational Acceleration
g'	$= [(\rho - \rho_a)/\rho_a] \cdot g$, Local Effective Gravitational Acceleration
g'_0	$= [(\rho_0 - \rho_a)/\rho_a] \cdot g$, Initial Effective Gravitational Acceleration
g'_c	Local Centerline Maximum Effective Gravitational Acceleration
g'_*	$= (\pi/4)^{1/4} g'_0 / Fr$
H	Ambient Water Depth
h	Offset Distance of the Wall from Centerline of the Nozzle
h_0	Assumed Uniform Sea Water Depth
I	Local Incident Light Intensity
I_0	Incident Light Intensity at the Laser Source
I_c	Fluorescence Intensity Received by the Light-sensitive Medium of the CCD Camera
I'	Fluorescence Energy Emitted per Unit Volume
K_0	Zero-order, Modified Bessel Function of the Second Kind
k	Turbulent Kinetic Energy
k_{num}	Various Proportionality Constants related to the Laser Fluorescence
L	Tidal Excursion Distance
L_j	Distance of the Jet Region
L_M	$= M_0^{3/4} / B_0^{1/2} = (\pi/4)^{1/4} D Fr$, Jet/Plume Characteristic Length Scale
l	Penetration Length of the Laser Beam
M	Local Specific Momentum Flux A Quantity of Mass
M_0	Initial Specific Momentum Flux
M^*	Mass Inject Rate
m	Arbitrary Constant
m^*	Effective Mass Inject Rate per Unit Water Depth
N	Number of Samples
N_{int}	Side of the IA in Pixels
Q	Local Volume Flux Brine Discharge Flow Rate
Q_0	Initial Volume Flux
R_1	$= \sqrt{(x - x_0)^2 (D_y/D_x) + y^2}$, Weighted Radii from the Real Source
R_2	$= \sqrt{(x + x_0)^2 (D_y/D_x) + y^2}$, Weighted Radii from the Image Source
R^*	$= \mu \sqrt{x^{*2} + \mu^2 y^{*2}}$
r	Radial Distance from the Jet Centerline Axis

Re	$= U_0 D / \nu$, Reynolds Number
Ri	Local Richardson Number
S	Dilution
S_i	Dilution at the Jet Impact Point
S_m	Dilution at the Jet Centerline Peak
S_r	Dilution at the Jet Return Point
S_t	Dilution at the Terminal Rise Height of the Jet
Sc	Schmidt Number
Sc_t	Turbulent Schmidt Number
SF	Object-to-image Scale Factor
s	Coordinate along a Linear or Curvilinear Trajectory or Path
T	Tidal Period
t	Time
t_0	Dummy Variable of Integration
t'	Dummy Variable of Integration
t^*	$= t V^2 / \sqrt{D_x D_y}$
U	Local Mean Velocity Component in the x or Axial Direction
U_0	Efflux Velocity
	Amplitude of the Oscillatory Tidal Current
U_c	Local Centerline Maximum Mean Velocity Component in the x or Axial Direction
$U_{\max}$	Maximum Velocity Estimated in the Flow Field
$U(t)$	Longshore Tidal Current Velocity
u	Local Instantaneous Velocity Component in the x or Axial Direction
u_i	Local Instantaneous Velocity for the i -th Sample
u'	Local Turbulent Fluctuation of the Velocity Component in the x or Axial Direction
$\overline{u'c'}$	$= \frac{1}{N} \sum_{i=1}^{i=N} [(u_i - U) \cdot (c_i - C)]$, Reynolds Flux
$\overline{u'v'}$	$= \frac{1}{N} \sum_{i=1}^{i=N} [(u_i - U) \cdot (v_i - V)]$, Reynolds Shear Stress
V	Local Mean Velocity Component in the z or Radial Direction
	Steady Longshore Current Velocity Averaged over the Tidal Cycle
V_i	Instantaneous Velocity Vector
v	Local Instantaneous Velocity Component in the z or Radial Direction
v'	Local Turbulent Fluctuation of the Velocity Component in the z or Radial Direction
W	Leaky Aquifer Function
w	Slot Nozzle Width

x, y, z	Cartesian Coordinates in the Horizontal, Lateral, and Vertical Directions Offshore and Longshore Directions
x_0	Horizontal Offset of the Nozzle Tip Offshore Distance of the Point Source Discharge
x_{ip}	Horizontal Distance of the Jet Impingement Point
x_m	Horizontal Coordinate of the Jet Centerline Peak
x_r	Horizontal Distance of the Jet Return Point
x^*	$= x/h_0$
x_0^*	$= x_0/h_0$
y^*	$= y/(Vh_0^2/D_y)$
z_0	Port Hight above the Bed
z_0/L_M	Bed Proximity Parameter
z_c	Vertical Coordinate of the Local Centerline Maximum Point
$z_{cc/2}$	Distance from the Bed to the Point at the Vertical Section at Which $C = C_c/2$ and the Concentration Gradient is Negative
z_m	Vertical Coordinate of the Jet Centerline Peak
z_t	Terminal Rise Height of the Jet Trajectory
$z_{uc/2}$	Distance from the Bed to the Point at the Vertical Section at Which $U = U_c/2$ and the Velocity Gradient is Negative
α	Entrainment Coefficient assuming Gaussian Cross-sectional Profiles $= (D_y/D_x)^{1/2}$, Dispersivity Ratio
α_t	Entrainment Coefficient assuming Top-hat Cross-sectional Profiles
Δs	Tracer Displacement between Δt
Δt	Time Interval between Two Consecutive Laser Pulses
$\Delta \rho$	$= \rho_0 - \rho_a$, Initial Density Difference
ϵ	Turbulent Dissipation
ε	Molecular Absorption or Extinction Coefficient of the Dye for the Incident Light
η	$= \omega y/U_0$
η_{H_2O}	Molecular Extinction Coefficient of Clear Water for the Incident Light
θ	Local Inclination Angle of the Jet Trajectory to the Horizontal $= \int_{t_0}^t D_{x,y}(t')/D_{x,y} dt'$
θ^*	$= \int_{\tau-\tau_0}^{\tau} 1 + \frac{1}{\nu} \sin \tau' d\tau'$
θ_0	Initial Inclination Angle of the Jet
λ	$= U_0^2/(4\omega D_y)$
μ	$= Vh_0/D$, Advection-to-diffusion Ratio
ν	Fluid Viscosity

	V/U_0 , Velocity Ratio
ν_t	Turbulent Viscosity
ξ	$= \omega x / U_0$
ξ_0	$= \omega x_0 / U_0$
ρ	Density of the Local Fluid
ρ_0	Density of the Source Fluid
ρ_a	Density of the Ambient Fluid
τ	Dummy Variable for Integratoin $= \omega t$
τ_0	$= \omega(t - t_0)$
τ'	Dummy Variable of Ingetration
ϕ	Quantum Efficiency, i.e., the Ratio of the Total Energy Emitted per Quantum of Energy Absorbed by the Molecule
Ω_y	$= 1/2 (\partial v / \partial x - \partial u / \partial z)$, Out-of-plane Vorticity
ω	$= 2\pi / T$

Chapter 1

Introduction

1.1 General Introduction

Driven by explosively growing demands and steadily reduced conventional supply of fresh water, significant technological advances and reduction in operational cost of desalination, the number of desalination plants in operation or being planned in large coastal cities worldwide has increased dramatically over the last decade (Global Water Intelligence editorial team, 2004). The desalination processes essentially remove the suspended matters and the dissolved minerals (including but not limited to salt) from seawater or brackish water to produce potable water; while the waste stream of elevated concentrations (the so-called brine) is typically discharged back to the coastal waters as the most cost-effective option. Desalination can cause potential environmental impacts (Sajwani, 1998) including: plant location; brine disposal; energy considerations; chemical disposal; atmospheric emissions; as well as various other impacts (noises etc).

Amongst the above, the brine discharges typically associated with the reverse osmosis (RO) processes have drawn particular attention due to the high salt concentrations and induced fluctuations in salinity levels around the discharge point which may affect human beings as well as the marine organisms, if they are not blended with other effluents, e.g., cooling water from thermal plants, to reduce the salinity before discharge (Mabrook, 1994; Pérez Talavera and Quesada Ruiz, 2001). In addition, the denser brine has a tendency to sink towards the seabed, causing potential adverse impacts to the benthic communities (Iso et al., 1994). Due to its chemical stability, salt (and hence salinity) does not decay spontaneously in ambient waters. On the contrary, it accumulates around the outfall area over an extended period of continuous discharge if the outfall is not well designed. An excessive long-term build-up of salinity in

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the surrounding coastal waters also elevates the salinity of the ambient waters at the intake and reduces the recovery ratio (the ratio of the produced portable water volume to the feed seawater volume) in the desalting process, which in turn increases the operational cost of the desalination plants. The mixing of the brine discharges is also intimately linked to the mixing of the dissolved chemicals used for cleaning, antifouling, anti-scaling and corrosion control purposes in the pretreatment processes.

To mitigate the environmental impacts, a brine outfall needs to be properly designed so that the discharge can be rapidly mixed with the receiving water and the concentrations within prescribed levels can be reached at the edge of a small regulated mixing zone (Del Bene et al., 1994; California Coastal Commission, 2004). A submerged outfall is typically the most appropriate option. The submerged outfall can be a single-port outfall or a multi-port diffuser. Although the multi-port diffuser generally enables more mixing and hence greater dilution of the discharged effluent than the single-port outfall, from an economical viewpoint, the single-port is much cheaper to construct and maintain and thus still remains as an attractive option to the plant operators. Discharges from the submerged outfall will rapidly mix with the entrained ambient water, and spread along the seabed as a negatively buoyant plume with an intermediate salinity and temperature (and therefore density) depending on the initial dilution and the bottom topography. Note that this contrasts with the submerged outfalls for partially-treated sewage and industrial effluents whereby the effluent plume would typically rise to the sea surface due to the positive buoyancy. The knowledge of the mixing behavior of dense jets is therefore essential to the outfall design and the associated environmental impact assessment.

The dense jet discharge from a single-port outfall has been investigated by a number of researchers in the past decades, and more recently, there is a renewed interest largely due to the rapid growth of the desalination industry globally. Based on previous experimental evidence (Zeitoun et al., 1970; Roberts et al., 1997), a discharge angle of 60° to the horizontal has been widely accepted as the optimum design scheme. However, the maximum rise height with the 60° inclination is relatively large for the reclaimed coastline of many cities where the near-shore bathymetry tends to be shallow and smaller discharge angles are more feasible (Jirka, 2008; Bleninger and Jirka, 2008). It is also worth noting that, in some cases, a horizontal discharge configuration could be adopted based on cost considerations and the relative ease for construction (Pérez Talavera and Quesada Ruiz, 2001).

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In the event of shallow coastal waters, when the dense jet discharge has to be aligned at a smaller inclination or even parallel to the adjacent seabed, the entrainment of ambient water from the boundary side of the dense jet can be significantly restricted while the open side remains unobstructed. Consequently, according to the Bernoulli's principle, a pressure difference across the jet flow can be induced, which acts as an external force to deflect the effluent towards the bottom boundary until an attachment, also known as the Coanda attachment, occurs. With the Coanda attachment, the discharge will then cling to and proceed along the boundary. For brine discharge, the Coanda attachment can result in further reduced mixing and excessive salinity along the seabed that may raise the adverse impact on the benthic community around the affected area.

It is worth pointing out that, throughout this thesis, the concentrated solutions of salt and other constituents as the reject produced in the end of the desalting process is referred to as 'desalination discharge' as used in the title of this study, and more frequently, as 'brine discharge' or simply 'brine' in the subsequent text. Strictly speaking, brine is defined as water with a high concentration of salt, whereas the actual reject from the desalination plants can contain a mix of salt and other substances, as well as heat. However, as previously mentioned, the salinity excess causes the primary environmental impact and is also the focus of the present study. In this regard, the loose use of the term 'brine' does not seem to be utterly inappropriate. Other terms such as 'desalination concentrate', 'seawater concentrate', 'effluent', etc., can also be commonly found elsewhere.

1.2 Objectives and Scope

In this study, the environmental impact of the brine discharge from desalination plant in a shallow coastal ambient is examined using the combination of experimental, analytical and numerical approaches. Effort is focused on two issues: in the near field, the mixing behavior of the horizontal, 30° and 45° dense jets as well as the influence of an adjacent boundary on the respective flows; and in the far field, the transient and steady-state salinity buildup due to the continuous brine discharge.

The theme of the present study centers on the 'shallowness' of the receiving coastal waters. Due to this dominant restriction, a smaller inclination of the discharge outfall would be more desirable, which further points to new tech-

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nical challenges. Specifically, the smaller inclination would lead to the closer proximity of the lower bottom, which is the seabed in real life, and the resulting potential boundary effect. Besides, the 30° and 45° inclined dense jets as a whole have not received as much research attention as their 60° ‘predecessor’ and the few recent studies are somewhat restricted in the scope of their investigations. Therefore, the gross mixing characteristics of the free dense jets with 30° and 45° inclinations have been revisited by employing the advanced laser diagnostic techniques, namely, the combined particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF). With the combined PIV and PLIF system, the velocity and concentration information can be acquired simultaneously, which significantly reduces the experimental time and eliminates the possible errors when tests had to be repeated to measure the velocity and concentration separately. The simultaneous measurement of the turbulent fluctuations of the velocity and concentration also makes the correlation of the two, i.e., the Reynolds flux, available and allows us to look into the turbulent mass transport that is crucial in the analysis of the mixing process. At the same time, comparisons with existing experimental results and model predictions have been performed extensively. Beyond the free dense jets, further investigation has been conducted on the potential boundary effects by reducing the dimensionless dynamic distance between the nozzle and the bottom. From the results, the boundary effects have been captured in some extreme cases through comparisons with the reference free dense jets.

Based on the experimental results, the characteristic geometrical features and gross mixing behaviors of the horizontal, 30° and 45° inclined dense jet are determined. The study on the boundary effect, or Coanda effect, is proved to be more difficult to perform as the development of the effect is shown to be gradual and no abrupt change is observed. Nevertheless, some close-to-critical thresholds of the controlling dimensionless height have been identified. It is hoped that these new results can assist in setting the proper port height above the seabed to avoid adverse boundary effects in the design of the brine outfall. The turbulence characteristics and turbulent mass and momentum transport have been analyzed for the offset horizontal dense jets. The associated turbulent viscosity ν_t and turbulent diffusivity D_t as well as the turbulent Schmidt number Sc_t have been derived.

As noted, many studies have focused on the mixing and diluting behaviors of brine discharges (see for example Del Bene et al., 1994; Doneker and Jirka, 2001; Pérez Talavera and Quesada Ruiz, 2001; Law et al., 2004). Comparatively, far

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less effort has been devoted to investigate the long-term cumulative effect by the continuous brine discharge into a shallow coastal water body of lesser salinity, which is also the objective of the present study. We investigate the salinity build-up processes due to the continuous brine discharge, focusing particularly on the salinity fluctuations in the presence of the mean and oscillatory tidal currents, as well as the effects of other relevant parameters including the anisotropy and possible time dependency of the dispersivities. Due to the shallowness, the salinity distribution in the vertical water-depth direction can reach uniformity very rapidly. As such, the macroscale far-field salinity build-up process can be approximated by a depth-averaged two-dimensional advection-diffusion problem that is more amenable mathematically. Based on some further assumptions, the transient model is finally developed and analyzed.

Ultimately, the aim of the present study is to provide additional regulatory references for the design of desalination discharges in shallow waters that are typical in most coastal regions. In addition, the turbulence results for the offset horizontal dense jets are reported for the first time as far as the author is aware. They can be useful in the development and validation of future numerical models concerned with the turbulent transport of mass and momentum for the respective flow.

1.3 Outline

This thesis is organized into eight chapters. Chap. 1 introduces the background of the present study. The objectives and scope of the study are also described in this chapter as well. Chap. 2 presents the literature review. The methodology, accomplishments and shortfalls of relevant previous studies are briefly summarized from the perspective of general environmental impact, near-field and far-field studies in parallel with the composition of the present study. Chap. 3 introduces the sophisticated experimental system including the experimental setup and procedures as well as some fundamentals of the key experimental techniques employed in the present study that are considered necessary. The experimental results and their comparison with published data for the 30° and 45° inclined dense jets are presented in Chap. 4. Results and discussions regarding the offset horizontal dense jets are documented in Chap. 5. The development and heuristic application of the mathematical model concerned with the far-field salinity build-up due to continuous brine discharge under mean tidal currents are presented in Chap. 6. Extension of the modeling study to incorporate the

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oscillatory tidal current is elaborated in Chap. 7. Finally, Chap. 8 summarizes all the findings during the course of this study together with some recommendations for possible future studies. The important Matlab routines used for post-processing the raw experimental data, the numerical integration algorithm for the mathematical model, graphs in addition to the representative ones presented in the main body as well as some detailed mathematical derivations are supplemented in the various Appendices.

Chapter 2

Literature Review

2.1 Introduction

This chapter summarizes briefly the current state of the desalination technologies and the market status (Section 2.2), the existing studies that cover the general environmental impacts of the brine discharge (Section 2.3), the studies in the near field that are related to the horizontal and inclined dense jets as well as the boundary effect (Section 2.4), and the studies in the far field relating to the salinity build-up (Section 2.5). The review is based on a thorough survey of the literature. The methodology, contributions and drawbacks of the various previous studies are presented and discussed. A brief review of the relevant experimental techniques is documented in the next chapter.

2.2 Overview of Desalination Technologies

Before embarking on the environmental impacts of the desalination discharge, it is of interest to have a brief overview on the current state of the desalination technologies and the market status on a global scale. More comprehensive overviews can be found in Buross (2000) and Cooley et al. (2006).

Desalination refers to any of several processes that remove excess salt and other minerals from water in order to produce fresh water that is suitable for human consumption or irrigation (Wikipedia, 2009). Distillation and reverse osmosis (RO) are the two dominant desalination technologies used in most desalination plants worldwide (market statistics are offered in the next paragraph). Distillation is the oldest and most commonly used method of desalination. Over time, it has developed into three different types, namely, multi-stage effect, multi-stage flash (MSF) and vapor compression, amongst which MSF is the easiest to

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operate and most reliable method. In the MSF process, seawater is heated in a vessel called the brine heater. This is generally done by condensing steam on a bank of tubes that carry seawater which passes through the vessel. This heated seawater then flows into another vessel, called a stage, where the ambient pressure is lower, causing the water to immediately boil. The sudden introduction of the heated water into the chamber causes it to boil rapidly, almost exploding or flashing into steam. Generally, only a small percentage of this water is converted to steam (water vapor), depending on the pressure maintained in this stage, since boiling will continue only until the water cools (furnishing the heat of vaporization) to the boiling point. The vapor steam generated by flashing is converted to fresh water by being condensed on tubes of heat exchangers that run through each stage. The tubes are cooled by the incoming feed water going to the brine heater. This, in turn, warms up the feed water so that the amount of thermal energy needed in the brine heater to raise the temperature of the seawater is reduced. Typically, a MSF plant can contain from 15 to 25 stages set at increasingly lower atmospheric pressures, the feed water could pass from one stage to another and be boiled repeatedly without adding more heat. In comparison to MSF, RO is relatively new, with successful commercialization occurring in the early 1970s. RO is a membrane separation process in which the water from a pressurized saline solution is separated from the solutes (the dissolved material) by flowing through a semipermeable membrane. No heating or phase change is necessary for this separation. The major energy required for desalting is for pressurizing the feed water. In practice, the saline feed water is pumped into a closed vessel where it is pressurized against the membrane. As a portion of the water passes through the membrane, the remaining feed water increases in salt content. At the same time, a portion of this feed water is discharged without passing through the membrane. Typically, a complete RO system also consists of pretreatment and posttreatment components as necessary steps to inhibit precipitation and the growth of microorganisms on the membranes as well as stabilize the water and prepare it for distribution (Buros, 2000).

According to the latest market statistics, “Desalination in 2008 - Global Market Snapshot” (Global Water Intelligence (GWI) and International Desalination Association (IDA), 2008), the world’s ten leading desalination countries have about 71% of all the capacity, amongst which the top three are Saudi Arabia (17%), United Arab Emirates (UAE, 13%) and the United States (13%). It is also indicated that, among the 13869 desalination plants that are contracted at the time of the study, the RO and MSF processes are mainly used, with each

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accounting for 59% and 27% of the total capacity respectively. The remaining 14 % is made up of the multiple effect, electrodialysis, and vapor compression processes, while the minor processes amounted to less than 1%. In terms of the geographic distribution of the different desalination technologies, many countries in the Middle East and North Africa are highly dependent on distillation plants to supply water to their urban areas. In addition, most plants installed in this region adopt a co-generation scheme, i.e. building dual purpose plants so that the high temperature steam that propels the turbine in the power generator unit is recycled to run through the brine heater in the distillation unit. On the contrary, majority of the plants in the US employ the RO process to treat brackish water. RO also tends to be the prevailing technology in the world's emerging markets in Spain, Australia, China and etc.

2.3 Environmental Impacts of Brine Discharge

As the impacts arising from brine discharge receive increasing concern, there are much ongoing efforts to identify the environmental impacts and propose a comprehensive assessment framework for regulatory purposes. Moreover, since very few well-recognized guidelines exist thus far, it is of interest to put together the recent advances on such topic to provide references to decision-makers and practitioners as well as identify the gap between research and application in reality.

2.3.1 Identification and assessment of the environmental impacts

Shams El Din et al. (1994) discussed how the operation of a MSF distillation plant affected the surrounding marine environment in a variety of ways. Corresponding to brine discharges, the authors enumerated the impact from rising temperature, higher salt content and other small amount of toxic metal cations. The authors also argued that, due to continuous operation and potential synergistic effects, the impact of desalination could not be taken lightly.

Mabrook (1994) studied the environmental impact of waste brine disposal from desalination plants on Red Sea, Egypt. The input brine discharge was measured to be dramatically different from the sea water in properties like pH, total dissolved solids (TDS), temperature, total hardness and chlorides, etc. The altered properties could seriously affect marine life, even lead to the disappear-

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ance of numerous species. As such, the author recommended a post-treatment process to adjust the above mentioned properties in the discharge water before disposal as well as an environmental impact assessment (EIA) for offshore discharges from the desalination plants.

In their comprehensive study, Morton et al. (1996) compared the environmental impacts of MSF and RO, which are the two major seawater desalination processes currently. As highlighted by the authors, the dominant environmental impact associated with the operation of seawater desalination plants was the discharge of warm concentrated brine, and the effects of the elevated temperature and salinity on the marine habitats was of significant concern. The authors further proposed that, since RO requires a relatively lower level of energy consumption while possesses higher conversion ratio (ratio of freshwater production to seawater abstraction) when compared with MSF, RO has less thermal impact than MSF but greater impact in terms of salinity increase in the receiving water. Therefore, we need to pay special attention to the RO desalination plant to monitor the excessive salinity discharged.

Höpner and Windelberg (1996) discussed the conceivable environmental impacts of the desalination plants on the coastal zone ecosystems, and more importantly, proposed a general framework for EIA based on a paradigmatic desalination plant in Arabian Gulf. Pertaining to the brine discharges, the authors pointed out that, for the Gulf as a whole, the effect from brine discharges was negligible as the variation of salinity caused by the natural evaporation was of higher order of magnitude. A more comprehensive framework for EIA was further proposed by Hoepner (1999) subsequently. The author confirmed the previously reported criterion that required the salinity change to be within 1 practical salinity unit (psu). In addition, the author highlighted two general mitigation measures to counter the impact of brine discharges: prudently choosing the discharge location to ensure that the effects on sensitive sub-ecosystems were minimized; and taking best advantage of the favorable hydrographic conditions and avoiding the adverse ones to the greatest extent. The latest framework incorporating the new challenges and recent progresses can be found in Lattemann and Höpner (2008).

Tsiourtis (2001) outlined the technical, societal, economical and environmental issues concerning the desalination. In a separate section dedicated to brine disposal, the author highlighted the importance of the prior knowledge of the prevailing currents as well as the seabed topography in the disposal site selection, and advocated the combined use of mathematical modeling and field

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survey in the operational monitoring. A concern about the disturbance of the seabed during the construction of the discharge outfall and pipeline was also raised in the overview.

Einav et al. (2002) presented a status report on the adverse environmental effects associated with the desalination processes, and in particular, elaborated the impacts of the concentrated brine discharge on the marine environment. The authors summarized the typical composition of the brine as well as the prevailing alternatives adopted for brine discharge together with their respective environmental impacts. They also argued that the severity of the impacts varies according to the physical nature of the marine environment (e.g. bathymetry, water depth, tides and currents, etc), the biological sensitivity of the marine biota as well as the type and size of the desalination plant *per se*.

More recently, a review on the characteristics of the discharge effluent from SWRO plants, the design considerations and recommendations for the new plants as well as the available mitigation measures for the existing plants to minimize the environmental impact of their discharges was contributed by Mauguin and Corsin (2005). Meerganz von Medeazza (2005) also outlined the major environmental impact caused by extensive brine discharge and recommended the countermeasures.

Apart from the closely-related industry and research community, governmental institutions and agencies at various levels have also expressed the awareness of the significance of the environmental impacts associated with brine discharges, and have put the relevant issues on their agenda. Among them, California Coastal Commission (2004) identified the most significant potential direct adverse environmental impact of seawater desalination to be that on marine organisms as a result of the seawater intake and discharge activities. Meanwhile, the concentrate management technologies was also identified in the “Desalination and Water Purification Technology Roadmap: A Report of the Executive Committee” (U.S. Bureau of Reclamation and Sandia National Laboratories, 2003) along with the membrane technologies, the alternative technologies, the thermal technologies and the reuse/recycling technologies as the key areas that underpin the next-generation desalination plants for the decade to come in the United States. More remarkably, in a separate section in its recently released guideline entitled “Desalination for Safe Water Supply: Guidance for the Health and Environmental Aspects Applicable to Desalination”, World Health Organization (2007) also discussed the concentration management and the related EIA issues.

2.3.2 Laboratory and field investigations

An investigation on the incipient lethal high salinity (ILHS), namely, the critical salinity at which the survival of different marine species changed remarkably, was performed by Iso et al. (1994). The authors simulated a process of seawater salinity rise in the laboratory, and examined the death timing and rate of some representative species. From the study, they proposed the ILHS to range from 50‰ to 70‰. A numerical analysis under a specific discharge condition was also conducted, and the achieved rise in salinity was expected to be around 1‰. Although this minor increase in salinity would not do severe harm to biota, the proposed ILHS still arouse a concern on the effect of brine discharge on coastal marine organisms, especially when a considerable increase in salinity is expected.

A valuable field study on the mixing process of brine discharges in south Canary Islands was reported by Pérez Talavera and Quesada Ruiz (2001). Samples were taken from the vicinity of the outfall and relatively distant area under an extremely calm sea condition that was considered to be an unfavorable condition for dilution. Dilution measurements showed that both salinity and turbidity fell within the local regulatory range, which further ensured the conformity with regulation under normal marine conditions. However, it was unexpected to find that, during the long-term observation, the brine was diluted in the entire water column rather than accumulated in the bottom. The authors attributed this to the short depth and the dynamics of the receiving water. Additionally, the bathymetry of the discharge area was also investigated. Based on the measurement, the water depth increased moderately away from the coastline, and this situation was found to favor the diffusion of the brine mass and give rise to a increased dilution in the offshore direction.

Another *in situ* monitoring of the brine discharge from the Alicante seawater reverse osmosis (SWRO) plant (SE Spain) was performed by Fernández-Torquemada et al. (2005). Three survey campaigns were made during the first year of the plant operation to determine the seasonal and spatial distribution of the brine plume and its impacts on the ecology. Monitoring of the salinity-sensitive *Posidonia oceanica* seagrass meadows and echinoderm indicated that the dynamics of the biological communities in the affected area was generally consistent with the measured variation of salinity due to brine disposal.

Subsequently, the monitoring of the *Posidonia oceanica* habitat which represents the most important ecosystem in the Mediterranean to assist the site selection and the specific discharge method used during the plant design stage was further elaborated by Latorre (2005). A more recent study on the tolerance

thresholds of *Posidonia oceanica* to the salinity increase due to brine discharge can be found in Sánchez-Lizaso et al. (2008). Meanwhile, Del-Pilar-Ruso et al. (2008) reported the effects of brine discharge on a group of indicator benthic organisms, the Polychaeta, also around the Alicante plant.

2.3.3 Numerical modeling

The study by Del Bene et al. (1994) was among the first modeling work concerned with the environmental impact of brine discharge both qualitatively and quantitatively. On the qualitative side, the authors clarified the concept of regulatory mixing zone pertaining to brine discharges. They argued that the use of the hydrodynamic initial dilution zone, which is measured by the distance the plume travels before it contacts the ocean floor, should be the appropriate definition of the mixing zone for submerged brine discharges. Based on a rule of thumb, the authors also claimed that an effluent dilution to 1 parts per thousand (ppt) above ambient tended to be a conservative guideline. On the quantitative side, the authors extended the widely used Cornell Mixing Zone Expert System (CORMIX) to B-CORMIX (Brine-CORMIX) to incorporate both positively and negatively buoyant discharges and also enabled the modelling of discharges from both surface and submerged sources. In principle, a heuristic rule-based expert system was used by CORMIX to classify a given discharge in conjunction with the associated ambient condition into one of dozens of prescribed flow classes to facilitate further treatment. CORMIX had been validated extensively by available field and laboratory data on mixing processes and approved by USEPA. Under the umbrella of CORMIX, B-CORMIX covered a variety of ambient flow conditions and bottom bathymetries, thus extended its range of application substantially. Notably, the authors had noticed the effect of bottom attachment on the dilution process and studied the characteristics of the impact point. However, compared with a later experimental study by Roberts et al. (1997) on the same issue, the conclusion drawn from the model prediction appeared to be dubious. As revealed by the more accurate LIF results, the centreline dilution pattern turned out to be more complex and reached the minimum at the impact point. On the contrary, the centreline dilution peaked at the impact point in the model prediction. Despite its crudeness in several aspects, this work is still considered a significant pioneering effort on modelling brine discharge. Subsequently, Doneker and Jirka (2001) upgraded the rule-based expert system to incorporate a user graphic interface (GUI) and renamed it CORMIX-GI. More features were implemented in CORMIX-GI to facilitate the mixing zone analy-

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sis, regulatory compliance and outfall design. The upgraded system was able to handle problems ranging from submerged single-port (CORMIX1), multi-port diffusers (CORMIX2) as well as surface discharge sources (CORMIX3), and was designed to distinguish between the Regulatory Mixing Zones (RMZ) and Toxic Dilution Zone (TDZ), the latter of which being a more strict dilution criterion. The system also incorporated potential boundary interactions that could be in the form of dynamic near-field wake or Coanda attachments.

More recently, ad-hoc hydrodynamic or oceanographic modeling studies are often performed to evaluate the near- and far-field brine dilution corresponding to different discharge options (see for example Jenkins and Wasyl, 2005; Miller, 2005; Hodges et al., 2006), which have been proved to be an efficient and effective tool in facilitating the decision-making process during the planning and conceptual design stage. To achieve a higher level of confidence in the simulation results, however, an associated field survey for model calibration and validation purpose is highly preferable (see for example Okely et al., 2007).

2.3.4 Case-study examples

Hoepner and Lattemann (2002) reported a case study on the environmental impacts from the chemicals contained in the brine discharges from the seawater desalination plants in the northern Red Sea. The authors identified the two major sources of chemical load in brine discharge, namely, the pretreatment additives and the corrosion products (heavy metals) that were both detrimental to the ecosystem.

Another case study on the environmental impacts of a desalination plant in Ashkelon, Israel was reported by Einav and Lokiec (2003). This desalination plant was ranked as one of the largest in the world and was designated to make up almost one quarter of the nation's shortfall in potable water supply. Potential environmental impact caused by the construction and operation of desalination plant of such a gigantic size was expected to be tremendous and demanded huge mitigation effort. Particularly, the excessive salinity problem was successfully solved by mixing the brine discharge with the hot water emission from a nearby power station. In addition to the salinity problem, a phenomenon of sedimentation of brines close to the seabed was observed by the authors. In the event that the function unit to produce mixture was not working properly and the brine was not well diluted before released into the sea, a build-up of salinity in the seabed was anticipated. The experience gained from dealing with the environmental impacts of the Ashkelon plant is of great significance to the forthcoming

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mega-plants to be built around the world.

A case study of the environmental impacts especially that from the brine discharge for five plants located in Canary Islands was reported by Jaime Sadhwani et al. (2005). Malfeito et al. (2005) shared the experience of a proper site selection in conjunction with the adaptive discharge scenario in successfully reducing the environmental impact of the brine discharge in the Javea desalination plant.

In a recent case study on a hybrid power and water distillation plant in the Gulf region, Alameddine and El-Fadel (2007) compared the effectiveness of various discharge configurations such as surface channels, submerged single-port outfalls as well as multi-port diffusers on diluting the brine using the CORMIX model. A general modeling guideline including sequentially the characterization of the brine and its impacts, the specification of the plant operating conditions and the ambient hydrodynamic characteristics, the definition of the modeling scenarios, the prediction of the dilution rates and plume development, the sensitivity analysis of the input parameters and the interpretation of the modeling results and overall assessment of the discharge options was clearly demonstrated. Based on the results of the sensitivity analysis, the authors also pointed out the major limitation of CORMIX to be the arbitrary use of length scales to determine the flow class as it often makes a small change in an input parameter result in a total change of the assigned flow class, which in turn leads to an apparent discontinuity in the resultant modeling predictions.

2.4 Near-field Studies

Generally, the process of the dilution of the discharge effluent in the coastal waters can be divided into an initial near-field dilution, or jet dilution, and a subsequent far-field dilution, or natural dilution. The near-field dilution mainly depends on the outfall geometry, the discharge velocity and the density difference between the effluent and the receiving seawater. Therefore, the near-field process can be readily controlled by engineering measures. The far-field dilution is the further advection and diffusion by the ocean currents and tides as well as other natural processes present in the sea. We present a review of the relevant studies on the near-field process in this section, and the far-field in the next section.

2.4.1 Inclined dense jets

For brine discharges in coastal waters, a submerged inclined outfall is typically suggested as it can produce a curvilinear trajectory for the dense jet before the

jet impacts the sea bed. Various studies had been conducted in the past to quantify the inclined dense jet characteristics.

2.4.1.1 Laboratory and field experiments

Zeitoun et al. (1970) conducted a pioneering experimental study on the outfall systems for desalination plants. In their study, the experiments of a dense jet at 30°, 45°, 60° and 90° discharge angles into a stagnant receiving water were performed. Based on the experimental investigation, nozzles inclined at the angle of 60° were found to produce the longest trajectory for entrainment and hence gave rise to the maximum dilution at the maximum rise level. The suggestion of an apparent ‘optimal angle of 60°’ was then adopted in a number of subsequent experimental studies (Pincince and List, 1973; Roberts and Toms, 1987; Roberts et al., 1997, etc).

Pincince and List (1973) studied extensively the process of the disposal of brine into an estuary. According to the results of laboratory bioassays, the authors suggested a dilution of 100:1 as a requirement before the plume impinged the seabed where the most susceptible benthic species reside. Model experiments using point-based conductivity probes to study the dilution of brine disposing into a flowing stream were conducted. When comparing with predictions from the integral model developed by Fan and Brooks (1969), the authors found that the flow trajectory was predicted with reasonable accuracy but the dilution was significantly underestimated. Through dimensional analysis, the authors also related the terminal rise height of the jet and the dilution at the peak of the jet trajectory to the initial angle and densimetric Froude number.

James et al. (1983) conducted a laboratory model study on the dilution of a vertical dense jet in a stagnant ambient to simulate the brine discharge associated with the construction of crude oil reserve in the salt domes along the Gulf of Mexico coast. The authors argued that, with continuous discharge and settlement of the dense effluent, a dense layer consisting of incompletely-diluted effluent would form and accumulate over time near the nozzle, which would further diminish the nozzle tip height above the layer, i.e., the effective riser height. It was noted that, because the effective riser height decreased as the thickness of the dense layer increased, the concentration at the bottom increased. The authors introduced the ratio of the riser height to the water depth to account for the effect of the bottom on the jet flow pattern, and a linear relationship was derived by means of regression analysis of experimental data. The relationship was further validated by field studies. It was concluded

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that, qualitatively, the higher the riser, the longer the trajectory of jet going downstream and the greater the dilution. However, their proposed formula were refuted by Roberts and Toms (1987) who argued that the inclusion of receiving water depth as an independent variable was apparently incorrect.

As a follow-up of James et al.'s work, McLellan and Randall (1986) carried out a field study in the Gulf to measure the vertical brine jet height and the bottom dilution for an operating multi-port outfall. Conductivity-temperature-depth (CTD) sensors were placed at specific stations within a sampling grid to collect dilution information. Meanwhile, underwater acoustic instruments were deployed to obtain the images of the individual jets. Considerable variations in the collected data from different campaigns were observed, however, in both the jet height and bottom dilution, indicating the effects of highly variable oceanic currents. Overall, the field data verified the laboratory results and suggested that slightly larger vertical height and dilution could be expected in the real offshore environment, with the latter appeared to be less dependent on the ambient current than the former.

An extensive series of experiments on the characteristics, i.e., dilution and rise height of inclined and vertical dense jets discharged into uniform cross-flow with various speeds and directions was reported by Roberts and Toms (1987). With zero cross-flow, i.e., the stagnant ambient case, it was found that the effect of source volume flux was not negligible for jet Froude number less than 25. The dilution of an inclined jet increased as the angle to the current increased from 0° (co-flow) to 180° (counter-flow). An example illustrating the application of the study in the design practice was presented. In view of its lower rise height and much higher dilution (nearly double), it was concluded that the inclined jet was generally preferable than the vertical jet under stagnant conditions. A number of empirical formulae were derived based on dimensional analysis and the experimental data to predict the impact dilution, terminal height and dilution at the peak.

Roberts et al. (1997) revisited the inclined dense jets using more advanced laser diagnostic tool of LIF together with micro-conductivity probe for the data acquisition close to the boundary. The jet was inclined upward at an angle of 60° to the horizontal, which was confirmed by previous studies to be an optimum design for the brine outfall to achieve maximum dilution. By dimensional analysis, a number of equations regarding the gross jet characteristics such as the terminal rise height, the dilution at the impact point, the downstream minimum dilution, the horizontal distances of the impact and minimum dilution

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points from the nozzle as well as the thickness of the horizontal spread region were derived, with the respective proportionality constants determined empirically using the experimental results. The turbulent fluctuations of the local concentrations were observed to decay in the streamwise direction away from the nozzle, which the authors attributed to the collapse of the turbulence and relaminarization of the flow due to the influence of density stratification. In order to investigate the potential effect of the turbulence collapse on the dilution process, the authors extended the measurement of dilution further downstream from the impact point. Beyond the impact point, the flow was found to turn into a predominantly horizontal turbulent free shear layer that entrained more ambient water. As a result, the dilution continued to increase until it reached the ultimate minimum value. The authors speculated that, henceforth, further mixing ceased presumably because a stable gravitational density field had been created and overwhelmed the formerly dominant turbulent kinetic energy that drove the mixing process. Based on the proposed turbulence-collapse theory, the authors argued that the end of the mixing zone should be redefined as the location where the discharge induced turbulence collapsed and thereby the ultimate minimum dilution reached. However, the underlying physical hypothesis needs further experimental justifications.

Zhang and Baddour (1998) investigated the maximum penetration of vertical round dense jets to simulate the discharge of brine from desalination plants and other industrial discharges into the ocean. Experiments were carried out with respect to small and large densimetric Froude numbers with the demarcation value set as 7.0. For $Fr > 7.0$, it was found that the effect of the source mass flux on the maximum jet penetration was negligible, and the maximum height was linearly proportional to the initial jet densimetric Froude number. The derived proportionality constant fell within the range of the reported results, which varied significantly from study to study. The authors attributed the large scatter among the reported results to the definition and the method used to measure the maximum height, the Reynolds number, the density difference as well as the mass flux. However, the selected density difference in their test series prepared for small Froude number appeared to be unacceptably large in terms of the Boussinesq approximation. For $Fr < 7.0$, the derived proportionality constant was found to be less than the previous results. The authors attributed this disparity to the effect of source mass flux.

As noted in the introduction, the maximum rise height with the 60° inclination tends to be large and might not be accommodated by the prevailing shallow

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coaster waters in the reclaimed coastline of many cities. Recognizing this constraint, a number of experimental studies focusing on the mixing behavior of a smaller discharge angle have been attempted recently (see for example Cipollina et al., 2005).

Cipollina et al. (2005) extended the study of negatively buoyant discharges in a stationary ambient to include the flow behaviors at different discharge angles, in particular 30° , 45° and 60° as well as different nozzle diameters, effluent densities and discharge flow rates. Their studies characterized the flow geometrical features including the maximum rise level and the impact point distance, etc.. All the normalized geometrical parameters were found to be very well correlated to the densimetric Froude number. The authors also checked the effect of fluid viscosity and found it to be insignificant within moderate variations. However, they did not cover measurements on concentration information which are crucial for environmental impact assessment purpose.

2.4.1.2 Theoretical and numerical modeling

Integral analysis has been widely used to study the gross behaviour of the turbulent jets and plumes. With the method of integral analysis, the kinematic equations (continuity, Navier–Stokes and scalar advection–diffusion equations) are integrated across the flow, giving rise to a set of conservation integrals for the mass, momentum, buoyancy and scalar concentration fluxes. The flow is typically assumed to be self-similar after a short distance from the exit (zone of flow establishment) with the mean axial velocity, buoyancy and scalar concentration taking some forms of Gaussian distribution. In conjunction with the assumption that the density difference between the flow and the ambient fluid is small (Boussinesq’s approximation) and that the fluid is fully turbulent and incompressible, the set of conservation equations can be integrated over a cylindrical flow segment (control volume) and yield a set of ordinary differential equations. To solve the system of equations numerically, another closure equation is required and the entrainment assumption and the spread assumption are the common options.

The integral modelling of vertical and inclined round positively buoyant jets in an unbounded stagnant and homogenous ambient fluid has been attempted extensively in the past decades (see for example Morton, 1959; Abraham, 1963; Fan and Brooks, 1969; Fischer et al., 1979; Wood et al., 1993). Recently, the state of the art has been advanced to the second order components (Wang and Law, 2002; Law et al., 2003; Yannopoulos, 2006), which account for both mean and

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turbulent mass and momentum fluxes using entrainment and spread hypotheses, respectively. On the practical application front, Jirka (2004) has developed and validated the integral model CorJet to supplement the widely used commercial package CORMIX and discussed its applicability limits in various buoyant-jet flows.

On the contrary, reported studies on the integral models for the round negatively buoyant jets, or dense jets, have been much less found in the literature (Abraham, 1967; Bloomfield and Kerr, 2000), particularly for models incorporating an inclined angle of discharge (Cipollina et al., 2004; Papanicolaou et al., 2008).

For horizontal and inclined jets with an initial density different from the receiving fluid, the trajectory of the jet axis will soon deflect from the initial angle of discharge due to the orthogonality of the vertical buoyancy force and the initial horizontal momentum. As a result, the predictions of the trajectory and additional features are much more complex than in the vertical cases, especially in the case of negative buoyant jets where flow reversals happen. In Abraham (1963, 1965), the rate of spreading of the horizontal buoyant jet was assumed as an empirical function of the local angle of inclination along the curved trajectory. However, the assumption was later discussed by Fan and Brooks (1966) to be dubious as the resulting entrainment rate was shown to be unphysically related to the distance from the origin rather than controlled entirely by local parameters. Fan and Brooks (1969) adopted a constant entrainment coefficient α to model the inclined buoyant jet in a stagnant uniform environment. Lane-Serff et al. (1993) developed an integral model to predict the trajectory and concentration of the inclined forced plume (i.e. buoyant jets) using the top-hat formulation and a constant α with a somewhat larger value of 0.1, and found that the shape of the plume depended only on the angle of the plume to the vertical at the virtual origin. The predicted density difference was also found to be consistently lower than the experimental counterpart due to the large α value adopted. In CorJet (Jirka, 2004), the empirical α function contains different terms that account for the asymptotic cases of pure jet, pure plume, pure wake, advected line puff and thermal, respectively, and can be reduced to $\alpha = 0.055 + 0.6 \sin \theta Fr^{-2}$ for buoyant jets in stagnant unstratified environment.

Motivated by the peculiar dynamics of buoyancy reversal in the explosive volcanic jets and the lack of appropriate α value for the negatively buoyant jet, an experimental study was performed by Kaminski et al. (2005) to address the entrainment behavior in the initial negatively buoyant jet regime and obtained a

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much reduced α_t of 0.057 (equivalent to Gaussian-type α of 0.040). Furthermore, recognizing that Priestley and Ball's model (Priestley and Ball, 1955) was generically built for the positively buoyant jets and may not cope with the inverted cases especially the observed reduction of entrainment, the authors revisited the previous work and derived a sophisticated formulation of the entrainment coefficient appropriate for arbitrary buoyancy. With a modified definition, the local Richardson number Ri in the new model turned negative for negative buoyancy, which then gave rise to a reduced α as observed in the experiment. The complete self-similarity assumption was relaxed in the model development. Instead, shape integrals of the unknown local velocity, buoyancy and Reynolds stress profiles were retained in the entrainment function and might be determined by best-fit experimental results wherever available. This new feature allowed the evolution of the self-similarity in different flow regimes to be accounted for, and was also used by the authors to explain the difference among the measured values of α found in the literature (see more details in Carazzo et al., 2006). The use of a lower entrainment coefficient for the negatively buoyant jets was also proposed by Papanicolaou et al. (2008) in recognizing that gross geometrical characteristics such as the terminal rise height, the horizontal distance to the impingement point as well as the corresponding dilution were considerably underestimated if α derived from positively buoyant jets was adopted in the modelling. Instead, a much reduced value of 0.03 was assumed for α_{jet} , which led to an improved agreement between the model predictions and experimental results.

There are also a number of numerical models developed to supplement their experimental counterparts mentioned in the previous section. In order to interpret the experimental data acquired from a preceding experimental study (Zeitoun et al., 1970), Zeitoun et al. (1972) built a novel numerical model to evaluate the dispersal of the brine effluent. The major novelty of the developed model was that both the entrainment coefficient and non-dimensional coefficients with respect to the distribution profiles were allowed to vary as functions of the port densimetric Froude number and a Froude number defined by the ambient flow for the first time. All the functions were then determined empirically by fitting the model predictions at the peak of the jet axis to the obtained experimental data at this position. The model gave a reasonable prediction of the trajectory of the jet axis and the dilution at the peak of the jet. The major deficiency of the developed model was that it overestimated the lateral spreading factor. As a result, the entrainment relationship was not satisfactorily reproduced. A preliminary conceptual design procedure making use of the empirical

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formulae was demonstrated as well.

A numerical model of inclined dense jets in a stagnant environment was developed by Cipollina et al. (2004) in the attempt to facilitate the design of dense effluent diffusers. Similar to the experimental counterpart (Cipollina et al., 2005), the model inputs were four jet parameters, namely, the flow rate, density, inclination angle and diameter, while the outcome was the prediction of the jet behavior as trajectory, spreading and dilution. The model adopted the entrainment assumption and used an arbitrary α value of 0.06, which surprisingly led to a good agreement with the experimental results in the predicted jet centerline, the impact point distance and the horizontal location of the jet peak. However, the model predictions of the jet boundary and terminal rise height were unsatisfactory. A sample application of the model to the design of a hypothetical dense effluent diffuser was also presented. It is also worth noting that, when a sloping seabed was involved, the authors found that jets angled moderately less than 60° produced a larger dilution and a smaller jet maximum rise.

More recently, Kikkert et al. (2007) developed analytical solutions from an integral model to predict the behavior of the inclined negatively buoyant jets and compare with the data from previous studies and their validation experiments using both Light Attenuation (LA) and LIF techniques. The analytical solutions gave reasonable predictions to the flow path and the maximum jet height for various discharge angles ranging from 0 to 75° and initial Froude number from 14 to 99. However, the inner spread was underestimated. The predictions of the minimum integrated dilution at the maximum centreline height and the impact point were also shown to be underestimated.

In their recent overview on brine discharges based on the latest laboratory data and CorJet modeling results (Jirka, 2008; Bleninger and Jirka, 2008), the authors concluded that in the case of a sloping bottom, or equivalently, an elevated discharge port from the seabed, smaller inclinations of 30° and 45° can produce the highest dilution at the maximum centerline height and a higher dilution at the impact point, as well as better offshore transport of the mixed effluent under weak currents and the ability to be accommodated by shallow near-shore ambient. A general design procedure incorporating the new findings was also outlined by the authors.

Oliver et al. (2008) developed a $k-\epsilon$ model of inclined dense jets and compared the model predictions with recent experimental results. The $k-\epsilon$ model was part of a standard computational fluid dynamics (CFD) package—CFX. Two approaches were employed and compared when implementing the model.

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While one approach followed the standard parameter settings in CFX, the other approach calibrated the turbulent Schmidt number used in the tracer transport equation against positively buoyant vertical discharges before applying to inclined negatively buoyant discharges. The calibrated approach was shown to improve the predictions for some bulk parameters, e.g., the tracer spread and dilution when compared to predictions from the standard model. However, the overall effect on the model performance was noted to be limited. Predictions from both models were found to match the experimental results in trajectory, but appeared to underestimate the flow spread and the integrated dilution at the centreline maximum height. Model predictions also confirmed the presence of the buoyancy-induced instability on the lower half of the flow.

2.4.2 Horizontal dense jets

As noted in the previous section, previous researchers have proposed an optimum design scheme for the brine outfall as a round submerged discharge inclined at 60° to the horizontal seabed (Zeitoun et al., 1970). In practice, however, a horizontal discharge configuration is occasionally adopted based on cost considerations and the relative ease for construction (Pérez Talavera and Quesada Ruiz, 2001).

There have been very few studies on the mixing of three-dimensional horizontal negatively buoyant jets near a parallel boundary (also referred to as offset dense jets) reported in the literature as far as the author is aware. It is noted, however, that a similar but dynamically inverted process of horizontal positively buoyant jets in the presence of bed and free surface boundaries in stationary ambient waters has been reported before. The configuration of the flow could be an ascending horizontal buoyant flow above a parallel solid boundary (e.g., Balasubramanian and Jain, 1978; Jirka, 1982; Sobey et al., 1988; Johnston and Volker, 1993; Johnston et al., 1994), or alternatively, a descending horizontal dense flow below a parallel solid or free surface boundaries (e.g., Knudsen and Wood, 1990; Li, 1997; Wood, 2002). Note also that two-dimensional offset jets have been widely used in various other industrial applications, for instance, burners, boilers, gas turbine combustion chambers, and fuel injection systems (see the summary in Nasr and Lai, 1998); In addition, three-dimensional non-buoyant wall jets have been studied extensively in the past, and the relevant results can be compared for references (Rajaratnam and Subramanya, 1968; Newman et al., 1972; Rajaratnam and Pani, 1974; Launder and Rodi, 1983; Law and Herlina, 2002; Herlina and Law, 2002). It is also worth mentioning

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that Law et al. (2004) studied the double diffusive effect associated with the horizontal neutral jet which was a mixture of heat and salinity and typical of the hybrid desalination and cooling water discharges.

Since the abovementioned studies are in most cases not explicitly related to the present problem, detailed description about them is neglected except for limited examples. Specifically, a study on the horizontal buoyant jets by Balasubramanian and Jain (1978) is introduced in this section, and various studies on the same flow but subject to potential boundary effects are presented in the next section. However, comparisons of the experimental results with the various reference studies are provided as appropriate and discussed in Chap. 5.

Balasubramanian and Jain (1978) conducted an experimental investigation on the horizontal buoyant thermal jets in quiescent shallow water. The flow field, including both near field and far field, was separated into four sub-regions: buoyant jet region, zone of surface impingement, internal jump region and flow away (counter flow or surface jet) region. Among those sub-regions, the buoyant jet region, which consisted of the zone of flow establishment (ZFE), the zone of established flow (ZEF) and the zone of surface impingement (ZSI), was of the principal concern due to their dominant influence on the mixing process. By means of dimensional analysis, the spatial distribution of the temperature rise was deduced to be a function of the densimetric Froude number, the ambient water depth and the port diameter. Due to its upward rising trajectory, the positively buoyant heated jet was shown to be highly affected by the surface stability. Based on the experimental data, the authors further discovered that the surface layer was stable for lower jet densimetric Froude numbers and higher submergence ratios. However, in their experimental setup, 160 thermistors supported by aluminum channel sections were positioned to measure the temperature distributions just below the water surface. Consequently, the large number of intruded apparatuses might have brought in non-negligible disturbance to the flow field, but the authors had not noted any of its potential impact nor did they prepare any countermeasure.

2.4.3 Boundary effects on jets

In his review paper on turbulent buoyant jet in shallow waters, Jirka (1982) discussed the influence of both the bed and free surface confinements for a range of geometries, and also highlighted the resultant reduction in the associated dilutions.

As noted in the introduction, when a jet discharge is placed close to an

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impermeable boundary, the Coanda attachment can occur, which in turn result in impaired mixing and hence adverse environmental impacts on the benthic community. While the Coanda effect on a positively buoyant jet near the bottom was investigated previously by Sobey et al. (1988), no parallel study can be found for the negatively buoyant (i.e., dense) jets including brine discharges so far.

Sobey et al. (1988) studied the round positively buoyant jet discharging horizontally into stationary shallow ambient water. Intuitively, the proximity to the bed and the free surface might play a significant role on the flow pattern. Based on this consideration, the authors introduced two dimensionless parameters to account for the effect of the geometrical constraints, namely, the free surface proximity parameter $(H - z_0)/L_M$ and the bed proximity parameter z_0/L_M , where H is the ambient water depth, z_0 the port height above the bed and $L_M = M_0^{3/4}/B_0^{1/2}$ the jet/plume characteristic length scale. Experiments were carried out to measure the temperature distribution in vertical planes at different downstream locations under different submergence levels, water depths and source densimetric Froude numbers. The jet trajectory, centerline dilution and horizontal and vertical half widths were obtained and compared with the predictions for unbounded flow from the integral model developed by Fan and Brooks (1969). Satisfactory agreements were observed for cases with moderate bed proximity parameter except during the transition to a surface jet. For z_0/L_M less than about 0.1, apparent deviations exhibited and were attributed to the Coanda effect. As the nozzle approached the bed, the entrainment was substantially reduced which in turn affected the dilution. The entrainment was also found to be affected by the surface boil arising from the interaction of the ascending jet with the free surface. Altogether, some deficiencies are noted in this study. Firstly, the impact of the discharge instability was not well distinguished from the Coanda effect. Since both effects coupled with each other naturally, attempts to separate the two by experiments were proved to be very difficult. Secondly, the selection of temperature as the tracer scalar was subject to greater experimental uncertainty. Although the authors had defined three integral parameters to account for the heat dissipation, the heat conservation was still in doubt. In this regard, it was recommended to choose other more stable solute as tracer, such as dye. Also, the point probe technique used in their experiment was not considered to be accurate enough according to the present-day criterion.

Knudsen and Wood (1990) extended the study of boundary effects to conditions involving ambient current, whereby a number of possible flow patterns

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might occur. The buoyant jet was injected horizontally from a single port that was attached to a trolley and placed close to the free water surface representing the horizontal boundary. The trolley was towed at a constant velocity through the stationary ambient water to provide the ambient current. The phenomenon of Coanda attachment was observed when the port approached the water surface as well as when the Froude number was sufficiently large. Moreover, it was found that jet under counter-flow (ambient flow opposite to the discharge) was prone to be unstable as indicated by its more variable trajectories compared with flow under still or co-flowing condition. Finally, a number of criteria were summarized by the authors to categorize a flow into the generalized different flow patterns, and the critical value was found to be almost twice as large in the co-flow condition as in the stationary ambient reported by Sobey et al. (1988).

In their combined measurement of velocity and temperature for pure and buoyant jets in shallow waters, Johnston and Volker (1993) discovered that dilutions of both jets were significantly reduced irrespective as to whether the buoyancy existed or not. Experimental results also confirmed the threshold z_0/L_M value that was critical for the occurrence of Coanda attachment to be approximately 0.1. Even for the non-Coanda flow, on which the influence of Coanda effect was insignificant and consequently the attachment did not take place, a delay in rising relative to unbounded jet was observed. Another remarkable finding by the authors was that the length of the potential core of the pure jet appeared to be shorter in shallow environment. Subsequently, Johnston et al. (1994) built an integral model to simulate this specific flow. The model consisted of a number of sub-models that individually accounted for local effects caused by the presence of the bed and free surface boundaries. Based on previous and companion experimental results, the Coanda effect was incorporated and quantified in the WALJET and INTERMEDIATE-JET sub-models, corresponding to the strongly- and weakly-influenced scenarios respectively. More sophisticated planar laser induced fluorescence (PLIF) technique was employed by Li (1997) to study the horizontal buoyant jet near a solid boundary in a co-flowing ambient. The critical condition obtained was very close to Knudsen and Wood's result, implying that the free surface acted essentially similar to a the solid boundary. To further elucidate the effects of different boundary types on the behavior of buoyant flow, Wood (2002) conducted experiments by injecting brine plume below both types of boundary. Contradictory with Li's finding, it was found that the influence of the rigid surface extended further below the boundary than that of the free surface, which translated to a critical z_0/L_M value of approximately

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0.25 for the rigid boundary while 0.17 for the free surface case. Free surface was also found to cause a much elongated separation distance than rigid surface. The differences were attributed to the rate of momentum loss due to friction at the boundary and the extent to which entrainment is reduced in a vertical plane. Despite the difference between the two types of boundary, interestingly, in cases when both boundaries are in close proximity to the nozzle, the flow can deflect towards either one depending on which is dynamically closer to the nozzle (Tsunoda et al., 2006).

It is also worth noting that Coanda effect was incorporated and accounted for in the expert system CORMIX1 developed by Jirka and Doneker (1991) as a boundary effect together with the wake effect. As discussed by the authors, Coanda attachment was dependent primarily on the initial inclination angle θ . A quantitative criterion for the occurrence of Coanda attachment was further given as $\tan \theta < 0.2 - z_0/L_j$, where L_j is the distance of the jet region. For a stagnant environment, L_j was replaced by the jet/plume characteristic length scale L_M defined earlier.

2.5 Far-field Studies

In List and Imberger (1973), the authors predicted that, as a result of the continuous input, there would be a general increase or buildup in the background level of pollutant concentrations. In the case of brine discharge, the excessive concentration will be the salinity excess. Despite the significance of assessing the salinity buildup, which is the primary long-term environmental impacts of the continuous brine discharge as noted previously, relevant work has been scarce in the literature. However, extensive modeling studies have been performed in the past decades to predict the transport and dispersion of an analogue discharge, i.e., the waste-water or sewage, in the ocean in order to address the resulting water quality concerns. A number of significant studies are summarized in the following. Meanwhile, it is noted that the transport problem in the context of groundwater is very similar to the problem under current investigation in terms of the governing equation as well as the initial and boundary conditions. Hence, we have also referred to a number of relevant groundwater studies.

In their comprehensive review on the near-field and far-field fluid mechanics related to the waste-water disposal in the ocean, Koh and Brooks (1975) dedicated one section on the further dispersion of the waste plume in the ocean following the jet mixing and the establishment of the waste field. The dispersion

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was delineated in the horizontal and vertical directions. Specifically, the horizontal diffusion coefficient K_x was found to be correlated with the size of the diffusing patch in a 4/3 power law, i.e., $K_x = AL^{4/3}$ ($10^{-1} \leq L \leq 10^8$ ft), where L is the size of the diffusing patch. Meanwhile, there was no evidence of any significant dependence of K_x on stability or total depth. The authors further pointed out the overall scarcity of existing data on vertical diffusion, and referred to the few studies concerning the dependence of K_y on the Richardson number, the density stratification, as well as the wave characteristics. With regard to the application of the Fickian approach and the 4/3 power law for eddy diffusivity to the real waste-water plume, the authors argued that the approximate solution developed by Brooks (1960) is adequate for resolving the horizontal diffusion from a finite line source of pollutant in a steady current. The authors further stressed the necessity to pay attention to the advective transport on top of the diffusion, and cautioned the increase of the background pollutant level once the continuous discharge and the flushing current reached the steady state, and advocated the placement of the outfall further offshore to increase the travel time to the beaches for the bacterial decay.

A random-walk type far-field model was developed by Chin and Roberts (1985) using the Lagrangian particle-tracking approach. The model used the source conditions of the rise height, dilution, waste field thickness and the volume flux of the effluent as output from near-field models, and incorporated the measured coastal current meter data to infer the ensemble particle distribution and thus simulate the dispersion. The model was well validated by comparisons with field results for both instantaneous and continuous releases during stratified and unstratified periods.

Roberts (1999) used two models to predict far field behavior of the waste-water plume, namely, a short-term statistical model (FRFIELD) that was coupled with the near-field model (NRFIELD) and directly used simultaneous measurements of current speed and direction collected from Acoustic Doppler Current Profiler (ADCP) in the field (Mamala Bay, Hawaii), and a long-term model that assessed the potential buildup of contaminants in the vicinity of the discharge resulting from flushing, horizontal diffusion and bacterial decay. The spatial variations around the diffuser of statistical measures of the impact of surfacing plumes were predicted. Specifically, the visitation frequency, or the probability of plume impaction at a point, was predicted to decrease rapidly with distance from the diffuser, and so did the the frequencies of exceedence of various coliform densities. Any outfall impacts on the beaches were also revealed

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to be extremely low. In terms of the long-term effect, it was implied that physical dilution caused by flushing and large-scale diffusion was very high such that no significant buildup of contaminant was expected. The modeling results also indicate that worst-case conditions, for example, direct onshore transport of the plume combined with the lowest initial dilution and lowest bacterial decay rates were often assumed to assess the beach impacts, were extremely improbable, and their use could lead to overly conservative outfall designs and treatment levels.

It is also worth noting that although the major emphasis of the widely used software package CORMIX (described in Section 2.3) is on the geometry and dilution characteristics of the initial mixing zone, predictions on the far-field processes, including the initial buoyant spreading driven by gravity and the subsequent passive diffusion induced by ambient turbulence, are also incorporated. In CORMIX GI (Doneker and Jirka, 2002), boundary interaction that occurs when the flow impacts either a surface or bottom, or forms a terminal layer in a stratified ambient, was used to characterize the transition from near field to far field. A specific postprocessing tool called ‘FFlocatr’ was then invoked to compute the far-field plume trajectory and dimensions in nonuniform rivers or estuaries.

One, two and three-dimensional solutions for instantaneous, continuous and steady-state pollution sources in uniform groundwater flow were given by Hunt (1978). The practical application was further presented by the author to: (1) determine how long a continuous source must be in place before steady-state conditions were approached; (2) determine the effect of a finite aquifer depth upon solutions for an aquifer of infinite depth; (3) calculate maximum concentrations for instantaneous sources under two different sets of conditions; and (4) determine the time required for solutions for a point source and a source of finite size to approach each other.

Wilson and Miller (1978) derived the analytical solution for the two-dimensional plume in uniform groundwater flow. The authors employed the method of temporal convolution in the derivation. In principle, if the solution for instantaneous point source was given as $C_i = f(x, y, t)$, by convolution with respect to time, we could achieve the solution for a continuous source provided other conditions kept invariant, namely, $C_c = \int_0^t f(x, y, t - \tau) d\tau$. In addition, a graphical method utilized to better visualize the plume and estimate relevant parameters was introduced by the author. A practical application was also demonstrated in the study.

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A modeling study on the effect of coastal water depth variation upon mixing and spreading of brine in the sea water was reported by Purnama et al. (2003). As commonly practiced in modeling study, a number of assumptions were made to simplify the formulated problem. Specifically, tidal effect, temperature and density variations were ignored; brine was assumed to be well mixed vertically over the water depth; the current was steady and remained parallel to the shoreline. Consequently, the diffusion in the current direction was elongated and neglected as a further approximation; the variations of current velocity and diffusivity in the offshore direction were assumed as power functions of the water depth only. The bathymetric condition was approximated to be a moderate straight slope in the near-shore region and a flat bottom with an overlying constant water depth afterwards. The point source was represented by a source term with Dirac delta function in the governing equation. The boundary condition was no-flux condition at the shore. The authors derived the solutions in the near-shore and far-shore regions separately, and then matched the respective solutions from the two geometries at the intersection to reach the general solution. The contours of the salt concentration were then presented by the authors. They also investigated the salinity distribution along the beach, which was a highly sensitive area with respect to the environmental concern, and identified the peak salinity as well as its location accordingly. The general idea that further reduction in salinity could be achieved by extending the discharge outfall further offshore was also verified by the authors.

Subsequently, assuming simple channel geometry, Purnama et al. (2005) developed a mathematical model to assess the impact of the seawater desalination on the regional salinity in the already hyper-saline and environmentally fragile semi-enclosed Arabian marginal seas of the Arabian Gulf and Red Sea. Thereafter, they extended their study to the effects of an oscillatory tidal flow in dispersing the brine discharge occurring in the Gulf of Oman (Purnama and Al-Barwani, 2006). More recently, they showed that the maximum shoreline salinity would remain constant throughout the tidal cycles and thus can be used as an indicator for regulatory purpose (Al-Barwani and Purnama, 2008).

2.6 Summary

Published studies on the general environmental impacts of brine discharge, the resultant near-field and far-field processes in shallow coastal waters are reviewed and summarized in this chapter. This thorough review provides a solid basis

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and clear starting point for the present study.

It is noted that 30° and 45° inclined dense jets have been covered by a few recent studies. However, concerns have been expressed on the inadequacy of the limited data set to support the development of predictive models (Jirka, 2008; Bleninger and Jirka, 2008), not to mention the disparity among the reported results in some gross flow characteristics. It is thus necessary to revisit the problem with the advanced laser diagnostic tools, i.e., PIV and PLIF. It is also noted that the effect of the bed proximity, or the so-called Coanda effect, on the behavior of the inclined and offset horizontal dense jets has never been examined before. We aim to fill these blanks with the respective experimental investigations in the present study. Due to the availability of the turbulence data from the simultaneous PIV and PLIF measurement in the 2D center plane, the cross-sectional distributions of the turbulence characteristics and Reynolds flux were also analyzed for the offset horizontal dense jets, which further made possible the calculation of the associated turbulent viscosity, diffusivity as well as the turbulent Schmidt number.

In addition, according to the literature survey, very few studies have been performed to investigate the long-term cumulative effect by the continuous brine discharge into the seawater from the far-field perspective, especially the transient process of the salinity buildup. Therefore, we attempt to examine the temporal evolution in the present study. Moreover, we study the fluctuations in salinity in the presence of the oscillatory tidal currents as well as the effects of other relevant parameters including the anisotropy and possible time dependency of the dispersivities in the buildup process.

With the various research gaps and challenges identified herein, they can now be addressed individually in the following chapters.

Chapter 3

Experimental Methodology

3.1 Introduction

As noted in the introduction, the advanced laser diagnostic tools of the combined particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF) are employed in the present experimental investigations to measure simultaneously the velocity and concentration fields of the flows of interest. In this chapter, we first review the major previous studies using combined PIV and PLIF as their experimental methods, through which we can then have a general idea about how the technique has been evolved to its current state (Section 3.2). Then we describe in detail the specific setup used in the present study. The key components and accessories, their configuration and work mechanism are elaborated (Section 3.3). Afterwards, the general experimental procedures are introduced and discussed (Section 3.4). In the end, the relevant experimental uncertainties are identified and analyzed (Section 3.5). Note that the uniqueness of the individual experiments will be pointed out in the pertaining chapters.

The experimental program was conducted in the Hydraulic Modeling Laboratory of the School of Civil and Environmental Engineering, Nanyang Technological University.

3.2 Combined PIV and PLIF Technique

3.2.1 Overview

In the past decades, traditional intrusive techniques such as pitot tubes or hot wire anemometry (HWA), and non-intrusive laser Doppler velocimetry (LDV) or acoustic Doppler velocimetry (ADV) have been widely used to measure ve-

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locity in various fluid flow. Single-point measurements have the advantage of relatively high temporal resolution, or sampling frequency. However, they do not provide whole field information of a flow at one time. To reconstruct the spatial velocity distribution of a steady flow, one can repeat point measurement at different locations, although the procedure is tedious and time-consuming. If the flow is unsteady, such an attempt becomes very difficult or even impossible. With the evolution of lasers, modern cameras, and computer hardware, whole field velocimetry techniques have emerged. Differing from the point-based techniques, the state-of-the-art planar velocimetries such as particle image velocimetry (PIV) and particle tracking velocimetry (PTV) are capable of resolving the spatial variation of the turbulent flows. In recent years, PIV and PTV have been used extensively to measure complex spatially varying turbulent flows such as the negatively buoyant jets addressed in the present study.

The fundamental working principle of PIV is straightforward. Instantaneous marker locations are optically frozen by brief pulses of laser light and recorded on a sensor medium such as a video array detector. The recorded images are then correlated to obtain the instantaneous velocity, V_i , from the basic kinematic relation:

$$V_i = \frac{\Delta s}{\Delta t}$$

where Δs is the marker displacement within two consecutive laser pulses and Δt is the time interval in between.

An early in-depth account of the PIV technique was provide by Willert and Gharib (1991).

On the other hand, probe-based techniques like micro-conductivity probes, have been used for many years to measure tracer concentration. These techniques are intrusive to the flow and also suffer from the spatial limitation mentioned above. This problem has been overcome with the advent of the laser induced fluorescence (LIF) technique. Early applications (Papanicolaou and List, 1988) provided a time series of local concentration with high temporal resolution at a single spatial point but did not yield the spatial distribution of the concentration field. More recently, the planar laser induced fluorescence (PLIF) technique has been invented and used to measure the two-dimensional concentration field.

The PLIF technique involves exciting the fluorescent dye tracers with light at a wavelength within the range of its absorption spectra. The dye then emits light at longer wavelengths with the intensity being proportional to the local dye concentration and the incident light. The emitted fluorescent light distribution

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is recorded by a camera. After a careful calibration, the recorded intensity field can be converted to the corresponding concentration field.

For a milestone document, see van Cruyningen et al. (1990), in which the ability of PLIF technique to investigate the mixing of turbulent air jet was demonstrated for the first time.

3.2.2 Review of previous studies

This section reviews the existing studies using the combination of PIV/PTV and PLIF to study the turbulent jets, which is also the experimental approach adopted in the present study. As noted in the introduction, a successful coupling of the two experimental techniques will reduce the time consumed and eliminate the potential errors induced by repeating the experiments if concentration and velocity are to be measured at different times. The combined technique also makes available the simultaneous measurement of instantaneous velocity and concentration and the associated turbulent flux, which in turn will shed light in the mass transport process and facilitate addressing the relevant environmental concern.

Fukushima et al. (2000) combined the technique of PIV and PLIF to investigate the mixing process of an axisymmetric turbulent jet. The authors used a Nd:YAG pulsed laser for the illumination of PIV and a continuous wave Argon-ion laser for PLIF, respectively. In this manner, the common disadvantage of using pulsed laser for PLIF was avoided, although it certainly increased the difficulty and workload of the alignment. It is noted that the PIV and LIF measurements were made sequentially in order to completely avoid mutual interference. The time interval between pulses and the exposure time were prudently chosen and the total duration of the measurement was 1.5-7.6 ms which was shorter than the Kolmogorov time scale. Mean quantities and fluctuation components were evaluated. Satisfactory agreement with the results from direct numerical simulation (DNS) and previous experimental data was observed. In addition, the authors proposed a mass balance checking method based on the mass balance equation, and the mass balance for their experiment was found to be reasonably well with the small discrepancy attributed to the finite spatial resolution of the measurement and the highly intermittent concentration fluctuation. Surprisingly, the LIF measurement was in double-frame mode as PIV but only the second LIF frame was used.

Hu et al. (2000) investigated almost the same flow as Fukushima et al.'s but with a focus on the near-field (from nozzle exit to five nozzle diameters down-

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stream) using combined PIV and PLIF system with a different configuration. Beam splitter was used to separate the LIF light and the scattered laser light. To ensure the purity of the received light, band-pass and high-pass filters were fitted in the cameras for PIV and LIF, respectively. An improved spatial correlation analysis method named hierarchical recursive method was developed in the study to process the PIV images. As indicated by the authors, the recursive operation started with a large interrogation window size and search distance. By using the results of the previous iteration step as the approximate offset values in the next iteration step, the interrogation window size and search distance were reduced successively. It was revealed that, with this new method, the final interrogation window was normally up to 8 by 8 pixels with spurious vectors being less than 2%. Compared with the interrogation windows commonly used in the conventional correlation algorithms which was 64 by 64 or 32 by 32 pixels, the improvement in the accuracy and efficiency was arguably evident.

The combined PIV and PLIF system utilized in the present study was originally developed by Law and Wang (2000). The pulse duration of the adopted double pulsed mini Nd:YAG laser was of the order of several nanoseconds which was significantly shorter than the characteristic time scale of the dominant turbulence. Hence, the flow field could be regarded as frozen and the turbulent characteristics could be captured faithfully in real time. Apart from the temporal effect, the pulsed laser outperformed the continuous wave Argon-ion laser in its large instantaneous energy output which was favorable for LIF measurement. However, spatial non-uniformity and temporal unsteadiness were also consistently present in the output energy intensity of pulsed laser as its inherent shortcoming. The smaller dimension of the mini Nd:YAG laser was remarked to fit for the often limited laboratory space. More importantly, the potential interference between the seeding particles used for PIV and the fluorescent dye used for LIF was addressed after a careful and comprehensive study. Other effects including the sampling frequency and attenuation of laser intensity were also examined. The maximum sampling rate was noted to be constrained by the transfer speed of the computer hardware. The authors also pointed out the relatively low spatial resolution of the PLIF measurement in the direction perpendicular to the laser plane, which was further explained to be dictated by the PIV measurement that set the limit of the off-plane motion of seeding particles during the pulse interval. In this regard, any further attempt in order to improve the spatial resolution of LIF independently would be meaningless. However, as identified by the authors, the spatial resolution in measured velocity in the laser

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plane was 5.7 mm which was larger than the Kolmogorov length scale ranging from 0.1 to 1.0 mm in the studied area. As a result, comprehensive analysis of the turbulence spectrum or dissipation could not be performed. Moreover, taking advantage of the built-in correction modules in the FlowManager software (®Dantec Dynamics), the geometric distortion associated with the measurement could be amended satisfactorily. As a validation of the newly developed combined system, it had been applied to study a turbulent buoyant jet discharging vertically into a stagnant environment. Various mass transport quantities were measured and compared with existing data, and overall agreement was shown to be good. The authors also highlighted the significant timesaving by the simultaneous measurement. It is also worth noting that, subsequently, a refined second-order integral model for the round buoyant jet was developed by the authors with the turbulent mass transport being resolved in a unprecedentedly high accuracy using the combined technique (Wang and Law, 2002).

A single-camera coupled PTV and LIF technique was developed by Cowen et al. (2001). The advantages of the developed system were summarized as: (1) alignment and registration issues associated with dual-camera PIV and LIF system were avoided; (2) independent laser sources were used for each technique, namely, pulsed Nd:YAG laser for PIV and continuous wave Argon-ion laser for LIF. By equipping both techniques with well-suited laser source, the resulting measurements were more desirable. It was stressed that using expanded Nd:YAG for LIF measurement would inevitably suffer from its poor repeatability and lower signal-to-noise ratio away from the light sheet centerline. Apparently, however, the novel configuration would induce excessive complexity in recording the PIV and LIF images in a non-interferential manner, and the authors coped with this challenge successfully with a three-image-sequence solution, in which the instantaneous velocity field was derived from the first and last images while the middle image captured the concentration information. Various adverse effects such as photo-bleaching, vignetting and attenuation arising from improper configuration or operation were carefully studied and ensured to have slight or no impact on the results. A validation experiment employing the new setup to study a neutrally buoyant turbulent jet was presented, and the results were found to compare well with previous experimental results.

Webster et al. (2001) developed another combined PTV and PLIF system and used it to conduct simultaneous measurements on a turbulent jet. The PTV technique adopted by the authors followed that of Cowen and Monismith (1997). Although the associated analysis method seemed more computationally

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intensive, the advantage of the PTV technique was highlighted as it was capable of producing a non-uniform grid of vectors in comparison to conventional PIV technique. The obtained mean velocity, turbulent stresses, mean concentration, concentration variance and turbulent flux data were all observed to exhibit self-similarity in the far-field of the flow, and satisfactory agreement with previous results was also reported.

Borg et al. (2001) performed simultaneous velocity and concentration measurement in the near-field of a turbulent low-pressure jet by using a combined PIV and PLIF system. The mean and fluctuating velocity and concentration data and the correlations were found to be consistent with large eddy simulation (LES) results as well as published experimental results in the literature. The authors iterated that the energy variation from pulse to pulse as well as in the distribution over the laser sheet might be the shortfall of pulsed laser to be used for LIF measurement. Extremely careful calibration was conducted prior to the concentration measurement and the variation was found to be about 2.5% of the mean energy and thus had insignificant effect. The authors also pointed out that the continuous injection of tracer and fluid into the finite-dimension test tank would increase the background tracer concentration as well as the flow volume, which needed to be accounted for especially for the transient problem. It is noted that the source dye concentration of $15 \mu\text{g/l}$ adopted in the experiment was considerably lower than in other similar experiments. Given further that the 25 mJ laser power per pulse was also relatively low, the configuration seemed not to be ideal for LIF measurement. The image capture rate of 2 Hz was also somewhat low.

More recent examples of combined use of PIV and PLIF can be found in (Law et al., 2003; Su and Mungal, 2004; Feng et al., 2007).

3.3 Experimental Setup

This section contains a detailed description of the experimental setup adopted in the present study. Firstly, the facilities and accessories used are introduced. Thereafter, the PIV and PLIF technique as well as a combined system of the two which is the major component of the overall setup are elaborated.

3.3.1 Facilities

A schematic diagram of the overall experimental set-up for the experiments of inclined dense jets is shown in Fig. 3.1. The experimental setup for the offset

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horizontal dense jets is identical to the inclined dense jets except for some minor adjustments.

Figure 3.1: Schematic diagram of experimental setup (not to scale)

The test tank was made of glass and had a dimension of 2850 mm (L) by 850 mm (W) by 1000 mm (H). The thickness of both the bottom and side walls was 15 mm. The tank was reinforced and supported by a stainless steel framework. The bottom of the tank was elevated to be 0.85 m above the ground, hence a moderate space was created to accommodate the laser equipment. The transparent bottom allowed the laser light to be shone from below the tank.

A Perspex platform of 2000 mm (L) by 800 mm (W) was installed above the tank floor to simulate the sea bed, as well as to allow the nozzle tip to protrude for experiments of the inclined dense jets. The platform was fixed at one end to the tank using ballast.

The effluent was injected from a glass nozzle. The nozzle was connected to a reinforced flexible hose and clamped to a stainless steel frame. The center of the nozzle tip was elevated to a certain height, z_0 , above the platform surface, which can vary with a moderate range depending on the specific experiment. The nozzle was sufficiently long to ensure fully developed turbulent flow conditions at the exit.

The effluent was seeded with polyamid seeding particles with a nominal diameter of $50 \mu\text{m}$ and a small amount of a fluorescent dye, Rhodamine B. The relative density difference between the effluent and the ambient water, $\Delta\rho/\rho_a$, can vary in a small range (about 1-2%), with the ambient water density inside the test tank kept constant while the effluent having a density slightly larger.

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The jet flow was produced by a constant head tank situated about 1 m above the discharge port. The head tank was used instead of a pump because the investigation of the near-bed covered the region near the nozzle, and the constant head tank produced less fluctuation in this region. The dimensions of the head tank were 600 mm (L) by 300 mm (W) by 500 mm (H). A partition panel (300 mm (L) by 400 mm (H)) was placed in the tank to divide the head tank into a constant head chamber and a drain chamber of equal volume.

A separate storage tank was used to store the source solution. Two peristaltic pumps were used to pump the source solution from the storage tank to the constant head chamber during the experiments. If the pumping flow rate was higher than the jet discharging rate, the constant head chamber would overflow and the water level inside would remain constant. The drain chamber collected the overflowed solution from the constant head chamber and drained them back to the storage tank and recirculated. A calibrated electromagnetic flow meter was installed between the constant head tank and the nozzle exit to measure the flow rate in the experiment. Note that for the test series F in the inclined dense jet experiments, the effluent was injected directly by the peristaltic pump.

3.3.2 Accessories

3.3.2.1 Fluorometer

A fluorometer was used to measure the Rodhamine B concentration in the source and calibration solutions. The fluorometer was the model TD-700 manufactured by Turner Design. When properly calibrated, the fluorometer is able to measure the fluorescent tracer concentration of the sample with the optimal sensitivity and measuring range. In this study, the measuring range of the fluorometer was set to 0-500 $\mu\text{g/l}$ with a resolution of 0.1 $\mu\text{g/l}$.

3.3.2.2 Balance

The Mettler-Toledo AG285 analytical balance was used for precision weighing of the seeding particles and the Rhodamine B. The dual-range balance has a maximum capacity of 210g, and the resolution is 0.01 mg in the range of 0-81g and 0.1 mg from 81g above, respectively. The balance has built-in fully automatic calibration technology (FACT).

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3.3.2.3 Density meter

A DMA 35N portable density meter manufactured by Anton Paar GmbH was employed to measure the density of the solution and the ambient water in the test tank. The density meter has a resolution of 0.1 kg/m^3 .

3.3.2.4 Flow meter

A calibrated electromagnetic flow meter (KROHNE Altometer SC80AS, capacity $0\text{-}0.9121 \text{ m}^3/\text{h}$, accuracy 1%) was installed between the constant head tank and the nozzle exit to measure the flow rate in the experiment.

3.3.2.5 Peristaltic pump

Two peristaltic pumps (Masterflex 7549, Cole-Parmer Instrument Co.) were used to pump the source solution from the storage tank to the constant head chamber during the experiments. The flow rate provided by the peristaltic pump was fully controllable. The indicator reading on the display panel of the peristaltic pump was carefully calibrated to the actual flow rate before the experiments. Through the calibration, it was found that the maximum flow rate of 48.3 ml/s can be set with a high accuracy of $\pm 0.167 \text{ ml/s}$ (0.35%). The maximum delivering head is 8 m.

The main reason for using the peristaltic pump instead of other types of pump, e.g., centrifugal pump, was that the fluid was not in any contact with the pump, thus the pump was kept from corrosion by the saline solution. In addition, the peristaltic pump can produce an acceptably constant flow rate even under drastic water level changes in the source tank.

3.3.3 Combined PIV and PLIF system

The velocity and concentration fields of the various experimental flows were simultaneously measured in the symmetrical vertical centerline planes using the combined PIV and PLIF technique developed by Law and Wang (2000). The combined PIV and PLIF approach had been shown to be able to quantify the mixing process in an accurate manner (Law and Wang, 2000), with PIV providing the instantaneous and time-averaged profiles of the velocity distribution and PLIF giving access to the concentration distribution concurrently to analyze the dilution. It is noted that various effects such as the camera pixel-by-pixel response, the unsteadiness of the pulsed laser intensity, photo-bleaching and saturation, the attenuation of laser intensity due to dye absorption and the presence

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of salt in the solution on the PLIF measurement as well as the potential interference between the PIV and PLIF techniques pertaining to the current combined system has been addressed by Wang (1999). For brevity, it is neglected herein.

A schematic diagram of the combined system is shown in Fig. 3.2.

Figure 3.2: Schematic diagram of the combined PIV and PLIF system (adapted from Wang (1999))

3.3.3.1 Particle image velocimetry (PIV)

In the present study, the instantaneous velocity of the experimental flows was measured using a PIV system manufactured by Dantec Dynamics. The overall advantage of PIV technique over the traditional point-based techniques and its basic principle is briefly introduced in the beginning of this chapter. In the following, the individual component of the PIV system employed in the present study is reviewed.

Seeding particles In PIV, it is actually not the velocity of the flow that is measured, but that of the particles suspended in the flow. It is required that the seeding particles have to be chosen as small as possible to follow the flow faithfully and passively, i.e., to follow the motion of the fluid without significant lag and yet not to alter the flow dynamics. However, at the same time, particles

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must be large enough to scatter sufficient light so that distinct particle images can be captured, which guarantees the accuracy of the subsequent image analysis. A narrow particle diameter distribution would also be desirable. Meanwhile, the particles should be neutrally buoyant in the fluid.

Typically, the diameters of the seeding particles used for PIV measurement range from 0.1 to 50 μm . In this study, polyamid particles with a nominal diameter of 50 μm are selected (density: 1.03 g/cm³; size distribution: 30-70 μm ; refractive index: 1.5).

Mini Nd:Yag laser A dual-cavity frequency-doubled Q-switched pulsed mini Nd:YAG laser (New Wave MiniLase) was placed below the test tank to illuminate the flow. This arrangement greatly reduced the penetration length of the laser light in the water, thus reduced the potential attenuation of light intensity. The laser has an energy out of 25 mJ per pulse and emits green light with a wavelength of 532 nm. By using the Q-switch, the pulse duration can be as short as 7 ns, which produces a stroboscopic effect and freeze the movement of the particles during the illumination. The maximum pulse repetition for each cavity is 15 Hz. The time interval between pulses are dictated by experimental parameters including the object-to-image scale factor and the maximum velocity of the flow. In this study, each laser pulse lasted for 10 ns with the delay between pulses set to 2000 μs .

The light sheet was created by cylindrical optics and had a typical thickness of 3 mm and a divergence angle of 32°. By careful prior alignment, the two laser beams from the two cavities were ensured to be co-linear and illuminated exactly the same spatial area. The laser was mounted on top of a lead screw base and can be moved to any desired location during the experiments.

CCD cameras and optical filters Images were taken by two charged-coupled device (CCD) cameras (Kodak Megaplug ES1.0, resolution 1008×1016 pixels), one for PIV and the other for PLIF. The images were recorded in black and white (256 greyscale) and digitized at 8 bits per pixel by an image digitizer and processor. The CCD chip, which has an equal number of storage cells corresponding to the light-sensitive pixels, is 9.1×9.2 mm² with pixel pitch (i.e., the center-to-center distance between adjacent pixels on the CCD chip) of 9 μm both horizontally and vertically, pixel size of 3.4×7 μm^2 and a fill factor, which is defined as the ratio of its light-sensitive area to its entire area, of 60%.

For PIV measurement, the first pulse of the laser pulse pair is timed to expose the first frame and the second pulse to the second frame. Once exposed,

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the first frame is immediately transferred from the light-sensitive cells to the storage cells of the CCD chip, implying that the first frame is only exposed to the laser light and not interfered by the ambient or background light. After a short delay, the second frame is exposed by the second laser pulse. The two frames, the first in the storage cells and the second in the light-sensitive cells, are subsequently transferred to the PIV processor for correlation analysis. Hence, the second frame is exposed not only to the laser light but also to the ambient or background light. Consequently, to safeguard the image quality, we need to use dark room and switch off the room light during the measurement to keep the ambient light intensity as minimum. In addition, the CCD camera for PIV was fitted with a 532 nm band-pass filter to only allow a narrow band of 3 nm wavelength around 532 nm that is scattered by the seeding particles to pass through. The maximum frame rate with the double-frame mode is 15.3 Hz.

FlowMap PIV 2000 processor The FlowMap PIV 2000 processor, which has a modular structure, was supplied by Dantec Dynamics and constituted the core of the PIV system. The processor consists of three modules, namely, correlators units, input buffers and a synchronization board. The maximum number of correlator units and input buffers that can be installed is 4 for both of them provided that the total number of the two modules together does not exceed 6.

The correlation algorithm is embedded in the correlator unit. It has a maximum data transfer rate of 6M pixels per second. When necessary, multiple correlators (up to 4) can be installed and work in parallel to provide a higher processing speed. Hence, it affords close to real time analysis of the observed flow.

Two input buffers, one for DPIV and the other for PLIF cameras, were configured in the processor. The input buffers, unlike standard frame grabbers, concurrently read images from a CCD camera and store them in a memory area. These images can then be either divided into interrogation segments to be sent to the correlator units or directly to the PC. The readout of a frame into memory lasts about 66 ms, so a PIV frame pair is read out into the PIV buffer after 132 ms. The PLIF frame is read out into the PLIF buffer at the same time. This poses another upper limit of around 7.5 Hz on the sampling rate of the combined PIV and PLIF.

All activities in the PIV system are synchronized by the synchronization board. This module provides connection and communication links to the illu-

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mination system and the cameras as well as other user-customized devices.

RAID cabinet As discussed above, compared to the frame readout rate from the camera, both the correlator and hard disk writing (if directly writing the raw PIV image pairs to a hard disk without processing) speeds are relatively slow. The captured images thus accumulate in the input buffers. This would limit the sampling duration significantly.

In order to employ the combined PIV and PLIF for complex flow measurements, the system must be able to capture the flow field with sufficiently high temporal frequency for an adequate duration. A relatively long measuring duration up to a few minutes that should be sufficient to establish the mean flow behavior for most laboratory experiments is made possible by utilizing a RAID cabinet, which serves as an intermediate transfer buffer before large block size 1MB bitmap images are slowly being processed and written to the PC hard disk.

FlowManager software The FlowManager software came with the FlowMap processor as well as the laser equipment supplied by Dantec Dynamics. It served as the central control interface of the combined system and integrated functions including configuring the data acquisition and analysis modes as well as managing the data in a database. It is worth pointing out that the multi-selection (of the acquired images) choice as well as the option of a chain analysis provided by the FlowManager software made sequential and automatic multi-step processing of the hundreds of images possible. Links to external mechanical (the motorized traverse system used in this study), computational (Matlab), illustration (Tecplot) tools are also incorporated.

Numerical processing and analysis The numerical processing and analysis of the raw images are documented in detail in Dantec FlowMap® PIV Instrumentation Installation & User's guide (1998). A general description of the correlation analysis method is presented as follows.

The velocities of PIV are measured based on Interrogation Areas (IA) rather than randomly distributed individual particles. The imaged area is divided into a lot of small IAs. Each IA generates one velocity vector. There are usually a number of seeding particles in an IA. To work out the mean displacement in an IA, a 2D spatial correlation, either auto-correlation or cross-correlation, is performed. Normally the spatial correlation is carried out indirectly by performing two consecutive Fourier Transforms, a normal Fourier Transform followed by

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an inverse Fourier Transform. Dividing this by the time interval between laser pluses, an average velocity vector is computed.

There are two important factors influencing the signal-to-noise ratio in the PIV measurement using the correlation analysis. The first is the maximum particle displacement allowed. This limit is based on the Nyquist sampling criterion associated with the discrete Fourier transforms whereby the maximum recoverable spatial displacement in any direction is limited to half the interrogation window size in that direction. However, this displacement is often too large for the technique to work properly. Therefore, the particle displacement between consecutive frames in the acquired PIV image was required to be within $1/4$ IA. The concentration of the seeding particles in the recorded images is another concern in PIV measurement. While a low concentration of particles will make it difficult or even impossible to achieve the minimum number of particles per IA required to minimize the signal dropout (i.e., the particle in either the first frame or second frame of the image pairs are outside the IA), a high density of particles in the images lowers the signal-to-noise ratio due to the difficulty in detecting individual particles. As far as the combined PIV and PLIF system is concerned, a high seeding particle concentration is also detrimental to PLIF measurements due to the absorption of Rhodamine B onto the surface of the seeding particles which leads to the higher induced fluorescence. Taking into account all the above factors, a minimum of 5 particles per IA is typically recommended.

Near the IA edges there is an increased likelihood of signal dropout, i.e., the particle in either the first frame or second frame of the image pairs are outside the IA. Thus, to increase the contribution of the particles near the edges to the velocity calculation the cross-correlation plane was determined to apply 50% relative overlapping of the IAs.

In the present study, the instantaneous PIV images were analyzed using the Adaptive Correlation function provided in the FlowManager software. Evolved from the standard cross correlation method described above, the adaptive correlation method is basically an iterative procedure that calculates velocity vectors with an initial IA of the size N time the size of the final IA and uses the intermediate results as the input for the next IA of smaller size, until the final IA size is reached. For the present analysis, the final IA is configured as 32×32 pixels and the number of refinement steps as 2, thus, the initial IA size is 128×128 pixels. The 50% overlapping in both horizontal and vertical directions between neighboring IAs also contribute to the increase of the spatial resolution.

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Raw vectors from the adaptive correlation included both valid and invalid vectors. The invalid vectors (termed outliers) due to the noise peaks in the correlation function were almost inevitable, and were eliminated or substituted by validation procedures.

The FlowManager software provides three data validation routines that are based on logical mathematical algorithms, namely, peak validation, range validation and moving average validation. The peak validation routine validates or rejects individual vectors based on the peak values returned in the correlation plane where the vector displacement is measured. In this method, it is assumed that the highest peak corresponds to the signal and the second highest peak and below represent noise. The criterion is to reject any vectors for which the signal-to-noise ratio is less than a certain prescribed threshold. In the present experiments, this threshold value is set as 1.2. The range validation validates or rejects individual vectors based on the expected minimum and maximum values of the vector magnitude and/or horizontal and vertical components. Vectors outside a certain range prescribed by the user are considered outliers and hence rejected. In the present study, the range of the vector length is chosen as the validation criterion. The moving average validation validates or rejects vectors based on a comparison with adjacent vectors on a chosen averaging area (5×5 in the present setting) and may subsequently replace the rejected vectors by make-up vectors estimated from n ($n=3$ in the present setting) iterations of interpolation of the neighboring values. Spurious vectors are identified via the prescribed value of the ‘Acceptance factor’ (0.1 in the present setting), which sets an upper limit on the velocity vector gradient obtained inside the averaging area. As a result, the vector map is smoothed out locally depending on the size of the averaging area as well as the maximum velocity gradient allowed.

Finally, routines for further derivation of the vorticity field and streamlines from the velocity field are also incorporated in the FlowManager software.

3.3.3.2 Planar laser induced fluorescence (PLIF)

The basic principle of PLIF is depicted in the beginning of this chapter. The PLIF technique allow two-dimensional measurement of instantaneous scalar fields, i.e., the concentraion of a tracer species, in a non-intrusive manner.

In PLIF, a laser source is used for the excitation of a fluorescent dye present in the flow field. A fraction of the laser light is absorbed and a fraction of this absorbed energy from the laser source is spontaneously re-emitted, or fluoresced. The ratio of the total energy emitted per quantum of energy absorbed by the

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molecule is called the quantum efficiency, ϕ . Assuming weak excitation (i.e., no saturation and photo-bleaching effects involved), the fluorescence energy I' emitted per unit volume is defined as

$$I' = k_1 \phi \varepsilon I c \quad (3.1)$$

where I is the local incident light intensity, c the local concentration of the fluorescent dye, ε the molecular absorption or extinction coefficient of the dye for the incident light, and k_1 a proportionality constant. In the range of weak excitation, both ϕ and ε are constant. Again, Eq. 3.1 indicates that the fluorescence intensity is proportional to the local dye concentration and the incident light intensity provided that the coefficients are constant.

The intensity of the laser beam, i.e., I in the above relationship, decays as it penetrates through the dyed solution. The attenuation arises from two main parts, namely, the attenuation by the clean water and that by the dye, the latter of which increases with the dye concentration obeying the Beer-Lambert law,

$$\frac{dI(s)}{ds} = -(\varepsilon c(s) + \eta_{\text{H}_2\text{O}})I(s) \quad (3.2)$$

where s is the coordinate along the laser propagation path and $\eta_{\text{H}_2\text{O}}$ the molecular extinction coefficient of clear water for the incident light. Integrating Eq. 3.2 from $s = 0$ to $s = l$ where l is the penetration length of the beam yields,

$$I(l) = I(0)e^{-\varepsilon \int_0^l c(s)ds - \eta_{\text{H}_2\text{O}}l} = I_0 e^{-\varepsilon \int_0^l c(s)ds - \eta_{\text{H}_2\text{O}}l} \quad (3.3)$$

where I_0 is the incident light intensity at the laser source. It is worth noting that, in the present setting, the divergence of the laser sheet also causes the laser light to decay along its path of propagation. However, we can focus the discussion on the absorption effect for now. Substituting Eq. 3.3 into Eq. 3.1 leads to,

$$I' = k_1 \phi \varepsilon c I_0 e^{-\varepsilon \int_0^l c(s)ds - \eta_{\text{H}_2\text{O}}l} \quad (3.4)$$

Likewise, the fluorescence intensity received by the light-sensitive medium of the CCD camera, I_c , can be described as,

$$I_c = k_2 I' e^{-\varepsilon' \int_0^{l'} c(s')ds' - \eta_{\text{H}_2\text{O}}' l'} = k_1 k_2 \phi \varepsilon c I_0 e^{-\varepsilon \int_0^l c(s)ds - \eta_{\text{H}_2\text{O}}l - \varepsilon' \int_0^{l'} c(s')ds' - \eta_{\text{H}_2\text{O}}' l'} \quad (3.5)$$

where k_2 is the coefficient that accounts for the light passage through the various optics (e.g., filter, aperture, etc.), and ε' , $\eta_{\text{H}_2\text{O}}'$, s' , l' are the counterparts to ε ,

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$\eta_{\text{H}_2\text{O}}$, s , l with the added prime indicating that they are pertaining to the emitted fluorescent light. The greyscale value of a pixel in the image can be related to the received fluorescence intensity by further taking into account the camera response in the pixel of interest. Notably, the responses of the different pixels for the CCD camera used in the present study have been verified to be effectively linear with the incident light intensity varying from the dark level (around 23 greyscale for the camera used) to the maximum 255 greyscale in Wang (1999).

In Eq. 3.5, only the integral terms, i.e., the attenuation arising from the dye, are not locally dependent and thus can not be resolved by the calibration processes. As such, it is essential to keep the dye concentration low to ensure no significant attenuation of the laser light intensity due to the absorption.

In this study, Rodhanmine B was added to the effluents as tracer, which was excited by the 532 nm (green) laser light and emitted fluorescent light at a peak wavelength of 575 nm (orange). The absorption and emission spectra of Rhodamine B is presented in Table 3.1.

Table 3.1: Properties of Rhodamine B from Berlman (1971)

Dye	Absorption spectrum (nm)			Emission spectrum (nm)		
	Lower	Upper	Max	Lower	Upper	Max
Rhodamine B	460	590	550	550	680	590

For the concentration measurements of a tracer dye, it is important to estimate the rate of molecular diffusion relative to diffusion due to turbulent mixing. This is indicated by the Schmidt number Sc , which represents the ratio of momentum diffusivity (i.e. fluid viscosity ν) to the molecular diffusivity of a species, D_m . The molecular diffusivity of Rhodamine B in water at a temperature of 20°C is $3.6 \times 10^{-10} \text{ m}^2/\text{s}$, which yields a Schmidt number of ≈ 2800 . This implies that the present scalar transport phenomena are dominated by turbulent diffusion rather than by molecular diffusion of the species.

The laser light was provided by the same Nd:Yag pulsed laser used for PIV. Notably, Law and Wang (2000) has discussed the advantages and limitations of using pulsed laser for PLIF measurement and the choice of the Nd:Yag laser was justified. The fluorescent light was then captured by the CCD camera in greyscale images. The PLIF camera was fitted with a 570 nm low-pass filter to block off the scattered 532 nm laser light and all ambient light and let through the fluorescent light only. Unlike the PIV camera, the PLIF camera was set to work in a single-frame mode and each PLIF image was taken from a pulse pair that was the same as the PIV pulse pair. This meant that the PLIF image

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was double exposed by the two consecutive laser pulses. The purpose of the double exposure arrangement for PLIF image was to improve the sensitivity of the PLIF measurement. Also, it ensured that both the measured velocity and concentration were the time mean values during the pulse interval.

For the PLIF camera, the zero-concentration background image was found to have an intensity of approximately 23 greyscale, which is the dark level of the camera. Within a typical imaging window, a relatively high concentration of 100 $\mu\text{g/l}$ Rhodamine B solution (following Wang (1999) which is higher than what typically used in most previous studies) would lead to an image intensity of only approximately 120 greyscale with the aperture fully opened and the sensitivity set to its highest state. The range is rather low relative to the full greyscale of 255. The problem of low intensity may be improved by increasing the dye concentration at the source. However, at higher concentrations, the concern on the above-mentioned laser light attenuation due to the absorption by the dye would then arise. In Wang (1999), the attenuation effect was examined empirically, with the molecular absorption coefficient of Rhodamine B for the 532 nm laser light ε determined to be $0.0176 \text{ (m}\cdot\mu\text{g/l)}^{-1}$. The molecular absorption coefficient for the 575 nm fluorescent light ε' should be much smaller than ε , which can be explained in two folds: firstly, a much large fraction of the fluorescent dye molecules are taking the 532 nm incident light as it is more towards the absorption peak; secondly, the fluorescent light is the product of the first-stage absorption that is dependent on the laser beam absorption, consequently, the reabsorption should be less intense.

3.3.3.3 Calculating Reynolds fluxes

The simultaneous PIV and PLIF measurement affords us to calculate the Reynolds fluxes. Based on the large number (N) of samples, the Reynolds flux is approximated to be,

$$\overline{u'c'} = \frac{1}{N} \sum_{i=1}^{i=N} [(u_i - U) \cdot (c_i - C)]$$

where u_i and c_i are the local instantaneous velocity and concentration for the i -th sample, respectively, and the capitalized terms denote the corresponding mean quantities averaged over the N samples.

To calculate the Reynolds flux, re-sampling of the scalar map is necessary as this step ensures that the resulting scalar values refer to the same coordinate system as the PIV results, i.e., for each vector produced in an IA, there is a corresponding scalar value averaged over the same region. The calculation

is incorporated in FlowManager by first calculating the instant Reynolds flux maps and then perform the average.

3.4 Experimental Procedures

In this section, the general experimental procedures common to all experimental tests are presented, which consist of six main stages: preparation, laser alignment, camera focusing and image re-sampling, selecting PIV measurement parameters, PLIF calibration, data acquisition and data analysis.

3.4.1 Preparation

Before each experiment, the test tank was drained, cleaned and filled to a certain depth depending on the specific experiment to ensure that the rise of the jet flow would be kept well below the free surface. A small amount of seeding particles were scattered into the ambient water around the measurement area to enhance the velocity measurements in the vicinity of the flow. The tank was filled 2 to 3 hours prior to the experiments, during which the water was left to settle to ensure the condition of stagnant ambient.

Concurrently, the source solution, which was a mixture of tap water, salt (NaCl), dye and seeding particles of desired concentrations and density, was prepared. The density of the solution and ambient water in the test tank was measured by the density meter. The dye concentration in the solution was measured by the fluorometer.

3.4.2 Laser alignment, camera focusing and image re-sampling

The Nd:Yag laser used in this study was mounted on top of a lead screw base and can be moved to any desired location during the experiments. The emitted laser light was aligned to coincident with the vertical center plane of the nozzle to illuminate the target area by adjusting the four leveling feet at the base of the laser support.

The two CCD cameras faced each other from the opposite sides of the tank, and both were mounted on rails carried by a motorized traverse system. The axes of both cameras were perpendicular to the laser light sheet to ensure that no geometrical distortion occurs in the images. When the two cameras were moved to position, a reference object, steel rule or self-constructed grid, was

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lowered into the tank and aligned with the center plane of the nozzle, to assist in adjusting the focus of the cameras and to ensure that the cameras captured exactly the same target area. By placing a reference object in the measurement plane, we obtained a relationship between pixels on the CCD chips and physical distance in that plane, i.e., the object-to-image scale factor of the captured images. The typical object-to-image scale factor (inverse of the commonly used magnification) was 9.95, which resulted in a field of view of $90.5 \times 91.2 \text{ mm}^2$. The associated resolution was 11.14 pixels per mm in the illumination plane. For the present multiple-window measurements, the horizontal and vertical offsets of the local window from the nozzle exit, which is the universal origin in the overall coordinates, can be inferred from the portion of the labeled grid covered in the local calibration images. A sample pair of images of the labeled grid is shown in Fig. 3.3. From the pictures, it is clearly shown that both cameras are well-focused and no geometrical distortion is involved in the captured images. Meanwhile, the field of view of the two cameras coincides with each other. Note that the two images are captured in room light with both cameras set to single-frame mode to allow a longer exposure time. The difference in the brightness of the two images is due to the non-uniformity in the illumination.

Figure 3.3: Sample images of the reference grid for camera alignment

After this step, both cameras were first fitted with a 532 nm band-pass filter. A small amount of seeding particles was then scattered inside the tank where the cameras were focusing, and adaptive correlation was applied to the captured images of the seeding particles. These camera-alignment pictures were saved for the re-sampling of the PLIF images in later stages. In re-sampling, the correlation results quantified the exact displacement between the PIV and PLIF images and related the PLIF-coordinates to their PIV counterpart, which

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was critical for the combined measurements.

3.4.3 Selecting PIV measurement parameters

Based on the criterion of the concentration of the seeding particles discussed earlier and trial run results, the optimum concentration of the seeding particles for the present study was determined to be 0.1 g/l.

The time interval between laser pulses, Δt , is an important parameter in the PIV measurement as it determines the maximum and minimum velocities that can be measured. Based on the maximum particle displacement during pulse interval discussed previously, a preliminary upper-bound limit can be calculated using the following formula:

$$t \leq \frac{0.25 N_{\text{int}} SF d_{\text{pixel}}}{U_{\text{max}}}$$

where U_{max} is the maximum velocity estimated in the flow field, N_{int} the side of the IA in pixels (which is 32 in the present study), SF the object-to-image scale factor and d_{pixel} the pixel pitch (e.g., 9 μm for the Kodak ES1.0 camera used in the present study). Note that the computed t is in the unit of μs .

Meanwhile, the maximum time interval is also limited by the magnitude of the out-of-plane motions. The out-of-plane component of velocity causes particles in the first frame of an image pair to move out of the IA before the acquisition of the second image. Likewise, particles can move into the IA and appear only in the second image. These unpaired particle images result in extra uncorrelated information or noise. The noise can result in an incorrect correlation peak being chosen by the correlation algorithm, which biases the velocity measurements towards zero if we assume that the incorrect peaks are randomly distributed.

The IA was finally chosen to be 32×32 pixels along with the time interval between pulses as 2000 μs in the present study.

3.4.4 PLIF calibration

PLIF calibration was required before each experiment. The whole tank was filled with calibration solutions of ascending nominal concentrations, namely, 0 $\mu\text{g/l}$ (which was clean water and rendered the background image), 20 $\mu\text{g/l}$, 40 $\mu\text{g/l}$, 60 $\mu\text{g/l}$ and 80 $\mu\text{g/l}$. 30 images were captured for each calibration solution. A digital mask was manually created from the calibration image of each exper-

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imental run. The masks block off regions of obvious laser light reflections or obstructions. Least-square fitting was then carried out to relate the gray scale values in the captured images to the corresponding dye concentrations. The fitting was performed in a pixel-by-pixel manner to account for the variation in laser intensity across the light sheet due to the inherent spatial non-uniformity through the optics and the attenuation when the laser light passed through the dyed ambient water. The dye concentrations used in both the experiment and calibration were kept small to minimize the attenuation effect. Notably, to achieve reliable PLIF measurements, the concentration of the measured dye concentration was kept in the range of 0-100 $\mu\text{g/l}$ to maintain the linearity of the fluorescence intensity versus the concentration. Once the calibration was completed, the settings of the camera and the laser were kept the same throughout the entire experiment. A sample pixel-by-pixel calibration curve is presented in Fig. 3.4.

Figure 3.4: Sample pixel-by-pixel calibration curve

3.4.5 Data acquisition

When an experiment began, the regulable gate valve placed on the flow path was gradually open until the reading of the flow rate from the electromagnetic flow meter attained the predetermined value (note that for the test series F in the inclined dense jet experiments, the peristaltic pump was simply set to the desired flow rate and the flow was initiated to run through the bypass system). After the flow rate was observed to be stable (normally took about 60 seconds), the room light was shut off and the laser was switched on. The LIFO buffer was then turned on to capture the images until 300 records were taken for each position. The traverse system subsequently carried the cameras to the next window, of which at least 10% overlap was accommodated to ensure continuity in the captured images. The water in the test tank was then replaced. The steps were repeated for each position until the full trajectory of the flow under investigation was captured. In order to maintain the measured dye concentrations in subsequent windows to be within the calibrated range, we had to gradually increase the source dye concentration when moving the camera downstream. During the course of the experiments, room temperature was kept at $\sim 20^\circ\text{C}$ by air-conditioning to prevent any possible effects due to thermal convection in the test tank.

For a typical experimental run, the sampling frequency was set at 5 Hz for the combined measurements. The sampling duration lasted up to 60s, during which the 300 PIV and PLIF images were captured to ensure that the measurements were sufficient for performing time-average. The relatively short duration also prevented the possible adverse effect due to the accumulation and recirculation of the injected fluid in the confined test tank.

As explained in the introduction, the proximity to the bed plays a significant role in affecting the flow pattern. For a specific bed proximity z_0/D , experiments with different densimetric Froude number Fr were conducted to investigate the dependence of bed influence upon z_0/L_M . The same experimental procedures were repeated for a series of tests.

The experimental parameters for the various test series are tabulated in the respective chapters. A sample pair of instantaneous images of PIV and PLIF is shown in Fig. 3.5.

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Figure 3.5: Sample raw images (offset horizontal dense jet)

3.4.6 Data analysis

The instantaneous PIV images were analyzed using the Adaptive Correlation function of the FlowManager software, with IA being 32×32 pixels corresponding to a typical spatial resolution of $2.87 \times 2.87 \text{ mm}^2$. The overlapping of the IA was 50%, so that a 62×62 vector field was calculated for each image. As noted earlier, the overlapping is necessary due to errors inherently exhibit close to the edges of the IAs. Raw vectors from the adaptive correlation included both valid and invalid vectors. The invalid vectors (termed outliers) due to the noise peaks in the correlation function were almost inevitable, and were eliminated or substituted by validation algorithms (in this study, both Range and Moving-Average validations were performed in sequence). The 300 instantaneous moving-averaged velocity maps for each window were then time-averaged to obtain the mean velocity field. In the mean velocity map, only valid vectors were retained to obtain a better representation of the velocity field. The mean velocity maps from the individual windows were then pieced together to form the entire flow field.

For concentrations, the fluorescence intensity values were first converted to the concentration values using the prepared in-place calibration curve. The concentration values were then re-sampled by using the vector map produced by the alignment of the two cameras as described earlier. The 300 instantaneous data were then time-averaged to obtain the mean concentration map. Finally, the quantitative concentration data of the individual windows were normalized with their respective source dye concentrations, and then assembled to produce the full concentration map. The mean scalar images of the different windows were combined in a similar fashion as the mean velocity vector maps to produce

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the concentration distributions for the entire jet flow. The Matlab routine used to stitch the multiple-window results can be found in Appendix A.1.

The instantaneous velocity vector and concentration scalar maps corresponding to the sample raw PIV and PLIF images shown in Fig. 3.5 are illustrated in Fig. 3.6. The velocity vector map to the left is rendered after the range and moving-average validation, with the blue arrows representing the valid vectors and the green arrows representing the substituted ones. In the concentration contours to the right, the different colors denote the different concentration levels. Note that image re-sampling has been applied in the processing of PLIF data.

Figure 3.6: Sample analyzed results

3.5 Analysis of Experimental Uncertainties

The overall measurement accuracy in PIV is mainly dependent on the the physical measuring process, including the particle image diameter, the seeding density, the particle image displacement and the velocity gradient with the IA, etc, and the methods of evaluation of the collected data, or image processing. Uncertainties in the PLIF measurements originate from the calibration and the measurement itself. By maintaining the ambient temperature at a constant degree (20°C), the effect of the thermal-sensitivity of the Rhodamine B on the PLIF measurement was reduced to minimum.

3.5.1 Effect of sampling frequency

The limited sampling frequency and duration is certainly a constraint of most experimental setups and including the setup for the present study. The sufficiency of determining turbulence properties with a specific averaging time and sampling frequency had been addressed by Law and Wang (2000) for buoyant jet studies based on the consideration of Nyquist frequencies as follow.

Turbulent fluctuation of a physical quantity such as velocity is directly related to the turbulent energy content in a system (Tennekes and Lumley, 1983): $\overline{u'^2} = 2 \int_0^\infty E(f)df$, where $E(f)$ is the spectral energy density at a particular frequency f . Theoretically it is necessary to obtain and integrate the entire energy spectrum to determine the magnitude of the turbulent fluctuation. In reality this is of course impossible to achieve and in fact may not be necessary to do so. A measurement of reasonable accuracy can be obtained if most of the energy content in the associated phenomena is captured within the measuring frequencies, i.e., $\overline{u'^2} \cong 2 \int_{f_l}^{f_u} E(f)df$, where f_u and f_l are the upper and lower limits in the measuring frequencies. With the present system, the upper limit of the turbulent energy spectrum that the system is capable to resolve is the Nyquist frequency of 2.5 Hz. Despite the low value, the frequency would be sufficient for the determination of the turbulent fluctuation in those mixing processes with bulk of the energy production occurring at a much lower frequency. For example, in the verification experiments (Papanicolaou, 1984) of a vertical pure jet into stagnant ambient, information is available on the turbulent energy spectrum for the axial velocity, radial velocity and the concentration. For the axial velocity, the energy production occurs primarily in the range of 0.1 to 1 Hz. From 0.1 Hz to approximately 3 Hz the spectral turbulent kinetic energy decreases over 3 orders of magnitude. Comparatively, the turbulent energy spectrum for the radial velocity and the concentration do not decay as rapidly with a decrease of about 2 orders of magnitude in the same range. Following this reasoning, in Wang and Law (2002), the large-scale times (using the formula suggested by Papanicolaou and List, 1988) were estimated to be 0.8 s and 2.8 s for the vertical jets and plumes into stagnant ambient. They then adopted a sampling duration of 60 s and frequency 5 Hz, and showed that the measurements were adequate for statistical turbulence analysis based on the analysis of conservation of total mass and total momentum (including turbulence contributions). In the present study, although no direct measurement of the turbulent energy spectrum exists for the horizontal and inclined dense jets under investigation, by analogy and also given the fact the phenomenon is similar, the measurement frequencies

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with the present set-up should still be adequate to yield accurate results for turbulence properties.

3.5.2 Effect of number of samples

In order to perform a reliable measurement, an assessment of the minimum data samples needed to achieve the statistical significance was actually performed during the trial run that is concerned with a flow typical of the present study, i.e., inclined near-bed dense jets. The experimental conditions are given in Table 3.2. Two time independent sets of data were acquired for the same region with 300 and 600 image pairs respectively. Processing of these two data sets was performed in the same manner, i.e., using 32×32 pixels IAs and the same correlation and validation schemes. The distributions of the mean velocity vector and associated root-mean-square (RMS) of the horizontal velocity component fluctuation, $\sqrt{u'^2}$, for the first measurement window ($\sim 10D$) are illustrated in Fig. 3.7 and 3.8.

Table 3.2: Experimental conditions of the trial run

Inclined angle θ	Nozzle diameter D (mm)	Distance z_0 (mm)	$\Delta\rho/\rho_a$ (%)	Discharge velocity U_0 (m/s)	Reynolds number Re	Densimetric Froude number Fr	Jet/plume characteristic length scale L_M (mm)	Bed proximity parameter z_0/L_M
45°	10.75	12.92	1.984	1.173	12672	25.5	258.40	0.05

Figure 3.7: Mean velocity vector map

Little or no difference is observed between the mean and turbulent velocity distributions generated when using 300 and 600 image pairs. The same conclu-

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Figure 3.8: RMS velocity fluctuation map

sion can be drawn on the mean and RMS concentration maps shown in Fig. 3.9 and 3.10.

Figure 3.9: Mean concentration scalar map

A better assessment of the statistical convergence of the measured mean PIV and PLIF data can be made by plotting the variation of the first- or second-order statistics, e.g., the ensemble mean and RMS, with number of samples at a certain location in the measurement domain. Herein, using the total number of 600 samples, 100, 200 and 300 samples were selected independent from each other. Variations of the mean and RMS values with sample size (100, 200, 300 and 600) for the two velocity components and concentration are obtained by extracting the data along a line of measuring points. As indicated in the following velocity and concentration maps (Fig. 3.11), the data-extraction lines are chosen identically from the PIV and PLIF measurement domain, connecting

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Figure 3.10: RMS concentration map

the two endpoints (400, 400) and (900, 900), in pixels, which roughly align with the center of the 45° inclined jet. The variation of the mean and RMS velocity components and concentration are revealed in Fig. 3.12-3.17 respectively.

Figure 3.11: Illustration of data extraction line

From the comparison of the results associated with the different sample sizes, it is evident that mean and RMS values derived from 100 samples contrast significantly with that derived from larger sample sizes, whereas data from 300 and 600 samples are generally consistent with each other. Taking into consideration the experimental time required, 300 image pairs were thus chosen for each experimental run in the present study.

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Figure 3.12: Mean horizontal velocity component U

Figure 3.13: Mean vertical velocity component V

Figure 3.14: Mean concentration C

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Figure 3.15: RMS of horizontal velocity fluctuation $\sqrt{u'^2}$

Figure 3.16: RMS of vertical velocity fluctuation $\sqrt{v'^2}$

Figure 3.17: RMS of concentration fluctuation $\sqrt{c'^2}$

3.5.3 Effect of IA size

As noted previously, the spatial resolution of the smallest velocity structures in PIV is determined by the size of the perspective projection of the IA in the measurement plane. This is further determined by the object-to-image scale factor, SF , the size of the IA on the image plane (in pixels) and the pixel pitch. Since SF is a setup parameter and the pixel pitch is a fixed property of the camera, the only variable remaining to be adjustable is the size of the IA on the image plane. A rough idea about choosing the IA size is given by the spatial scales involved in the flow (which we do not know entirely), and the dynamic range of measured velocities. Thus, the size of the IA should be small enough to pick up the small scales present in the flow and yet large enough to get the largest possible dynamic range. An evaluation of the best suitable size of the IA for the flow under investigation is achieved in Fig. 3.18 where the performance of 16×16 , 32×32 and 64×64 pixels IA is tested on the same 300 images (all the other processing parameters are held constant).

As illustrated from the figures, a smaller IA does not necessarily lead to more accurate results and yet also tends to capture more noise present. Finally, based on considerations such as smoother velocity distributions (i.e., a good signal-to-noise ratio), computational effort and processing time, the issue of maximizing the number of vectors in the output vector map as well as satisfying both the requirements of a large dynamic range and a good spatial resolution, IAs of 32×32 pixels were used to process the acquired PIV images.

3.6 Summary

The experimental setup of combined PIV and PLIF system is introduced in this chapter along with other components. The different parameters that are critical to the good performance of the combined system are configured, followed by a description of the general experimental procedures. The potential environmental uncertainties associated with the present setting are also addressed. Altogether, the current setup has been proved to be capable of measuring the turbulent flows that will be presented in the next chapters accurately .

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(a) Velocity vector map (16×16 pixels)

(b) RMS velocity contours (16×16 pixels)

(c) Velocity vector map (32×32 pixels)

(d) RMS velocity contours (32×32 pixels)

(e) Velocity vector map (64×64 pixels)

(f) RMS velocity contours (64×64 pixels)

Figure 3.18: Comparison of PIV results with different IA sizes

Chapter 4

Inclined Dense Jets with Boundary Interactions

4.1 Introduction

As noted in Chap. 1, for brine discharges in coastal waters, a submerged inclined outfall is typically suggested as it can produce a curvilinear trajectory for the dense jet before the jet impacts the sea bed. In 1970, Zeitoun et al. conducted experiments on various discharge angles and reported that an inclination of 60° produced the longest trajectory for entrainment and thus the highest dilution. The suggestion of an apparent ‘optimal’ angle of 60° was then adopted in subsequent experimental studies by Pincince and List (1973), Roberts and Toms (1987) and Roberts et al. (1997), among others. In these studies, both trajectory and dilution data had been obtained.

However, the maximum rise height with the 60° inclination is relatively large for the reclaimed coastline of many cities where the near-shore bathymetry tends to be shallow and smaller discharge angles are more feasible. Recognizing this limitation of 60° configuration, studies focusing on the mixing behavior of a smaller discharge angle have been attempted recently by Cipollina et al. (2004, 2005), Kikkert et al. (2007) and Jirka (2008), etc.

In this chapter, we present an investigation on the mixing of dense jets inclined at 30° and 45° with different densimetric Froude numbers in the laboratory. The objective is to further quantify the mixing behavior of the inclined dense jets and provide additional regulatory references. Advanced laser diagnostic techniques of combined PIV and PLIF described in the previous chapter were adopted as the measurement approaches (Law and Wang, 2000). Based on the experimental results, the characteristic geometrical features of the dense

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jet, including the centerline peak and the return point as well as the dilutions at the characteristic positions, are determined and described in the following sections. Other characteristic features, such as the velocity and concentration spread widths and the centerline maximum velocity and concentration decay along the jet axis, are also analyzed. In addition to the free jet behavior, the investigation includes the effect of the bed proximity, or the so-called Coanda effect, as discussed below.

When a jet discharge is placed close to an impermeable boundary, the entrainment of ambient water from the boundary side of the jet can be significantly restricted while the opposite side remains unobstructed. Consequently, due to the Bernoulli's principle, a pressure difference across the jet is induced, which acts as an external force to deflect the jet flow towards the surface of the boundary until an attachment, also known as the Coanda attachment, occurs. With the Coanda attachment, the discharge will then cling to and proceed along the boundary. For brine discharge, the Coanda attachment can result in reduced mixing and excessive salinity along the seabed that may bring severe adverse effect to the benthic community around the affected area. While the Coanda effect on a positively buoyant jet near the bottom was investigated previously by Sobey et al. (1988), no parallel study can be found for the negatively buoyant (i.e., dense) jets including brine discharges so far.

The proximity of the discharge outlet to the bed, z_0 , which is the distance between the center of the nozzle tip and the bottom, can be measured by two length scales, namely, the diameter of the nozzle, D , and the jet/plume characteristic length scale L_M , which is defined as $L_M = M_0^{3/4}/B_0^{1/2} = (\pi/4)^{1/4} D Fr$. The resulting non-dimensional parameters z_0/D and z_0/L_M can both be used to assess the extent of proximity, and the latter is often termed the bed proximity parameter and widely used to account for the boundary effect for positively buoyant jets (Sobey et al., 1988). In the context of inclined dense jets, the inclination of the nozzle also plays an important role in the development of the Coanda effect in addition to the proximity to the bed. Intuitively, given the same z_0/D and z_0/L_M , the Coanda effect should be more significant for the smaller inclinations. In the laboratory, we conduct a group of tests with various reduced nozzle heights and increased nozzle diameters and hence a much decreased z_0/D (experimental series N) for two inclinations (30° and 45°), and compare the results with that of the reference tests with the same inclinations but with the nozzle placed well above the lower boundary in terms of the value of z_0/D (experimental series F). At the same time, the values of z_0/L_M for the

two series are designed to overlap. The comparison of the results would then allow the determination of which of the two non-dimensional parameters of z_0/D and z_0/L_M is dominant in determining the extent of the boundary influence, if any. It is hoped that these new comparative results can facilitate the design of the brine outfall in terms of setting the proper height for the port above the seabed to avoid adverse boundary effects.

4.2 Experimental Setup and Procedures

The experimental setup has been schematized in Fig. 3.1, along with the majority of the facilities and equipments employed being described in Chap. 3. In the following, only the ad-hoc experimental setup and procedures pertaining to the current investigation are introduced.

The test tank was filled to the depth of 0.60 m to ensure that the rise of the inclined jet flow would be kept well below the free surface. For series F, an inclined Perspex tube of 5.8 mm internal diameter (D) was connected to a reinforced flexible hose and clamped to a stainless steel frame. The center of the nozzle tip was elevated to be 24 mm (i.e., $z_0/D = 4.14$) above the platform surface. For series N, an inclined Perspex tube with an inner diameter of 10.75 mm was used instead, and the center of the nozzle tip was fixed at 11.17 mm and 12.92 mm for 30° and 45° cases, respectively. The proximity of the nozzle to the bed after normalized by diameter was thus maintained at 1.04 and 1.20, respectively, which was much less than series F. For series F, the effluent was injected by a peristaltic pump. Whilst for series N, a constant head tank situated about 1 m above the discharge port was used instead. The previously described combined PIV/PLIF system was used to quantify the mixing processes.

As explained in the introduction, the proximity to the bed plays a significant role in affecting the flow pattern. For a specific bed proximity z_0/D , experiments with different densimetric Froude number Fr were conducted to investigate the dependence of bed influence upon z_0/L_M . For series F, when an experiment began, the peristaltic pump was simply set to the desired flow rate and the flow was initiated to run through the bypass system. For series N, however, the regulable gate valve placed on the flow path was gradually open until the reading of the flow rate from the electromagnetic flow meter attained the predetermined value. After regulating the flow for 5 minutes and the flow rate was observed to be stable, the measurements started. Note that up to 24 windows were required to cover the whole jet trajectory for the largest flow rate at the 45° inclination.

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For smaller flow rates and at 30° , fewer windows were typically needed. As mentioned previously, in order to maintain the measured dye concentrations in subsequent windows to be within the calibrated range, we had to gradually increase the source dye concentration when moving the camera downstream, from a value of $120 \mu\text{g}/L$ at the first window to a maximum value of $422 \mu\text{g}/L$ at the farthest downstream window.

For a typical experimental run, the sampling rate was set at 5Hz for the combined measurements. The sampling duration lasted up to 60s, during which the 300 PIV and PLIF images were captured to ensure that the measurements were sufficient for performing time-average and statistical turbulence analysis as discussed in Chap. 3.

A total of 15 tests (10 for series F and 5 for series N) were performed. The experimental conditions are tabulated in Table 4.1.

Table 4.1: Experimental conditions

Exp. No.	Inclined angle θ	Nozzle diameter D (mm)	Distance z_0 (mm)	$\Delta\rho/\rho_a$ (%)	Discharge velocity U_0 (m/s)	Reynolds number Re	Densimetric Froude number Fr	Jet/plume characteristic length scale L_M (mm)	Bed proximity parameter z_0/L_M
F1	30°	5.80	24.00	0.995	0.238	1390	10.0	54.62	0.44
F2	30°	5.80	24.00	0.995	0.356	2074	15.0	81.69	0.29
F3	30°	5.80	24.00	0.995	0.503	2934	21.1	115.43	0.21
F4	30°	5.80	24.00	0.995	0.602	3508	25.3	138.15	0.17
F5	30°	5.80	24.00	0.995	0.727	4236	30.6	166.83	0.14
F6	45°	5.80	24.00	0.995	0.238	1390	10.0	54.62	0.44
F7	45°	5.80	24.00	0.995	0.356	2074	15.0	81.69	0.29
F8	45°	5.80	24.00	0.995	0.507	2956	21.3	116.35	0.21
F9	45°	5.80	24.00	0.995	0.606	3530	25.5	139.06	0.17
F10	45°	5.80	24.00	0.995	0.765	4456	32.2	175.55	0.14
N1	30°	10.75	11.17	1.984	0.507	5478	11.0	111.70	0.10
N2	30°	10.75	11.17	1.984	0.338	3652	7.4	74.47	0.15
N3	45°	10.75	12.92	1.984	1.173	12672	25.5	258.40	0.05
N4	45°	10.75	12.92	1.984	0.586	6336	12.8	129.20	0.10
N5	45°	10.75	12.92	1.984	0.391	4224	8.5	86.13	0.15

4.3 Results and Discussions

4.3.1 Jet axis trajectory and overall flow characteristics

Fig. 4.1 presents the superimposed time-averaged full-field velocity vector and concentration contour maps representative of series N (N2). A reference vector with the magnitude of the efflux velocity is provided in the map together with a vertical color bar to indicate the concentration scale. On the whole, the corresponding velocity and concentration maps are well overlapped due to the

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careful alignment of the two cameras, and we were able to capture the full field information for all tests. The only exception was N3 due to its strong initial momentum and the elongated trajectory, and thus only the upstream portion of the discharge was captured. However, the covered portion of N3 is still included in the comparisons that follow.

Figure 4.1: Superimposed mean velocity vector and concentration contour maps (N2)

The jet axis, or jet centerline, typically characterizes the overall jet flow. The jet centerline was traditionally derived from the maximum velocity or concentration location at various cross sections. For an inclined dense jet, the cross sections are tilted at varying degrees at different downstream locations as the jet was deflected continuously by the combined effect of momentum and buoyancy. Rigorously, extracting the points with the local maximum concentration or velocity and thereby forming the centerline trajectory would require the prior determination of the respective local cross sections. At the same time, to determine these local cross sections, we need the information of the local tangent of the axis. This recursive problem can only be solved by iteration, which will be quite time-consuming if the present flow with a large extent needs to be resolved. Instead, we assume the centerline of the inclined dense jet to be the streamline starting from the center of the nozzle tip and derived it from the obtained velocity vector map henceforth (realized by the Matlab routine documented in Appendix. A.2). The concentration axis mostly coincided with the velocity axis. It is noted that, however, as discussed in the near-bed horizontal dense jet (Shao and Law, 2009), the concentration axis tends to descend sooner and at a faster rate than its velocity counterpart. As a result, the two axes would diverge at some point and move further apart towards the downstream direction. The divergence of the two axes induced many important effects for the flows with lower bed proximity parameter as discussed later. The jet centerline for N2 superimposed on the respective velocity magnitude contours is illustrated

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in Fig. 4.2.

Figure 4.2: Jet centerline trajectory superimposed on the contours of velocity magnitude (N2)

Centerline trajectories with the same z_0/D but different Fr thus different z_0/L_M for series N are compared in Fig. 4.3. Unlike in Fig. 4.2, the nozzle offset has been accounted for such that the new origin coincides with the nozzle tip. As expected, for the same inclination, dense jets with greater Fr shoot farther away from the nozzle. Except for the incomplete trajectory of N3 ($Fr = 25.5$ in Fig. 4.3(b)), all trajectories appear to be visually symmetrical between the ascending and descending portions in the figures. The reported asymmetry in the centerline trajectory for dense jets (Ferrari and Querzoli, 2004), with a steeper descending beyond the centerline peak is not apparent in series N.

Figure 4.3: Comparison of centerline trajectories with different Fr (series N)

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The normalized trajectories by L_M are shown in Fig. 4.4. For both 30° and 45° , the different trajectories for series N are found to nearly collapse after normalization. Also shown in the figures are reported results in Kikkert (2006), in which the source was set well above the boundary so that the boundary had no influence at all. With 30° , the previous data scatters within the range of the present results. The trajectory of F1, which corresponds to the least Fr , overshoots the remainders by a significant amount but still remains symmetrical about its peak. In contrast, the trajectories of F2 and F3 with larger Fr tend to descend sooner and exhibit an apparent asymmetry, verifying that the trajectory of the free dense jet tends to be less symmetrical when Fr is larger (Ferrari and Querzoli, 2004). The normalized trajectories of F4, F5, N1 and N2 are similar with a milder ascending slope and steeper descending slope, which implies the boundary influence detailed in the following section. While for 45° , the trajectories are mostly similar.

4.3.2 Gross geometrical and mixing features

For a desalination plant, the design of the brine outfall must include the determination of the gross geometrical characteristics of the brine plume, including the terminal rise height, the horizontal location of the return point as well as the dilution achieved at the characteristic locations (shown in the definition sketch in Fig. 4.5). These information enable the assessment of the environmental impact for regulatory purposes.

Using dimensional analysis, the various geometrical and mixing quantities can be shown to be proportionally correlated to the jet densimetric Froude number, Fr , as well as, in some cases, the nozzle diameter, D (Roberts et al., 1997). Thus, a number of proportionality coefficients are defined to account for the dependence. Various previous studies have attempted to derive the coefficients empirically from the experimental results, and they are summarized in Tables 4.2 and 4.3 together with the coefficients obtained in the present study. The coefficients derived from the present study fall into two subsets, one corresponding to free dense jets without boundary effect, which is also the case for the previous studies, and the other corresponding to the cases involving boundary effect. The demarkation of the two subsets is based on coefficients obtained from the experimental data of both series F and series N. For 45° , the coefficients are found to be similar for all tests, whereas for 30° a distinction can be identified for tests with z_0/L_M values below and above 0.15. Hence a major outcome from this exercise is that z_0/L_M is revealed to be the deciding factor

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(a) 30°

(b) 45°

Figure 4.4: Normalized centerline trajectories

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Figure 4.5: Definition sketch for inclined dense jets

for the demarkation of boundary influence.

Table 4.2: Comparison of experimental coefficients (30°)

Quantity	Proportionality coefficients	Present study		Zeitoun et al. (1970)	Cipollina et al. (2005)	Nemlioglu & Roberts (2006)	Kikkert et al. (2007)		
		$0.10 \leq z_0/L_M \leq 0.15$	$z_0/L_M > 0.15$				LA data	LIF data	Model prediction
Terminal rise height	$C_1 = z_t/DFr$	1.05		1.15	1.08	1.40	1.00	1.19	1.02
Horizontal location of return point	$C_2 = x_r/DFr$	2.88	3.00	3.48	3.03	3.30	3.14	3.44	2.95
Return point dilution	$C_3 = S_r/Fr$	1.18	1.45	-	-	1.90	-	-	-
Vertical location of centerline peak	$C_4 = z_m/DFr$	0.66		-	0.79	-	0.56	0.66	0.62
Horizontal location of centerline peak	$C_5 = x_m/DFr$	1.70	1.54	-	1.95	-	1.75	1.85	1.70
Centerline peak dilution	$C_6 = S_m/Fr$	0.62	0.66	0.36	-	-	-	-	-

4.3.2.1 Terminal rise height

Upon discharge, an inclined dense jet will rise to a height at which the vertical component of the initial momentum reduces to zero due to the gravitational deceleration and then fall onto the bed. This height of terminal rise, defined as z_t , is a crucial parameter in brine discharge design as regulations typically mandate the effluent brine plume to remain well below the free water surface. Notably, however, a diverse terminology has been used in the literature for this parameter (e.g., maximum height of the top boundary in Zeitoun et al.

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Table 4.3: Comparison of experimental coefficients (45°)

Quantity	Proportionality coefficients	Present study	Zeitoun et al. (1970)	Cipollina et al. (2005)	Nemlioglu & Roberts (2006)	Kikkert et al. (2007)		
		$z_0/L_M \geq 0.05$				LA data	LIF data	Model prediction
Terminal rise height	$C_1 = z_t/DFr$	1.47	1.43	1.61	2.00	1.60	-	1.61
Horizontal location of return point	$C_2 = x_r/DFr$	2.83	3.33	2.82	3.20	3.26	-	3.04
Return point dilution	$C_3 = S_r/Fr$	1.26	-	-	1.70	-	-	-
Vertical location of centerline peak	$C_4 = z_m/DFr$	1.14	-	1.17	-	1.06	-	1.13
Horizontal location of centerline peak	$C_5 = x_m/DFr$	1.69	-	1.80	-	1.84	-	1.88
Centerline peak dilution	$C_6 = S_m/Fr$	0.46	0.42	-	-	-	-	-

(1970), terminal rise height in Roberts and Toms (1987) and Roberts et al. (1997), maximum rise height in Madni and Ahmad (1989), final fountain height in Bloomfield and Kerr (2002), maximum rise level in Cipollina et al. (2005) and Jirka (2008), maximum height of the outer edge in Kikkert et al. (2007)). Hereinafter, ‘terminal rise height’ is adopted in the present study when referring to this term.

Beside the inconsistency in the terminology, the approaches employed to determine the terminal rise height also differ among various past studies and the reported results are therefore very likely subject to significant uncertainty as discussed in Jirka (2008). They pointed out that the reported results of terminal rise height were usually determined as the visual boundary of the captured flow images (photographic or digital), which involves considerable parametric uncertainties due to the type and amount of dye used, the illumination level, the sensitivity of the recording media as well as the arbitrary determination of the cutoff level on the edge. The last factor is particularly prominent as there is no widely accepted value in the literature so far. Notably, the commonly used integral model CorJet adopted two cutoff levels for the visual boundary, namely, 3% and 25% (Jirka, 2004). Herein, the cutoff level of 3% is applied to the acquired planar concentration data exemplified in Fig. 4.1 to derive the terminal rise height.

It is also noteworthy that the vertical density gradient tends to dampen

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turbulent fluctuations at the upper boundary where its value is negative while promote turbulence at the lower boundary where its value is positive. As a result, the upper edge becomes sharper and somewhat closer to the jet centerline, whereas the lower edge is more spread out as can be clearly seen in Fig. 4.2. Also, a transient behavior of the inclined dense jet in its penetration in the stationary ambient water was reported in Bloomfield and Kerr (2002), and differences between the initial and final rise height were identified. However, this transient behavior might be attributed to the fact that the dense jet flow was still developing. In the present experiments, the data acquisition lasted sufficiently long and the data analysis was performed on the captured flow only during the steady state.

The terminal rise height, z_t , derived from the mean concentration scalar maps is normalized by the nozzle diameter and plotted against the corresponding Fr in Fig. 4.6. Note that the nozzle height z_0 has been subtracted in the presented z_t . For both 30° and 45° , the data points from the two experimental series are consistent with the trend line of the previous results. Analytical solution developed by Kikkert (2006) is also added to the figure, which exhibits good agreement with the various experimental results. The apparent deviation for 45° shown in Fig. 4.6(b) is from Zeitoun et al. (1970).

The linear relationship between z_t/D and Fr can be better reflected by normalizing z_t by L_M , as $L_M = (\pi/4)^{1/4} D Fr$. From the results, z_t/L_M seems unaffected by the boundary effect as illustrated in Fig. 4.7, and is only a function of the initial discharge angle θ . Various previous results are also included for comparison. For the most part, the normalized terminal rise height increases monotonically with increasing θ as expected. The present results for 30° and 45° fall within the predicted ranges from Kikkert's analytical model. The recently reported results from Nemlioglu and Roberts (2006) appear to be larger while both the experimental and modeling results from Lane-Serff et al. (1993) tend to underestimate the terminal rise height. Given the comprehensive coverage of existing data, it is safe to conclude that the predictions of the terminal rise height by the analytical model developed by Kikkert (2006) are reasonable up to 60° .

Note that the coefficient of the terminal rise height, C_1 , is also found to be dependent on the densimetric Froude number in Roberts and Toms (1987) and Zhang and Baddour (1998) for inclined and vertical dense jets with small Fr , and the reported threshold values are 20 and 5 (note that a Fr different from the common definition was adopted in Zhang and Baddour (1998) and

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(a) 30°

(b) 45°

Figure 4.6: Normalized terminal rise height versus Fr

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Figure 4.7: Normalized terminal rise height as a function of initial discharge angle

thus a conversion is needed), respectively. Since the Fr values in the present experiments are well above 5, C_1 is considered independent of Fr in the present study.

4.3.2.2 Centerline peak

The centerline peak can be derived from the centerline trajectories determined earlier. The horizontal and vertical locations of the centerline peak, x_m and z_m , after normalized by the nozzle diameter, are plotted against Fr in Fig. 4.8 and 4.9, respectively. The results from the two experimental series are fairly consistent with each other except for x_m for 30° . As illustrated in Fig. 4.8(a), the last data point from series F (F5) is in line with the slope extending from series N (N1 and N2), which is apparently above the two preceding data points with intermediate Fr (F3 and F4). As discussed earlier, the boundary effect has come into play in F5, which corresponds to the least z_0/L_M in series F, and resulted in a lowered ascending slope. This in turn leads to an elongated x_m given the almost untouched z_m as shown in Fig. 4.9(a). For 45° , the boundary effect is less significant and hence less discrepancy is observed in Fig. 4.8(b).

The present results are generally in line with the predictions from Kikkert (2006) for the horizontal location while slightly higher for the vertical location. For 30° , the previous experimental results for intermediate and large Fr are consistently above Kikkert's predictions. For 45° , the published experimental data are more scattered but the predictions from Kikkert (2006) appear to fall

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within the range of the scatter.

(a) 30°

(b) 45°

Figure 4.8: Normalized horizontal location of centerline peak versus Fr

The horizontal and vertical locations of the centerline peak are further normalized by L_M and presented in Figs. 4.10 and 4.11. Reported experimental and modeling results are also added to the figures for comparison. In general, the results from the present study fall within the scatter of the various experimental results for z_m , but appear to be considerably lower than those reported in Cipollina et al. (2005) and Kikkert (2006) for x_m . The boundary-affected tests for 30° ($z_0/L_M \leq 0.15$, i.e., F5, N1 and N2) are denoted by upward triangles while the

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(a) 30°

(b) 45°

Figure 4.9: Normalized vertical location of centerline peak versus Fr

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other cases free from boundary effect are represented by downward triangles in Fig. 4.10. The boundary-affected results are considerably higher than the free jet counterparts as expected. For 45° , a common symbol is used for all results due to the limited boundary effect. Predictions from Kikkert (2006) are found to compare fairly well with the experimental data.

Also plotted in Fig. 4.11 is the empirical linear formula derived in Ferrari and Querzoli (2004), which reads $z_m/L_M = (0.0321 \pm 0.0059)\theta$. The dash-dot line represents the predicted value and the dotted lines represent the error bounds. Despite the innate crudeness of the linear correlation, this formula can serve as a quick assessment of z_m for θ greater than 30° as the corresponding experimental data set are shown to scatter between the predictions and the lower error bounds within this range.

Figure 4.10: Normalized horizontal location of centerline peak as a function of initial discharge angle

4.3.2.3 Horizontal distance of return point

The inclined dense jet falls back to the lower boundary eventually due to its negative buoyancy, and the location where the downward flow impinges onto the boundary is often referred to as the impact point or impingement point. Various previous studies (Roberts et al., 1997; Ferrari and Querzoli, 2004; Cipollina et al., 2005; Nemlioglu and Roberts, 2006; Kikkert, 2006; Jirka, 2008, among others) paid close attention to this geometric feature as mixing is significantly reduced after the impingement takes place with the effluent staying attached to

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Figure 4.11: Normalized vertical location of centerline peak as a function of initial discharge angle

the boundary afterwards. The dilution at the impact point is typically taken as an indicator of the adverse effect which the discharge would cause on the benthic environment. It is noteworthy, however, that the actual impact location is dependent on the source height and bed slope, and hence is site-specific. To make the results reported here generally applicable, the return point independent of the source height and bed slope where the flow returns to the source elevation is investigated in the present study. Some recent studies such as Cipollina et al. (2005) and Kikkert (2006) have also adopted this geometric characteristic (note that impact point was used to refer to the actual return point in Cipollina et al. (2005) while impact point and return point were used interchangeably in Kikkert (2006)). Although this return point may seem somewhat artificial physically, the practical nozzle height and bed slope are typically small relative to the entire mixing zone considered, and therefore the difference between the return point and the actual impact point may not be significant. If the nozzle height and/or the bed slope is large, however, then a dedicated study taking into account the nozzle height and bed slope would be necessary.

The return points can be determined from the centerline trajectories discussed earlier. However, it is clearly illustrated in Fig. 4.3 that, for some tests (e.g., N1, N3 and N4), the trajectories never manage to return to the source level within the extent of the measurements. However, for N1 and N4, due to the difference between the concentration and velocity centerline axes near the impingement region, the current centerline derived from the streamline may not

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contain the return point associated with the minimum dilution. According to Roberts et al. (1997), the impact point can be inferred from the variation of the concentration or dilution along the lower boundary. In principle, the concentration grows from zero to the maximum at around the impingement point, and maintains at the level for a short distance before drops again. The physical justification is that the jet impingement at the bottom will significantly reduce the entrainment of the ambient fluid in the immediately adjacent area, thereby causing the impact point to have the local minimum dilution. The same pattern applies at the source level slightly elevated from the base level as shown in Fig. 4.12, except for the area adjacent to the nozzle (because of the strong fluctuation present immediately off the nozzle in N4 and N5, this portion is excluded from Figs. 4.12(b) and 4.13(b)). However, this is not very apparent visually in the figure due to the large scale used for the vertical axis. The respective return points are denoted by asterisk which marks the local maximum concentration and thus the minimum dilution.

The normalized dilution, S/Fr , is plotted against the normalized distance from the nozzle, $(x-x_0)/L_M$, in Fig. 4.13. The profiles with the two different Fr for 30° nearly collapse as shown in Fig. 4.13(a). While Nemlioglu and Roberts (2006) showed a similar pattern of variation, their reported dilutions are considerably higher. For 45° , the previous and present results agree well although the two profiles with different Fr are more scattered as shown in Fig. 4.13(b). It also appears that the measurements of N4 did not extend sufficiently downstream compared to the other tests. However, it does not affect the assessment of the respective return point.

From Figs. 4.12 and 4.13, the dilutions beyond the return point are similar for the two Froude numbers in the figures ($Fr=7.4$ and 11.0 for 30° , and $Fr=8.5$ and 12.8 for 45°). This has an important implication that the excessive energy consumption associated with the higher Fr discharge did not yield higher dilution beyond the return point, and thus the lower Fr may be preferred. Furthermore, since dilution would obviously be small for very low Fr , this would imply that an optimal Fr exists that can produce the required dilution level most energy-economically.

The derived horizontal locations of the return point are normalized by the nozzle diameter and plotted against Fr in Fig. 4.14. The present results are consistent for 45° for all tests and close to the previous predictions. However, for 30° , the previous experimental results with intermediate and large Fr tend to be higher than the predictions. The functional relationship between x_r/L_M

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(a) 30°

(b) 45°

Figure 4.12: Variation of dilution along nozzle height level with different Fr

(a) 30°

(b) 45°

Figure 4.13: Normalized variation of dilution along nozzle height level

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and the discharge angle θ is revealed in Fig. 4.15. Present data are compared with available experimental and analytical results. As described in the previous section, the boundary-affected tests for 30° , i.e., F5, N1 and N2, possess a lagged centerline peak and hence a milder upslope. Meanwhile, the dominant boundary effect will give rise to a steeper downslope, and drive the flow to return to the source level slightly sooner and closer to the nozzle than their free jet counterparts as can be seen in Fig. 4.15. For 45° , the boundary effect is weak and hence a common symbol is used to represent all tests. It is noted that the analytical model of Kikkert (2006) was developed based on a hypothetical division of the entire flow into a jet-like and a plume-like regime. This is shown by the distinct separation of the two curves representing the two regimes in Fig. 4.15. The present experimental data appears to largely follow the analytical predictions in the plume-like portion. The previous experimental data exhibits significant scatter and tends to exceed the model predictions and present results in most cases. Notably, the empirical formula derived in Ferrari and Querzoli (2004) not only completely deviates from the trend for small angles, but also significantly overestimate for the other angles up to 60° .

4.3.2.4 Minimum dilution at centerline peak and return point

The dilution achieved within a prescribed mixing zone is of primary concern in the environmental impact assessment of the disposed effluent. Therefore, the minimum dilutions associated with some representative locations, such as the centerline peak and return point, along the centerline are of particular interest. Dilutions reached at the centerline peak and return point for the present study are normalized by Fr and plotted against the discharge angles θ in Figs. 4.16 and 4.17, respectively.

The minimum dilution at the centerline peak, S_m , for 30° and 45° were reported in Zeitoun et al. (1970). However, the data are outdated and have little relevance. The boundary-affected tests (F5, N1 and N2) have a slightly lower dilution level than their free jet counterparts despite their elongated trajectories described previously. The reduction can be attributed to the reduced entrainment due to the prominent boundary effect. On the other hand, the dilution coefficients are nearly identical for 45° for all tests.

The minimum dilution at the impact point, S_i , is of more environmental significance and has received far more attention in the past compared to S_m . As discussed earlier, the impact point is largely dependent on the specific nozzle height and hence the dilution at this location lacks the generality to the engi-

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(a) 30°

(b) 45°

Figure 4.14: Normalized horizontal location of return point versus Fr

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Figure 4.15: Normalized horizontal location of return point as a function of initial discharge angle

Figure 4.16: Minimum dilution at centerline peak as a function of initial discharge angle

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neering practice. In the present study, the dilution at the return point, S_r , which is independent of the nozzle height above the bottom, is proposed as a substitute. For comparison purpose, however, available data for both quantities are included in the presentation. As shown in Fig. 4.17, the experimental data are highly scattered. However, as expected, the impact point dilution is generally higher than the return point dilution.

Results over a wide range of θ in Nemlioglu and Roberts (2006) suggested that the discharge angle has little effect on the impact point dilution in the range of 30° - 75° . As far as the return point dilution is concerned, the conclusion also seems to be valid for the present results. Due to the reduction of the overall distance from the nozzle to the return point, the return point dilution for the boundary-affected tests (F5, N1 and N2) is lower than the free jet counterparts for 30° ; while for 45° , the boundary effect is less prominent and hence a universal dilution coefficient is adopted for all tests. Notably, there is substantial scatter in the reported results and thus it is not obvious that 60° would be optimal in terms of the impact point dilution. Note also that, the impact point dilutions reported in Kikkert (2006) were based on integrated concentrations that were measured using the light attenuation method in the direction perpendicular to the jet center plane. As such, they are not included in the comparison.

Figure 4.17: Minimum dilution at the return point as a function of initial discharge angle

The ratios of S_r/Fr to S_m/Fr for 30° are determined to be 2.2 and 1.9 for free and boundary-affected jets, respectively; While for 45° , the ratio is fixed at 2.7. For 60° inclination, Kikkert et al. (2007) proposed the ratio to be 2.8 from

the analytical model prediction, and also obtained an experimental ratio of 3.2.

4.3.3 Centerline maximum concentration decay

Once the centerline trajectory is determined, the variation of the maximum concentration, or the minimum dilution, along the centerline can then be obtained. The various normalized centerline maximum concentration profiles are presented in Fig. 4.18. Some data scatter can be observed along the profiles, which are partly due to the multiple imaging windows used to cover the entire flow region. For 30° , the concentration remains essentially constant up to approximately $3D$, which is the extent of the potential core region. After that, the concentration begins to decrease steadily until the corresponding impingement point is reached. The rate of decrease of concentration is much milder after the impingement point and the profiles almost flatten. For 45° , on the other hand, the potential core region is significantly shorter as the concentration appears to drop almost immediately off the port exit. Subsequently, a similar trend of concentration decrease and flattening as 30° is noted. Note that the boundary-affected tests appear to be less diluted than the free jet counterpart for 30° .

4.3.4 Centerline maximum velocity decay

The variation of the normalized maximum centerline velocity magnitude with the normalized downstream distance is presented in Fig. 4.19 in logarithmic scale. As seen from the figure, the different decay processes all collapse well onto the same pattern. For 30° , the potential core region with a constant velocity extends to about $3D$, which is consistent with the observations made from the concentration counterpart. For 45° , however, the maximum velocity magnitude appears to remain constant close to the nozzle, which differs from the concentration results.

4.3.5 Cross sectional concentration profile

In buoyant jet studies, a Gaussian profile is often assumed for the concentration distribution at the cross sections when the jet has entered the zone of established flow (ZEF). Following the determination of the jet axis, the cross-sectional concentration profiles at various downstream locations for N1 were extracted from the planar PLIF data using the Matlab routine documented in Appendix. A.3, and presented as representative in Fig. 4.20. The thick solid line represents the centerline trajectory which was determined as the streamline originating from the center of the nozzle tip, and the thin solid curves represent the various

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Figure 4.18: Comparison of centerline maximum concentration decay

cross-sectional concentration profiles from $x = 3D$ onward with a uniform $3D$ interval. It is noted that the individual profiles have been scaled up for better visualization. As seen from the figure, the profiles exhibit a well-developed axisymmetric Gaussian pattern from $3D$ until $12D$, at which location the lower half spreads much wider compared to the upper counterpart. The asymmetry is exacerbated at $21D$ and the maximum concentration at this location is found to shift below the streamline centerline, indicating that the concentration axis starts to deviate from the velocity axis. It is also noteworthy that, at the tail end, the last two cross-sectional distributions exhibit a typical wall-jet pattern, which implies that the jet undergoes a transition to a wall jet after the impingement takes place. Similar evolution can be observed in the other tests (see Fig. B.1). For 45° , the curvature of the trajectory is larger, and the cross-sections are more tilted consequently. The deviation of concentration axes from the center streamline is found to initiate even before the centerline peak in N3.

Non-dimensionalized cross-sectional profiles of C/C_c (C_c is the local centerline maximum concentration) are plotted against r/b_c (r is the radial distance and b_c is the concentration spread width using the e^{-1} notation) and compared

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(a) 30°

(b) 45°

Figure 4.19: Comparison of centerline maximum velocity magnitude decay (log scale)

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Figure 4.20: Cross-sectional concentration distributions at various downstream locations (N1)

with the standard Gaussian profiles in Fig. 4.21. Despite the scatter, a Gaussian pattern can be observed for the upper half of the various cross sections, whereas the lower-half widens to a considerably larger extent relative to the upper half counterparts presumably due to the buoyancy-induced distortion, which will be discussed in detail in a later section.

Figure 4.21: Normalized concentration profiles at various downstream cross sections (N1)

The cross-sectional concentration profiles of series F were also extracted, and two typical plots for 30° and 45° are presented in Fig. 4.22. From the figure, it can be clearly observed that the upper half of the jet achieved self-similarity and collapsed onto the Gaussian profile when the cross section was more than $6D$ downstream of the discharge nozzle. However, the lower half closer to the bottom boundary deviated from the Gaussian profile. The distortion increased with the distance from the nozzle until the centerline peak was reached. Beyond the centerline peak, the distorted profiles collapsed roughly onto one curve. The

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overall processes are consistent with the observations made in Kikkert et al. (2007).

(a) F1

(b) F6

Figure 4.22: Normalized concentration profiles at various downstream cross sections (series F)

4.3.6 Cross sectional velocity profile

The planar axial velocity component, U profiles at various downstream locations for N1 are presented in Fig. 4.23. Symmetric Gaussian distribution is clearly revealed for the first couple of cross sections. For 30° , the symmetry held up to 12D for the large Fr (N1) and 6D for the small Fr (N2, see Fig. B.2(a)). For 45° , the range is longer, 21D for the large Fr (N3) and 9D for the small Fr (N5). Beyond that, the widening of the lower half becomes prominent. Consistent

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with the concentration counterpart, the velocity profiles transit to the wall-jet pattern beyond the impingement as shown clearly in Fig. 4.23.

Non-dimensionalized cross-sectional profiles of U/U_c (U_c is the local center-line maximum U) are plotted against r/b_u (b_u is the velocity spread width using again the e^{-1} notation) and compared with the standard Gaussian profiles in Fig. 4.24. It is found that the upper half roughly follows the Gaussian pattern. On the contrary, the lower-half consistently deviates from the Gaussian profile fit by the upper half distribution. The cross-sectional velocity profiles for series F were also studied and shown to exhibit similar patterns. For brevity, they are not presented herein.

Figure 4.23: Cross-sectional axial velocity component distributions at various downstream locations (N1)

Figure 4.24: Normalized axial velocity component profiles at various downstream cross sections (N1)

4.3.7 Buoyancy-induced instability

For a free jet, the entrainment is uniform around its perimeter and thus the development of the cross-sectional profiles is typically symmetrical with respect to the centerline axis. For a dense jet discharged at an angle to the horizontal, however, the jet spreading is enhanced in the lower half due to the buoyancy-induced instability, i.e., the negative buoyancy causes the instability of the heavier plumes and as a result, the spreading is enhanced. At the same time, the jet spreading is reduced in the upper part of the jet which possesses a stable stratification with the lighter ambient fluid on top of the heavier jet fluid. This has been observed in the normalized concentration and velocity profiles of the dense jets shown earlier. It is noted that similar observations of the asymmetric spreading of dense jets were made in Lane-Serff et al. (1993); Ferrari and Querzoli (2004); Kikkert et al. (2007). The asymmetry can be clearly identified from the bottom concave portion of the mean cross-sectional concentration contours measured in Lane-Serff et al. (1993). Notably, however, the mean concentration contours taken at both the centerline peak and the impact point in Kikkert (2006) still resembled the typical smooth oval-shape pattern although the asymmetry between the upper and lower halves was obvious. Ferrari and Querzoli (2004) have also pointed out the distortion in their captured instantaneous 2D images of the center plane.

It is yet unclear whether the asymmetry increases persistently with distance from the nozzle exit to the impact point. While Lane-Serff et al. (1993) argued this to be true using the vertical density profiles at various downstream locations, Kikkert et al. (2007) showed that the asymmetry ceased to grow once the centerline peak was reached, and the subsequent distorted profiles collapsed after normalization. The cross-sectional concentration and velocity profiles shown in Figs. 4.20 and 4.23 generally support the latter point of view. The disparity is presumably attributed to the fact that Kikkert et al. (2007) and the present study both extract the profiles from the perpendicular cross sections to the jet centerline, rather than along the vertical direction. Kikkert et al. (2007) further suggested that the severity of the distortion in the lower-half of the flow increases with angle within the range of 0° - 75° . Given the limited coverage of angles in the present study, the analysis on the angle dependence is not conducted herein.

4.3.8 Jet spread

A commonly-used measure to characterize the jet growth is the jet spread width based on Gaussian-fitting the velocity or concentration distribution and then noting the distance to the e^{-1} ratio of the centerline maximum value. In this manner, both concentration and velocity spread can be defined and the representative test (N1) is presented along with the previously extracted centerline trajectory in Fig. 4.25.

Figure 4.25: Jet velocity and concentration spread (N1)

As seen from the figure, in the upper layer, the concentration and velocity upper spread widths almost coincide with each other throughout the flow. As mentioned earlier, the concentration axis descends faster than the velocity axis. Thus, the actual concentration spread in the upper layer should be wider than what is indicated in the figure. Meanwhile, the concentration spread in the lower layer is overestimated and indeed, substantial deviation from the velocity spread can be observed. Despite the scatter, the enhanced lower spread due to the buoyancy-induced instability is clearly illustrated in the figure.

The trend of the spread is further revealed in Fig. 4.26, in which the various spread widths normalized by the nozzle diameter for two representative tests (N1 and N5) are plotted against the normalized downstream distance along the trajectory. The respective locations of the centerline peak and the return point are also marked in the figures. Moving away from the nozzle, the lower spread width increasingly exceeds the upper counterpart, and the contrast reaches a maximum at around the centerline peak. Beyond that, the lower spread starts to decline as the flow turns towards the bed and the bottom boundary starts to exert an influence on the flow. The lower spread is particularly dampened after the jet centerline impinges onto the bed. Eventually, the dense jet slowly transits to the wall-jet pattern. Without the bottom boundary, the concentration spread

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of the dense jet would continue to grow as noted in Ferrari and Querzoli (2004) and shown in Fig. 4.26(b). Note that their reported spread widths appear to be smaller than the present results in the linear growth range.

The spread width profiles for the various tests are plotted together in Fig. 4.27 after normalized by the respective Fr . The lower spread widths show more scatter than the upper spread widths in the initial growing range. Kikkert (2006) argued that, after normalized by DFr , the variation of the upper concentration spread width for different angles are to collapse onto the theoretical prediction. Within onefold DFr from the nozzle (which is approximately one L_M), the theoretical prediction shown in Fig. 4.27(b) is found to fall within the scatter of the various upper concentration spread width profiles. Further downstream, the growth of the boundary-affected flows tends to be lower than the prediction whereas the free jet counterparts for both 30° and 45° scatter around the prediction. The deviation is exacerbated as the concentration spread width derived from boundary-affected flows become less than the actual value when the downward deflection of the concentration axis from the velocity axis occurs. Again, the growth range is followed by the decline range due to presence of the bottom. The different profiles possess significant scatter and does not seem to collapse when falling. Similar trend can be observed for the upper velocity spread width in Fig. 4.27(d).

4.4 Summary

60° inclined dense jets had been recommended for brine discharges from desalination plants to achieve a maximum mixing efficiency. However, the terminal rise associated with 60° is relatively high and thus the angle may be too large for disposal in shallow coastal waters. In this study, we investigate the behavior of dense jets discharging at smaller angles of 30° and 45° in a stationary ambient. Combined Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) were used as the measurement approaches that captured the velocity and concentration fields, respectively. Based on the experimental results, the characteristic geometrical features of the inclined dense jets, including the location of the centerline peak and the return point where the dense jet returns to the source level, etc., are quantified. The mixing and diluting behaviors are also revealed through the analysis of the axial and cross-sectional velocity and concentration profiles. In addition to the free inclined discharges, the present study also examines the effect of the proximity to the bed. Through

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(a) N1

(b) N5

Figure 4.26: Variation of velocity and concentration spread width along the trajectory

the comparison of the results between two experimental series with distinct z_0/D but overlapping z_0/L_M , the latter is identified as the deciding factor for the boundary influence. For 30° , it is found that the bed influence became significant when z_0/L_M is less than approximately 0.2, while for 45° , the boundary effect is considerably weaker and indiscernible for z_0/L_M down to the smallest tested value of 0.05. As such, the proportionality coefficients for 30° case are categorized into two subsets, namely free dense jets without boundary effect and that involving boundary effect. Comparisons with available coefficients reported in the previous studies are satisfactory.

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(a) Lower b_c

(b) Upper b_c

Figure 4.27: Variation of velocity and concentration spread width along the trajectory

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(c) Lower b_u

(d) Upper b_u

Figure 4.27: Normalized velocity and concentration spread width as a function of downstream distance (cont)

Chapter 5

Offset Horizontal Dense Jets

5.1 Introduction

As noted in previous chapters, the dense jet discharge from a single-port outfall has been investigated by a number of researchers in the past decades, and more recently, there is a renewed interest largely due to the rapid growth of the desalination industry globally. Based on previous experimental evidence (Zeitoun et al., 1970; Roberts et al., 1997), a discharge angle of 60° to the horizontal has been widely accepted as the optimum design scheme. However, the maximum rise height with the 60° inclination is relatively large for the reclaimed coastline of many cities where the near-shore bathymetry tends to be shallow and smaller discharge angles are more feasible (Chap. 4). It is also worth noting that, in some cases, a horizontal discharge configuration could be adopted based on cost considerations and the relative ease for construction (Pérez Talavera and Quesada Ruiz, 2001).

Fig. 5.1 illustrates the mixing processes for this discharge configuration. For a horizontal brine jet sufficiently far away from the seabed, the jet behaves as a free jet initially and substantial entrainment can take place before the jet impacts on the seabed due to the negative buoyancy. Ultimately, the flow becomes a wall jet or weak wall plume, depending on the decaying of the velocity and solute concentration (e.g., salinity) along the way. In the event of shallow coastal waters, when the horizontal dense jet discharge has to be aligned closely parallel to the adjacent seabed, the entrainment of ambient water from the boundary side of the dense jet can be significantly restricted while the open side remains unobstructed. Consequently, according to the Bernoulli's principle, a pressure difference across the jet flow is developed and acts on top of the negative buoyancy. In extreme cases, when the nozzle is placed too close to the bottom,

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the resulting pressure difference can grow sufficiently large to force the effluent to adhere to the bottom immediately after the discharge. This is often referred to as the Coanda attachment (a phenomenon similar to that described in Chap. 4), which is different from the gravity-induced attachment described above and may result in adverse effects such as a higher salinity along the seabed in the case of brine discharge as mixing is disrupted undesirably.

Figure 5.1: Flow pattern evolution of horizontal dense jets

Notably, the use of the term negative/positive buoyancy needs some clarification. Generally speaking, when a solid object or a parcel or stream of fluid is fully or partially submerged into another fluid, the surrounding fluid will exert a buoyancy force on the intruding solid or fluid if their densities differ, i.e., the intruder carries a buoyancy, negative or positive depending on the sign of the density difference and the initial kinematics of the intruder. If the vertical component of the initial momentum of the intruder is zero, i.e., the intruder is placed into the ambient fluid motionless or penetrates with a pure horizontal momentum like in the present case, the judgement is straightforward and based on the sign of the density difference only: if the density of the intruder is greater than the ambient fluid, the buoyancy is termed negative, and vice versa.

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Otherwise, if the vertical component of the initial momentum is nonzero, the resulting buoyancy force can act to accelerate the initial motion when they are in the same direction, in which case the buoyancy is termed positive, or decelerate the initial motion when they are opposite to each other, which corresponds to negative buoyancy. It is noted that in the latter case, due to the diverse combinations of the initial momentum and density difference, the scenarios of negative or positive buoyancy tend to be rather diverse. For instance, a jet with a higher density than the ambient discharging vertically upward from the bottom and a jet with a lower density discharging vertically downward from the top are categorized identically into negatively buoyant jets, i.e., with negative buoyancy.

As noted in Chap. 2, previous studies on offset horizontal dense jets are scarce. We consider a similar but dynamically inverted process of horizontal positively buoyant jets in the presence of bed and free surface boundaries in stationary ambient waters. The configuration of the flow could be an ascending horizontal buoyant flow above a parallel solid boundary (e.g., Balasubramanian and Jain, 1978; Jirka, 1982; Sobey et al., 1988; Johnston and Volker, 1993; Johnston et al., 1994), or alternatively, a descending horizontal dense flow below a parallel solid or free surface boundaries (e.g., Knudsen and Wood, 1990; Li, 1997; Wood, 2002). The various studies have been briefly reviewed in Chap. 2. Note also that offset jets have been widely used in various other industrial applications, for instance, burners, boilers, gas turbine combustion chambers, and fuel injection systems (Nasr and Lai, 1998). In addition, three-dimensional non-buoyant wall jets have been studied extensively in the past, and the relevant results can be compared for references (Rajaratnam and Subramanya, 1968; Newman et al., 1972; Rajaratnam and Pani, 1974; Law and Herlina, 2002; Herlina and Law, 2002).

In this chapter, we examine the influence of the Coanda effect on the offset horizontal dense jets by adjusting the discharge densimetric Froude number as well as the distance between the nozzle center and boundary, and investigate the resulting mixing patterns. The present study focuses on the initial free-jet-like and transitional regimes that precede the well-developed wall-dense-jet regime. In Section 5.2, the experimental setup and procedures that are adapted for the present investigation is described. The initial conditions at the nozzle exit that are noted to have significant influence on the subsequent flow development are presented in Section 5.3. Various gross flow behaviors, such as the impingement point of the flow, the axial and cross-sectional profiles of the mean velocity and

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concentration distribution, are addressed in Section 5.4. In addition, we report the turbulence characteristics and turbulent mass and momentum fluxes derived from the instantaneous velocity and concentration data, which were measured simultaneously by the combined PIV and PLIF method. Note that an unique advantage of the combined measurement is that the correlation between the velocity and concentration fluctuations, i.e., Reynolds flux can be resolved. The associated turbulent viscosity, ν_t , and turbulent diffusivity, D_t are derived from the acquired Reynolds shear stress and Reynolds flux results. With the availability of both the turbulent viscosity and turbulent diffusivity, the turbulent Schmidt number, Sc_t , is also calculated.

It is hoped that these experimental results can provide regulatory references on the relevant environmental issues, and support the development and validation of future numerical models concerned with the turbulent transport of mass and momentum in circular offset dense jets. It is worth noting that in most previous studies on buoyant jets mentioned above, the spreading of the buoyant flow in the vertical and lateral directions have been examined and compared by traversing the point-based measurements of the temperature and velocity across different downstream cross sections. The enhancement in the lateral growth and the corresponding suppression in the vertical growth beyond the point of attachment is a well known phenomenon. However, the PIV and PLIF measurements undertaken in the present study focused only on the vertical plane crossing the center plane of the nozzle. As such, discussion on the lateral growth of the dense flow is not attempted herein.

5.2 Experimental Setup and Procedures

The experimental setup is shown schematically in Fig. 5.2. As noted, the entire setup is very similar to that used in the inclined dense jet study presented in the previous chapter. Thus, only brief description is provided in the following unless a different setting is the case.

The test tank was filled to the depth of 0.26 *m*. A horizontal discharge tube of 12.95 *mm* internal diameter with a wall thickness of 3 *mm* was connected to a reinforced flexible hose, and clamped to a stainless steel frame. The tube nozzle was aligned horizontally with its center positioned at a small distance of z_0 from the base that was varied with a moderate range during the experiments. As in the near-bed inclined dense jet, z_0 is a crucial parameter that affects significantly the mixing processes for this configuration. The jet flow was produced by the

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same constant head tank system. A specific flowrate for the discharge was selected by controlling the regulable valve and was determined using the same electromagnetic flowmeter. The effluent had a fixed density of 1017.7 kg/m^3 while the ambient water density inside the test tank was kept at 997.8 kg/m^3 . As a result, the relative density difference between the effluent and the ambient, $\Delta\rho/\rho_a$, was maintained at 0.02. The same combined PIV and PLIF system was employed in the experiments. Due to the analogy of the flows, similar camera magnification and hence resolution was adopted in this study (typically 11.14 pixels per mm in the illumination plane).

Figure 5.2: Schematic diagram of experimental setup

By the same token, the proximity to the bed will play a significant role in affecting the flow pattern of the horizontal brine jet. As mentioned in Chap. 2, in Sobey et al. (1988), dimensional argument together with comparative analysis on the various parameters involved in the flow has proved the bed proximity parameter z_0/L_M as well as the free surface proximity parameter $(H - z_0)/L_M$ to be the only dominate parameters for horizontal buoyant jet in shallow water, provided that the boundary is smooth and the other effects such as bed roughness are not involved. The surface effect was accounted for through the submergence ratio H/D (2.63-7.05, Balasubramanian and Jain (1978); 3.64-10.91, Sobey et al. (1988)) and the free surface proximity parameter $(H - z_0)/L_M$ (0.054-2.26, Sobey et al. (1988)). In the present study, however, the effort was focused on the bottom bed proximity and thus both of these parameters were kept sufficiently large (20.08 for H/D and 1.16-2.53 for $(H - z_0)/L_M$) to avoid the possible influence. Specifically, with a fixed z_0 , the densimetric Froude number Fr was varied to investigate the bed proximity effect. A total of seven experiments were

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performed. The experimental conditions are tabulated in Table 5.1.

Table 5.1: Experimental conditions

Exp. No.	Nozzle diameter D (mm)	Distance z_0 (mm)	Water depth H (mm)	$\Delta\rho/\rho_a$ (%)	Discharge velocity U_0 (m/s)	Reynolds number $Re = DU_0/\nu$	Jet densimetric Froude number $Fr = \frac{U_0}{\sqrt{D \cdot g \Delta\rho/\rho_a}}$	Jet/plume characteristic length scale L_M (mm)	Bed proximity parameter z_0/L_M
H1	12.95	22.24	260	1.99	0.744	9686	14.8	180.40	0.123
H2	12.95	22.24	260	1.99	0.516	6721	10.3	125.18	0.178
H3	12.95	22.24	260	1.99	0.387	5041	7.7	93.88	0.237
H4	12.95	27.47	260	1.99	0.653	8500	13.0	158.31	0.174
H5	12.95	27.47	260	1.99	0.501	6523	10.0	121.50	0.226
H6	12.95	32.03	260	1.99	0.812	10575	16.2	196.97	0.163
H7	12.95	32.03	260	1.99	0.600	7808	11.9	145.43	0.220

The experimental procedures also largely follow that of series N in the previous case. For moderate flow rates, four to five windows were typically needed. In order to maintain the measured dye concentrations in subsequent windows to be within the calibrated range, we also had to gradually increase the source dye concentration when moving the camera downstream.

5.3 Initial Conditions at the Nozzle Exit

The exit condition of a jet plays an important role in the jet downstream development. In the current study, to ensure a fully-developed velocity profile at the exit, the length of the solid horizontal discharge tube was made to be more than 15 times nozzle diameter that should be sufficient for the flow to adjust fully after the reinforced flexible hose.

Furthermore, we had checked the exit mean and rms velocity profiles at the outlet for all tests (representative test H1 shown in Fig. 5.3 and 5.4 below, the rest are presented in Fig. B.3-B.14 in Appendix B). As illustrated in Fig. 5.3, the mean axial velocity appears to follow the one-seventh power law (dashed line) characteristic of the fully developed pipe flow in the upper half of the jet flow (negative abscissa), while in the lower half (positive abscissa), the data are more scattered resulting in some asymmetry, which is presumably attributed to the unstable density gradient in the lower part of the flow. Our judgement is however that this asymmetry is relatively small and would not affect the short development of the jet before it impacts the bottom boundary.

The scatter in the measured rms velocity fluctuation also appears to be somewhat larger in the lower half than in the upper half as shown in Fig. 5.4. For the better-collapsed upper half, the relative turbulence intensity $\sqrt{u'^2}/U_c$

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varies between approximately 5% ($r = 0$) and 15% ($r = D/2$), which falls in the previously reported ranges, e.g., 3–24% in Mi et al. (2001b) and 3–9.5% in Mi et al. (2001a) respectively. It is noted that the exit condition was obtained considerably further away from the nozzle exit, $x/D = 0.3 \sim 0.5$ in the present case, as compared to $0.05 \sim 0.1$ in Mi et al. (2001b,a), due to the optical distortion near the discharge nozzle for PIV, while this imposed less constraint for the hot-wire measurement in Mi et al. (2001b,a).

Figure 5.3: Radial profiles of the axial mean velocity U at the nozzle exit

Figure 5.4: Radial profiles of the axial rms velocity fluctuation $\sqrt{u'^2}$ at the nozzle exit

The radial profiles of the mean and rms concentration distribution for H1 are also extracted and presented in Fig. 5.5 and 5.6 for comparison. Unlike PIV, PLIF measurement can be taken at a region much closer to the nozzle due to the different functionality of the filter. Hence, the exit conditions for concentration were obtained at $0.02 \sim 0.2D$ in comparison to $0.3 \sim 0.5D$ for velocity. In most

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cases, the mean concentration profiles exhibit a top-hat distribution except for H5 and H6, which show slight fluctuations (Fig. B.21 and B.23). Consistent with the observations on the passive temperature scalar in Mi et al. (2001b), the rms values are quite uniform throughout the nozzle diameter, and much lower than their velocity counterparts.

Figure 5.5: Radial profiles of the mean concentration C at the nozzle exit

Figure 5.6: Radial profiles of the rms concentration fluctuation $\sqrt{c'^2}$ at the nozzle exit

5.4 Results and Discussions

5.4.1 Flow development

Fig. 5.7 presents a typical superimposed time-averaged full-field velocity vector and concentration scalar maps (from H1). A reference vector with the magnitude

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of the efflux velocity is provided in the map together with a vertical color bar to indicate the concentration scale. On the whole, the corresponding velocity and concentration maps are well overlapped due to the careful alignment of the two cameras. They also clearly illustrate the evolution from the starting offset dense jet to subsequent wall-dense-jet pattern, which indicates that sufficient windows have been applied to capture the flow transition. It is also interesting to note a recirculation zone exists underneath immediately off the nozzle in H3-5 and H7 (Fig. B.27(b)-B.27(d) and B.27(f)).

Figure 5.7: Superimposed mean velocity vector and concentration contour maps (from H1)

In order to have a better insight on the flow development, representative contours of the out-of-plane vorticity (also from H1), i.e., $\Omega_y = \frac{1}{2} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial z} \right)$, are also computed and plotted in Fig. 5.8. As seen from the figure, solid contours denote positive vorticity and dashed contours denote negative vorticity. The location of the clockwise vortex center is marked with asterisk.

Figure 5.8: Vorticity contour map (from H1)

5.4.2 Impingement

The mean velocity field has been used to locate the jet impingement point, or reattachment point. Unlike plane offset jets which exhibit strong two dimensionality with a typical return flow at the bottom, the present flow is generically

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three-dimensional, and the entrainment from the top and bottom significantly suppresses the reverse flow as can be observed from the vector map in Fig. 5.7.

A typical profile of the boundary streamwise velocity and concentration (from H6) is presented in Fig. 5.9. Despite the obvious scatter, especially for the concentration data which was caused by the reflection of laser light close to the Perspex bottom, the streamwise velocity and concentration profiles largely follow the pattern reported in Roberts et al. (1997). It grows from zero to the maximum at around the impingement point, and maintains at this level for a short distance before decreasing. We can thus locate the point of impingement as the location of the peak value. Note, however, the concentration profiles for H3, H5 and H7 (Fig. B.28(c), B.28(e) and B.28(f)) scatter too significantly to make any meaningful judgement, therefore, the impingement point for these tests are mainly determined by the velocity counterparts. For the other tests, generally, the two profiles peak at approximately the same point as illustrated in Fig. 5.9 and further in Fig. B.28. The various impingement points are quantified and tabulated in Table 5.2.

Figure 5.9: Boundary streamwise velocity and concentration profile (from H6)

Through dimensional analysis (Johnston et al., 1994), the non-dimensional horizontal distance of the impingement point, x_{ip}/L_M , of a horizontal buoyant jet can be expressed as a function of the bed proximity parameter, z_0/L_M . From Fig. 5.10, the data shows that the best-fit relationship is $x_{ip}/L_M = 2.508z_0/L_M + 0.629$. The present result appears to follow a similar trend with the pure offset air jet documented in Nasr and Lai (1998), which reports an power law of $x_{ip}/w = 2.630(h/w)^{0.855}$ for $h/w < 20$, where h is the offset distance of the wall from centerline of the nozzle, and w is the slot nozzle width. At the same time, the relationship contrasts vastly from the positively buoyant jet study reported in Johnston et al. (1994), which reveals a linear relationship of

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Table 5.2: Horizontal distances of the impingement points

Exp. No.	x_{ip}/D	x_{ip}/L_M
H1	12.6	0.90
H2	10.2	1.06
H3	8.2	1.13
H4	12.5	1.02
H5	11.3	1.20
H6	17.0	1.12
H7	14.4	1.28

$x_{ip}/L_M = 29.598z_0/L_M - 0.70914$. Obviously, the difference can be attributed to the change in the direction of the buoyancy. The impingement of the present flows with the bed was bound to happen due to the negative buoyancy, whereas in Johnston et al. (1994), the flow was initially driven by positive buoyancy and the impingement would only happen when Coanda effect dominated.

Figure 5.10: x_{ip}/L_M vs. z_0/L_M

5.4.3 Jet axis trajectory

The jet axis, or jet centerline, typically characterizes the overall flow trajectory. Based on the obtained data, two axes for the velocity vector and concentration maps can be derived separately. Specifically, the velocity axis is determined by the locus of points where the local mean streamwise velocity component, U , is the maximum, whereas the concentration axis connects the local concentration maximum points. To illustrate the jet trajectory moving towards the bottom boundary, both axes for H1 are plotted in Fig. 5.11. Note that the corresponding

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contour of zero vorticity is also included in the figure for comparison purpose. Theoretically, the region above the jet centerline, i.e., the upper shear layer, carries positive vorticity, whereas the lower shear layer carries negative vorticity. Therefore, the contour of zero vorticity is to coincide with the velocity axis. Indeed, it is clearly shown in Fig. 5.11 that the thick solid line representing $\Omega_y = 0$ coincides with the dotted line representing velocity axis throughout the entire region except for the first 3-4 diameters right off the nozzle, in which an obvious trough of the velocity axis can be identified. The same trough can be identified in the concentration axis as well.

Figure 5.11: Concentration and velocity axes superimposed by the contour of $\Omega_y = 0$ (from H1, the arrow marks the splitting point of the two axes)

From Fig. 5.11, it can be observed that the velocity and concentration centerline axes were identical before the impingement. However, an evident deviation of the two axes is observed just before the impingement, whereby the two axes split and the concentration axis descended in a faster rate with a greater curvature. The divergence point is marked by arrow in the figure. Similar splitting points are observed for all tests (Fig. B.29). It is found that, in most cases, they are coincident with the corresponding impingement points located earlier, except for H4 and H6, which is 10.5 in comparison to $x_{ip}/D = 12.5$ and 15 in comparison to $x_{ip}/D = 17$, respectively.

The divergence of the two axes can be explained as follows. For velocity, the jet will transit to a wall-jet pattern with zero velocity (no slip) at the wall, while for concentration the wall boundary condition imposes a zero vertical concentration gradient. The different requirements in the boundary condition lead to the divergence of the two axes at the impingement. However, the specific mechanism for the divergence to happen earlier in H4 and H6 than in the other tests is not clear. Potential reasons can be related to the stronger initial momentum, which give rise to a stronger dynamic pressure difference. It is noted that a similar trend has also been observed in positively buoyant jets in Li (1997), which showed the obtained concentration centerline tends to be closer to the

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lower edge.

To distinguish the effect of the nozzle height, z_0 (i.e., the bed proximity), and the jet densimetric Froude number, Fr , on the jet trajectory, the jet axes are grouped by the same z_0 and Fr and some representative scenarios are shown in Fig. 5.12. When z_0 is held constant, the axes corresponding to varying Fr tend to deviate at around 5-6D, with the lesser Fr descending faster as revealed in Fig. 5.12(a)-5.12(b). On the contrary, when Fr is held constant, as shown in Fig. 5.12(c) and Fig. 5.12(d), the two initially offset axes converge at around 10D.

When normalized by L_M , the different axes are found to collapse better as shown in Fig. 5.13. Referring to the various impingement points normalized by L_M as tabulated in Tab. 5.2, it is noted that the different axes start to separate at around $1L_M$, i.e., where the impingement occurs. Theoretically, upon hitting the wall, an internal hydraulic jump may occur. As a result, when z_0 is kept constant, the axis with a greater Fr , hence stronger initial momentum, can develop a larger conjugate depth after the jump than the ones with lesser Fr .

To illustrate the influence of the bed proximity parameter, z_0/L_M , which combines the effect of z_0 and Fr , the normalized axes of the various tests are re-categorized and presented in Fig. 5.14. It is clearly shown in the figures that the axes under different combination of z_0 and Fr but same z_0/L_M collapse nicely. It is also observed in the figures that, when z_0/L_M is smaller, i.e., the Coanda influence stronger, the attachment occurs earlier as expected. Also plotted in the figures are published data from Sobey et al. (1988) and Johnston and Volker (1993). The three sets of data were all obtained under the condition of $z_0/L_M < 0.1$, i.e., under a strong Coanda effect. The trend is further verified as these points all overlies the data from the present study. Note that, however, the previous data were all partially affected by the proximity of the free surface as indicated by the $(H - z_0)/L_M$ values shown in the figure, whilst in the present study, the covered $(H - z_0)/L_M$ is much larger in the range of 1.16-2.53.

Wright (1977) proposed that, for the horizontal buoyant jet in the stationary ambient water, with a certain distance from the efflux nozzle ($x < 5L_M$), the jet flow is dominated by its momentum and its trajectory follows $z/L_M = c_1(x/L_M)^3$, in which c_1 is an empirical constant. Without the boundary effect, this theory is also applicable to the horizontal dense jet if we take a reverse perspective, except that the constant is added a minus sign. Indeed, Katano et al. has fitted the centerline axis of a free falling horizontal cold water jet to $(z - z_0)/D = -0.0493Fr^{-2} \cdot (x/D)^3$ which is equivalent to

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(a) Velocity axis ($z_0 = 1.72D$)

(b) Concentration axis ($z_0 = 1.72D$)

(c) Velocity axis ($Fr = 10$)

(d) Concentration axis ($Fr = 10$)

Figure 5.12: Comparison of various concentration and velocity axes

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(a) Velocity axis ($z_0 = 1.72D$)

(b) Concentration axis ($z_0 = 1.72D$)

(c) Velocity axis ($Fr = 10$)

(d) Concentration axis ($Fr = 10$)

Figure 5.13: Comparison of normalized concentration and velocity axes

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$(z - z_0)/L_M = -0.0437(x/L_M)^3$. However, from the comparison shown in Fig. 5.14, it is obvious that the free cubic curve overshoots the present trajectories right from the start, which indicates that the Coanda effect has played a role in the present setting and made the trajectory curved faster towards the bed.

(a) Velocity axes categorized by different z_0/L_M

(b) Concentration axes categorized by different z_0/L_M

Figure 5.14: Normalized concentration and velocity axes categorized by z_0/L_M (+/o/*: present study; □/◇: Sobey et al. (1988); ☆: Johnston and Volker (1993); —: Katano et al. (1979))

5.4.4 Centerline maximum concentration decay

As mentioned earlier, the concentration centerline is identified as the locus of the points where the local concentration attains the maximum, i.e., where the

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minimum dilution occurs. Therefore, it is important to study the concentration centerline to cater for the primary environmental concern on how fast the high-salinity discharge is able to mix with the receiving water and be diluted. The various centerline maximum concentration profiles are presented in Fig. 5.15.

Figure 5.15: Comparison of centerline maximum concentration decay (---: Law and Herlina (2002))

It is noteworthy that the concentration remains essentially constant up to $5D$, which is the extent of the potential core region. After that, the concentration starts to drop steadily until the corresponding impingement point is reached. The decrease in concentration pauses for a short distance after the impingement point and the profile flattens. The turning points are consistent with the impingement points located in the previous section. The decay of concentration then continues afterwards. Also plotted in Fig. 5.15 is the typical decay curve of a wall jet derived in Law and Herlina (2002). Despite the scatter, the various profiles generally approach the wall-jet pattern at the tail end. It is noted that the wall-jet regime is beyond the downstream end of the measurement range. Therefore, the coverage of this regime is very limited as seen in the figures.

Typically, the decay curve follows the power law as exemplified in Law and

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Herlina (2002), and can be better revealed when plotted on logarithmic scale as shown in Fig. 5.16(a). Up to 5D, the concentration in the potential core remains nearly unchanged. Subsequently, the decrease due to entrainment occurs. The wall-jet pattern is plotted as a dashed line along with the previously reported horizontal positively buoyant jet data denoted by solid symbols (Li, 1997). These data lie well below the wall jet profile, which implies that a stronger mixing and hence higher dilution can be expected for the horizontal buoyant jet when compared with the wall jet at the same downstream location. This is attributed to the fact that more ambient water can be entrained for mixing when the buoyant jet is elevated from the bed. In Sobey et al. (1988), a nondimensionalized form of centerline dilution was defined as g'_*/g'_c , in which $g'_* = (\pi/4)^{1/4}g'_0/Fr$, g'_0 and g'_c are reduced gravity at the source and local jet centerline, respectively. Since the scalar concentration is proportional to the salinity and thus the fluid density, the nondimensionalized form can be converted to $(\pi/4)^{1/4}C_0/C_c/Fr$ for the current analysis. The data presented in Fig. 5.16(b) are represented by the same sets of symbols as in Fig. 5.16(a), and can be fitted to the given straight line. Although the approximate linear growth of the nondimensionalized dilution with the distance from the source can also be noted herein, the fitted equation differs prominently from that of a horizontal thermal jet reported in Johnston et al. (1994).

5.4.5 Centerline maximum velocity decay

The variation of the normalized centerline maximum streamwise velocity component, U_c , with the normalized downstream distance is presented in Fig. 5.17. As seen from the figures, the different decay processes collapse well onto the same pattern, and for some cases (H1 and H6), they approach the wall jet profile reported in Law and Herlina (2002) far downstream. The curve in dashed line characterizes the velocity decay in the radial-type decay region of the wall jet, which is estimated to be 20D downstream of the nozzle. For most tests, it is clear that this region is yet to be reached.

The decay profiles are plotted together and further compared with the profiles of free jet (Fischer et al., 1979), confined non-buoyant jet (Johnston and Volker, 1993) and wall jet (Rajaratnam and Pani, 1974; Law and Herlina, 2002) in Fig. 5.18(a). It is found that the centerline velocity of the offset jet decays much faster than free jet and wall jet for the covered range, but approaches the wall-jet pattern ultimately. The decay rate of the confined non-buoyant jet is identical to the present case except for the area adjacent to the nozzle, in which the non-

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(a) C_c/C_0 vs x/D (b) $(\pi/4)^{1/4} C_0/C_c / Fr$ vs x/L_M

Figure 5.16: Centerline maximum concentration decay profile (---: Law and Herlina (2002); solid symbols represent data from Li (1997), $\bullet$: $z_0/D = 1$ and $Fr = 24$; $\blacksquare$: $z_0/D = 10$ and $Fr = 24$; $\blacklozenge$: $z_0/D = 1$ and $Fr = 16$; symbol notation in (b) is same as in (a))

buoyant jet maintains its efflux velocity. The same trend can be observed when plotting on the logarithmic scale in Fig. 5.18(b). It is noteworthy that similar finding about the decay rate of centerline maximum velocity for a plane offset jet when compared with single jet and wall jet was also reported in Nasr and Lai (1998).

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Figure 5.17: Comparison of centerline maximum streamise velocity decay (---: Law and Herlina (2002))

5.4.6 Cross-sectional concentration profile

In jet modeling studies, a Gaussian profile is often assumed for the concentration distribution at the cross sections when the jet has entered the zone of established flow (ZEF), which is typically 5 to 6 diameters downstream of the nozzle. Within this short distance is the zone of flow establishment (ZFE), and the cross-sectional distribution follows a top-hat profile. In the present study, the offset jet is to impinge the bed and transit to wall jet subsequently, therefore, a wall-jet pattern is expected at far downstream. Following the determination of the jet axis, the vertical concentration profiles of the horizontal dense jet (from H5) at various downstream locations are extracted from the planar PLIF map and presented in Fig. 5.19. The vertical concentration profiles are plotted from $x=2D$ onward with a uniform $2D$ interval. The open circles mark the z -coordinates of the local maximum points, which are connected to give an illustration of the jet trajectory. It is noted that the trajectory undergoes abrupt drop when the impingement occurs and levels off afterwards. Since the concentration measured close to the boundary are not very accurate due to the optical

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(a) U_c/U_0 vs x/D (decimal scale)

(b) U_c/U_0 vs x/D (logarithmic scale)

Figure 5.18: Centerline streamwise velocity decay profile (●: Fischer et al. (1979); ■: Johnston and Volker (1993); ◆: Rajaratnam and Pani (1974); ---: Law and Herlina (2002); other symbol notation same as in Fig. 5.16)

difficulty, the maximum points are shown to be slightly elevated from the bed.

Nondimensionalized vertical profiles for the representative test before and after the impingement are plotted separately, and compared with the standard and half Gaussian profiles in Fig. 5.20, respectively. Specifically, the concentration profiles before the impingement point are nondimensionalized as C/C_c versus $(z_c - z)/b_c$, and as C/C_c versus $z/z_{cc/2}$ after the impingement point, in which C_c is the maximum mean concentration at the vertical section, z_c the corresponding z-coordinate of the maximum point, b_c the distance from the maximum point to the location where the concentration is e^{-1} of the maximum, and $z_{cc/2}$ the

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Figure 5.19: Vertical concentration profiles at various downstream locations (from H5)

distance from the bed to the point at the section at which $C = C_c/2$ and the concentration gradient is negative. Despite the scatter, it is found that the profiles evolve from top-hat to Gaussian before the impingement points and fairly good self-similarity is achieved for the upper half of the flows. Downstream of the impingement points, the profiles approach the wall-jet pattern as shown in Fig. 5.19. The agreement improves further downstream.

5.4.7 Cross-sectional velocity profile

The vertical streamwise velocity profiles at various downstream locations for H5 are presented in Fig. 5.21. The transition of the profile from the initial top-hat to intermediate Gaussian and ultimate wall-jet type is clearly illustrated. Compared with the concentration profiles for the wall-jet regime, the maximum points of the velocity profiles are elevated further away from the bed, and the overall profiles are asymmetric vertically, with the slope being much steeper below than above the maximum point. Following the concentration counterparts, the velocity profiles before the impingement points are nondimensionalized as U/U_c versus $(z_c - z)/b_u$, and as U/U_c versus $z/z_{uc/2}$ after the impingement points, in which U_c is the maximum mean streamwise velocity magnitude at the vertical section, z_c the corresponding z-coordinate of the maximum point, b_u the distance from the maximum point to the location where the velocity is e^{-1} of the maximum, and $z_{uc/2}$ the distance from the bed to the point at the section at which $U = U_c/2$ and the velocity gradient is negative. By further plotting the nondimensionalized profiles for the same test in Fig. 5.22, it is found that the velocity distribution deviates appreciably from the Verhoff profile characteristic of the wall jet (Law and Herlina, 2002), indicating again that the flow is still in the process of transition. It is also noteworthy that, unlike the concentration trajectories reported in the previous section, the velocity trajectories continue to descend even after the impingement occurs, illustrating the previous discussion

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(a) Jet regime

(b) Transition to dense wall-jet regime

Figure 5.20: Vertical concentration profiles at various downstream locations (from H5)

on the divergence of the two trajectories. Moreover, the velocity profiles in the ZEF are found to collapse onto the Gaussian pattern satisfactorily.

Attention is also given to the normal velocity (i.e., the vertical component, v), and the normalized profiles at the vertical sections at various downstream locations for H5 are shown in Fig. 5.23. As discussed in Law and Herlina (2002), due to the fact that the current PIV settings (for instance, the pulse-pair interval) are mainly determined by the characteristics of the dominant flow in the streamwise direction, the normal velocity measurement suffers a poorer accuracy, which can be illustrated by the reduced smoothness of the profiles. Nevertheless, the profiles indicate that the normal velocity is essentially negative prior to the

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Figure 5.21: Vertical streamwise velocity profiles at various downstream locations (from H5)

(a) Jet regime

(b) Transition to dense wall-jet regime

Figure 5.22: Vertical streamwise velocity profiles at various downstream locations (from H5)

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impingement, implying that the flow is always directed towards the bed. After the impingement points, the magnitude of the normal velocity reduces and the profiles experience strong fluctuations. Additionally, a significant randomness associated with the overall trajectory of the local maximum points is noted.

Figure 5.23: Vertical normal velocity profiles at various downstream locations (from H5)

5.4.8 Jet spread

A commonly-used measure to characterize the jet growth is the jet spread width based on Gaussian-fitting the data and then finding the distance from the centerline of the jet to where the local mean velocity or concentration value equals e^{-1} or $1/2$ of the local centerline maximum. For horizontal jets, the jet spread width is typically assessed by the half height both above and below the centerline in the vertical direction where half of the centerline maximum value is achieved. In this case, both concentration and velocity half heights can be defined and presented along with the previously extracted centerline trajectory (zero vorticity contour) in Fig. 5.24 (from H1).

Figure 5.24: Concentration and velocity spread superimposed by corresponding centerline trajectory (from H1)

On the whole, the concentration spreads in a considerably wider manner than its velocity counterpart as shown in the figure. The spreading rates for the upper and lower shear layers for both concentration and velocity are about the

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same, indicating that the presence of the bed (or Coanda effect) is insignificant for this case. The concentration lower half heights sink faster than their velocity counterparts due to the concentration-to-velocity spread ratio which is typically larger than 1.0. The lower half heights for velocity are expected to be slightly elevated from the bed downstream of the impingement points, but due to the aforementioned constraint of the PIV measurement close to the boundary, data in this region are subjected to errors and the lower half heights are hence not shown. Rajaratnam and Pani (1974) and Law and Herlina (2002) suggested that, the upper half heights for velocity and concentration are to increase linearly with the downstream distance after 20D from the nozzle in the wall jet, whereas here, the upper half heights are still undergoing slight reduction, implying that the wall-jet type of spread is yet to achieve.

The trend of the spread is further revealed in Fig. 5.25, in which the distance from the upper and lower half heights to the centerline, i.e., the half-widths, are plotted against the downstream distance. Also included in the figures are the variation of the velocity half-widths of a non-buoyant jet (Johnston and Volker, 1993), a buoyant jet (Lai, 2002) and a three-dimensional wall jet (Newman et al., 1972). Prior to the impingement point, the spreading rate for both concentration and velocity are found to be appreciably lower than the non-buoyant and buoyant jet. Subsequently, when the impingement occurs, the upper and lower half-widths for both concentration and velocity deviate abruptly, and the splitting points are approximately consistent with the previously determined impingement points. Notably, the regressed straight line describing the increase of the velocity half-width with the downstream distance reported in Newman et al. (1972) are within the scatter of the present data.

Figure 5.25: Comparison of concentration and velocity half-widths in upper and lower shear layers (—: Johnston and Volker (1993); ---: Lai (2002); -.-.-: Newman et al. (1972); rest are from test H1, present study)

The half-width profiles for the various tests are plotted together in Fig. 5.26 after normalized by the respective jet/plume length scale L_M . The concentration half-widths show more scatter than their velocity counterparts. Similar observation was reported in Sobey et al. (1988), and was attributed to the deviation of the vertical concentration profile from the Gaussian pattern closer to the bed. The regression of the half-width based on the integrated dilution for bed-affected buoyant jet was derived in Johnston et al. (1994) and is also included in Fig. 5.26(a) for reference.

5.4.9 Turbulence characteristics and turbulent momentum transport

The contours of both the turbulence intensities and Reynolds shear stresses for a representative test (H5, same in the following unless otherwise specified) are presented in Fig. 5.27. Generally, for both streamwise and normal turbulence intensities, the contours with maximum value can be identified in both the upper and lower shear layers, with a shadow area of weak turbulence sandwiched in between. Notably, the shadow area has a nearly identical extent as the potential core region, which was determined as approximately $5D$ in Shao and Law (2009). On the other hand, the Reynolds shear stress in the lower shear layer is of the opposite sign to that in the upper shear layer and also appears to be slightly greater in its magnitude.

The profiles of the turbulence characteristics in the vertical sections at various downstream locations are further extracted and presented in Fig. 5.28. Consistent with the preceding observations made on the planar contours, the vertical profiles for $\sqrt{u'^2}/U_0$ and $\sqrt{v'^2}/U_0$ are characterized by two prominent peaks associated with the upper and lower shear layers, respectively, and the lower peak tends to be slightly higher than its upper counterpart. Proceeding further downstream, the dual peaks diminish and become indistinguishable. For $\sqrt{u'^2}/U_0$, the profiles before the impingement points ($11.3D$ for the present test) show temporary resemblance. After the impingement occurs, the profiles are found to approach the wall-dense-jet pattern with the maximum moving towards the bed. While for $\sqrt{v'^2}/U_0$, the intensity diminishes towards the bed at all sections, implying that the no-flux conditions are imposed therein. The two opposite peaks marking the upper and lower shear layers are seen for the Reynolds stress profiles initially, and are diminishing rapidly after the respective impingement points, indicating that significant momentum transfer comes to an end after the flow hits the bottom.

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(a) Upper bc

(b) Lower bc

(c) Upper bu

(d) Lower bu

Figure 5.26: Comparison of concentration and velocity half-widths in upper and lower shear layers (---: Johnston et al. (1994); rest profiles represent H1-7)

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Figure 5.27: Contours of turbulence characteristics

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(a) Vertical profiles of streamwise turbulence intensity $\sqrt{u'^2}/U_0$ (b) Vertical profiles of normal turbulence intensity $\sqrt{v'^2}/U_0$ (c) Vertical profiles of Reynolds shear stress $\overline{u'v'}/U_0^2$

Figure 5.28: Vertical turbulence characteristics profiles at various downstream locations

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The different profiles are further nondimensionalized by the corresponding centerline maximum velocity, U_c and shown in Figs. 5.29-5.31. It is noted that the profiles are categorized as in the dense-jet regime and in the transition to the wall-dense-jet regime. In the dense-jet regime, except for H4 and H6 (Fig. B.30(g), B.30(i), B.31(g) and B.31(i)), the turbulence intensity in both the streamwise and normal directions shown in Figs. 5.29(a) and 5.30(a) are noted to peak at a slightly lower value than previously reported for unbounded vertical buoyant jets (Law and Wang (2000)), which ranges in 0.23-0.28 for the axial velocity and 0.16-0.21 for the radial velocity. The deviation is probably due to the fact that the current measurements were taken at the sections much closer to the nozzle. Notably, the prominent lower peak for $\sqrt{u'^2}/U_c$ and $\sqrt{v'^2}/U_c$ in the dense-jet regime merges into the wall boundary layer when transiting to wall-dense-jet and become indiscernible. Nevertheless, as shown in Figs. 5.29(b) and 5.30(b), the turbulence intensity is yet to achieve the self-similarity in the transitional stage. For $\sqrt{u'^2}/U_c$ shown in Fig. 5.29(b), the measured peaks at the intermediate downstream sections vary in the range 0.25-0.4, which falls in the reported range for three-dimensional wall jets (Newman et al. (1972) and Herlina and Law (2002)). Further downstream and close to the edge of the measurement window, the streamwise turbulence intensity grows unexpectedly large and are very likely suffering from significant experimental uncertainties. Notably, the turbulence intensity in the normal direction tends to be lower and peaks in the range 0.2-0.3 at intermediate downstream locations. Similar trend has been observed in Herlina and Law (2002) with the peak to be approximately 0.18. Again, as shown in Fig. 5.31, the nondimensionalized Reynolds shear stress in the dense-jet regime appears to be considerably lower than the reported peak value of approximately 0.02 for vertical buoyant jets (Law and Wang (2000)).

The variation of the various turbulence characteristics along the centerline is plotted in Fig. 5.32. The turbulence intensity in the streamwise direction is considerably higher than that in the normal direction, and both continue to grow even after the impingement occurs and hence are much greater than the previously reported level for vertical buoyant jets (Law and Wang (2000)), which ranges from 0.23 to 0.28 with an average value of 0.265 for $\sqrt{u'^2}/U_c$ and from 0.16 to 0.21 with an average value of 0.189 for $\sqrt{v'^2}/U_c$. The nondimensionalized Reynolds shear stress is also seen to fluctuate more strongly after the impingement points. However, these differences are partly attributed to the increased experimental uncertainty after the impingement points as the accuracy of PIV deteriorated significantly close to the wall due to the reflection of laser light.

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(a) dense-jet regime

(b) transition to wall-dense-jet regime

Figure 5.29: Vertical streamwise turbulence intensity profiles at various downstream locations

5.4.10 Turbulent mass transport

Combined PIV and PLIF technique is capable of capturing the instantaneous velocity and concentration data simultaneously, which will enable the calculation of their correlation and allow the analysis of the Reynolds flux term in the Reynolds-averaged scalar transport equation. In this section, we shall analyze the correlated velocity and concentration data and the resulting turbulent mass transport.

Shown in Fig. 5.33 is the mean Reynolds flux vector map, in which the length of the arrow is proportional to the flux magnitude and the direction of the arrow represents the flux direction. Notably, the mass transport initiates immediately off the nozzle exit and is directed from the area with a high concentration to the area with a low concentration. Therefore, the upper shear layer can be characterized by upward fluxes and the lower shear layer by downward fluxes.

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(a) dense-jet regime

(b) transition to wall-dense-jet regime

Figure 5.30: Vertical normal turbulence intensity profiles at various downstream locations

Figure 5.31: Vertical Reynolds shear stress profiles at various downstream locations

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Figure 5.32: Variation of turbulence characteristics along centerline

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An unmixed gap sandwiched by the two layers can be clearly identified close to the nozzle exit. As expected, the unmixed region coincides with the potential core region. The symmetry between the fluxes in the upper and lower shear layers is maintained until the flow impacts the bed, and after that, the fluxes in the lower layer are significantly suppressed.

Figure 5.33: Mean Reynolds flux vector map

The vertical profiles of the Reynolds flux in the streamwise and normal directions at various downstream locations are presented in Fig. 5.34. Similar to $\sqrt{u'^2}/U_0$ and $\sqrt{v'^2}/U_0$, the profiles of $\overline{u'c'}/(U_0C_0)$ are characterized by two prominent peaks corresponding to the two shear layers beyond the potential core region. However, contrary to the turbulence intensity distribution, the upper peaks of Reynolds flux are slightly higher than the lower peaks. This can be explained by the potential effect of the boundary confinement on the mass transport. Beyond the impingement point, the profiles are found to transit to the wall-dense-jet pattern similar to the turbulence intensity, but the maxima are maintained at almost the same height. On the other hand, for $\overline{v'c'}/(U_0C_0)$, the two peaks marking the upper and lower shear layers are initially anti-symmetric about the flow centerline, and diminish rapidly towards the bed. Again, the no-flux conditions at the bed are satisfied in both profiles.

The different profiles of the Reynolds flux are further nondimensionalized by the product of the corresponding centerline maximum velocity, U_c and centerline maximum concentration, C_c , and plotted in Figs. 5.35 and 5.36. Similarly, the profiles are grouped as in the dense-jet regime and in the transition to the wall-dense-jet regime. In the dense-jet regime, it is evident that the nondimensionalized profiles comprise a primary upper peak and secondary lower peak. The contrast between the two peaks grows further downstream due to the suppression of the lower peak as observed in Fig. 5.34. Close to the nozzle exit (typically 2D and 4D shown in Fig. 5.35), $\overline{u'c'}$ is zero at the centerline. When moving away from the potential core region, $\overline{u'c'}$ becomes finite at the centerline

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(a) Vertical profiles of streamwise Reynolds flux $\overline{u'c'}/(U_0C_0)$ (b) Vertical profiles of normal Reynolds flux $\overline{v'c'}/(U_0C_0)$

Figure 5.34: Vertical Reynolds flux profiles at various downstream locations

and the magnitude grows with increasing distance downstream. The centerline values in the various tests are found to be much lower than previously reported values of 0.024 for vertical buoyant jets (Law and Wang (2000)), which again can be attributed to the insufficient downstream extent of the measurement area. The upper peaks are significantly higher than the centerline value, whereas the lower peaks significantly lower, reaffirming the effect of the close proximity to the bed on the lower mixing layers. In the transitional stage, the measured $\overline{u'c'}/(U_cC_c)$ has a peak lower than the reported range of 0.025-0.045 for three-dimensional wall jets (Herlina and Law (2002)). It is again verified that the flow has not fully developed to wall-dense-jet.

The Reynolds fluxes in the normal direction are shown in Fig. 5.36. They are anti-symmetric about the centerline and have a peak value half of their counterparts in the streamwise direction, which is consistent with the previously observed relationship between $\sqrt{u'^2}/U_c$ and $\sqrt{v'^2}/U_c$. Again, the peak values in the various tests are found to be much lower than previously reported value of 0.018 for vertical buoyant jets (Law and Wang (2000)).

The profiles of the orientation of the turbulent flux vector are shown in Fig. 5.37. As seen in the vector map in Fig. 5.33, the orientation of the vectors

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(a) dense-jet regime

(b) transition to wall-dense-jet regime

Figure 5.35: Vertical streamwise Reynolds flux profiles at various downstream locations

Figure 5.36: Vertical normal Reynolds flux profiles at various downstream locations

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are anti-symmetric about the centerline. Specifically, the fluxes in the upper half are scattered around 30° , whereas the fluxes in the lower half around -30° , which is consistent with the finding in Feng et al. (2007). Moreover, despite the significant scatter, both fluxes are directed to be horizontal when transiting to wall-dense-jet regime.

(a) dense-jet regime

(b) transition to wall-dense-jet regime

Figure 5.37: Orientation of Reynolds flux vectors at various downstream locations

The widely accepted turbulent viscosity hypothesis suggests that the turbulent viscosity, or eddy viscosity, can be evaluated from the experimental data by the following equation (corresponding to the present case),

$$\nu_t = \frac{-\overline{u'v'}}{\partial U / \partial z} \quad (5.1)$$

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While the turbulent diffusivity, D_t , is defined as,

$$D_t = \frac{-\overline{v'c'}}{\partial C / \partial z} \quad (5.2)$$

ν_t and D_t are estimated from the various self-similar profiles following the procedures proposed in Chang and Cowen (2002). The nondimensionalized profiles of streamwise velocity are shown in Fig. 5.38. The sections chosen are before the impingement points, where as noted, a reasonable self-similarity of the profiles is achieved. The nondimensionalized profiles in Fig. 5.38 are used to calculate $\partial U / \partial z$, which is shown in Fig. 5.39. The profiles of the derivative is noted to be anti-symmetric about the centerline. The nondimensionalized profiles of Reynolds shear stress are presented in Fig. 5.40. Applying Eq. 5.1 to the results shown in Figs. 5.38-5.40, the turbulent viscosity can be estimated and plotted in Fig. 5.41. A wide variation across the jet can be seen at the various sections. In most cases, the maximum turbulent viscosity emerges in the shear-layer regions and declines towards the bed as well as the free stream.

Figure 5.38: Self-similar vertical profiles of streamwise velocity

Figure 5.39: $\partial U / \partial z$ profiles calculated from Fig. 5.38

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Figure 5.40: Vertical profiles of Reynolds shear stress

Figure 5.41: Vertical profiles of turbulent viscosity ν_t

Following the same procedures and using the results shown in Figs. 5.42-5.44, Fig. 5.45 shows the vertical profiles of turbulent diffusivity obtained at several downstream locations. The profiles exhibit a similar trend of variation as the turbulent viscosity shown in Fig. 5.41.

The ratio of ν_t to D_t is defined as the turbulent Schmidt number, Sc_t . It is an important modeling parameter for numerical simulation of turbulent flows. In numerical modeling practice, for simplification, the turbulent Schmidt number is often taken as a constant in the mass transport closure. Reported value of the average Sc_t varies from study to study, but are typically around 0.7. It is noteworthy that Law (2006) also reported a Sc_t of 0.69 based on his analytical estimation which is consistent with the value for isotropic turbulence. Fig. 5.46 shows the vertical profiles of Sc_t at several downstream locations determined in the present experimental study. A wide spatial variation of the value in the range 0.4-1 is clearly illustrated. Despite the scatter, the range centers around the anticipated value of ~ 0.7 .

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Figure 5.42: Self-similar vertical profiles of concentration

Figure 5.43: $\partial C/\partial z$ profiles calculated from Fig. 5.42

Figure 5.44: Vertical profiles of normal Reynolds flux

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Figure 5.45: Vertical profiles of turbulent diffusivity D_t

Figure 5.46: Vertical profiles of turbulent Schmidt number Sc_t

5.5 Summary

An experimental investigation on the effect of Coanda attachment pertaining to a horizontal dense jet discharge is conducted in the present study. The mixing behaviors of Coanda-influenced and non-Coanda-influenced dense jets are investigated by varying the discharge densimetric Froude number, Fr , as well as the bed proximity parameter z_0/L_M . Various aspects of the Coanda effect are revealed by the analysis of the experimental results. Turbulence characteristics of a circular dense jet offset by a small distance from a parallel horizontal boundary have been studied using the combined PIV and PLIF method. The cross-sectional profiles of the turbulence intensity, Reynolds shear stress and Reynolds flux reveal the characteristics of the flow transition from a dense-jet regime to a wall-dense-jet regime. In the dense-jet regime, the profiles at different downstream locations collapse after normalization, and the turbulent mass

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and momentum transport are found to be weaker than in the unbounded vertical buoyant jet. In the transitional regime, the turbulence characteristics grow stronger but self-similarity was not observed. The associated turbulent viscosity, ν_t , turbulent diffusivity, D_t , as well as the turbulent Schmidt number, Sc_t , have been derived from the presented experimental data.

Chapter 6

Salinity Buildup due to Continuous Brine Discharge under Residual Tidal Currents

6.1 Introduction

The environmental concerns of a desalination plant include the possible adverse impacts caused by the brine discharges. As noted in Chap. 1, the operation of the desalination plants leads to a continuous discharge of brine, which is a highly concentrated saline water, as a by-product into the sea water. Although the presence of salinity seems natural to seawater, an excessive input of salinity can adversely affect exposed marine organisms, particularly if the exposure lasts an extended period of time which would be the case for continuous brine discharges (Iso et al. (1994)). It is also recognized that an increase in the salinity of the ambient waters at the intake will impair the efficiency of salt removal and increase the operation cost in the long run. Another concern is the discharge of chemicals from the pretreatment processes into the seawater together with the brine releases.

Despite the significance of addressing this issue to meet the needs of the fast developing desalination industry, relevant work has been scarce in the literature. To fill this gap, a two-dimensional mathematical model simulating the build-up of salinity around the brine outfall is developed in this and next chapters.

A typical offshore brine disposal domain is schematized in plan view and side view, respectively in Fig. 6.1(a) and Fig. 6.1(b).

As seen from Fig. 6.1, the y coordinate is coincident with the shoreline, with positive and negative directions stretching out to infinity; while the x coordinate

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Figure 6.1: Schematic of a typical brine disposal domain

is perpendicular to the shoreline, with only the positive side extending to infinity. The y -axis is in fact regarded as a solid boundary herein. Therefore, this problem can be classified as a semi-infinite problem. A steady longshore current with a velocity of V flows in the positive y direction and parallel to the shoreline. The longshore current represents the “residual” current averaging over the tidal periods to suit the present need of analyzing the long-term salinity accumulation. Note that this residual current is typically much weaker than the maximum strength of the tidal current itself. In the brine disposal practice, the outfall is commonly extended further offshore to facilitate the mixing with seawater and to minimize the environmental impact. Therefore, indicated as an open circle in Fig. 6.1, the brine outfall in the present model is deployed at a distance of x_0 off the shore, and acts like a point source of concentrated brine injection. Because of the flat bottom, the seawater depth keeps invariant along x direction and is assumed to be h_0 .

Due to the existence of the continental shelf, the coastal water is typically shallow. By analyzing the contrast in length scales, it is apparent that the concentration variation in the vertical direction will be smoothed out rapidly compared to that in the x and y directions, thus we can assume a uniform concentration distribution vertically and simplify the situation into a 2-D problem.

It is noteworthy that the modeling of salinity dispersion associated with brine discharges into coastal environment has been attempted previously. Purnama et al. (2003) developed a mathematical model to investigate the effect of coastal water-depth variation upon mixing and spreading of brine discharge. The mathematical model successfully captured the steady-state features of the effect. However, since the transient term was omitted in the governing equation, the salinity build-up process was not represented in their model.

In the next section (Section 6.2), the mathematical model that addresses the above-mentioned problem is formulated. The developed model is then uti-

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lized to resolve a hypothetical discharge problem to demonstrate its applicability (Section 6.3).

6.2 Model Construction

Based on the assumption made in the previous section, the governing equation is casted by means of a control-volume analysis, and reads,

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} - V \frac{\partial C}{\partial y}$$

$$0 \leq x < \infty, \quad -\infty < y < \infty \quad (6.1)$$

where C denotes the volumetric solute concentration (salinity excess in this case) in the receiving water, and D_x and D_y the effective dispersivities averaged over the tidal cycle in x - and y -direction, respectively.

The boundary conditions applied herein are,

- Salinity excess tends to zero at great distances from the outfall, i.e.

$$C \rightarrow 0 \quad \text{as} \quad x \rightarrow \infty \quad \text{or} \quad y \rightarrow \pm\infty \quad (6.2)$$

- The shoreline acts as a solid boundary with a no-flux condition, i.e.

$$\frac{\partial C}{\partial x} = 0 \quad \text{at} \quad x = 0, \quad \text{for all } y \quad (6.3)$$

It is noted that, a diffusion of Fickian type is assumed in Eq. 6.1, i.e., the turbulent mass transport is proportional to the mean concentration gradient. While this simple model can be valid, the effective dispersivities are strongly flow-dependent and varying throughout the whole field. Obtaining the exact values of the effective dispersivity in all directions in any particular situation is difficult, and preliminary estimation is often based on empirical data. The values of the dispersivity are also time and length scale dependent. In tidal waters, while the released tracer patch is stretched, twisted and split by the combined effect of shearing, chaotic stirring and tidal trapping, the eventual effective longitudinal diffusivity attained after a few tidal cycles (which is about $35 \text{ m}^2\text{s}^{-1}$) can be orders of magnitude greater than the instantaneous shear dispersivity (which is about $0.1 \text{ m}^2\text{s}^{-1}$) (Smith and Scott, 1997). Here, we assume a homogenous and invariant transverse effective dispersivity for both x

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and y directions as a first step towards analyzing the problem, i.e.,

$$D_x = \text{constant}, \quad D_y = \text{constant} \quad (6.4)$$

Previous study has shown that, in a moderate range of the transverse distance with respect to the water depth, the mixing arising from the constant transverse dispersivity approximation agreed well with the actual turbulent mixing (Dasi, 2000).

Note also that, because plumes in steady currents become very elongated in the direction of flow, the concentration gradients in the longitudinal direction (y) were typically assumed small and neglected in the literature (Purnama et al., 2003), often known as ‘slender-plume’ approximation (Arya, 1999). Nevertheless, as recognized by Roberts and Webster (2002), this assumption is only valid for $y \gg 2D_y/V$, and also leads to zero concentration everywhere upstream of the source. To capture the salinity build-up in the vicinity of the outfall while recognizing the potentially weak residual current, we retain the turbulent dispersion in both x and y directions in the present model.

To solve the continuous source input problem, it would be favorable to start from an instantaneous condition. Suppose at zero instant, a quantity of mass, M , is injected into the water. By considering the boundary condition (6.3), we add an image source with identical intensity at $x = -x_0$ to ensure the no-flux condition at $x = 0$. Referring to the solution given in Bear (1972) to the general 2D instantaneous advection-dispersion problem, we get the solution as follow,

$$C(x, y, t) = \frac{m}{4\pi t \sqrt{D_x D_y}} \cdot \left\{ \exp \left[-\frac{(x - x_0)^2}{4D_x t} - \frac{(y - Vt)^2}{4D_y t} \right] + \exp \left[-\frac{(x + x_0)^2}{4D_x t} - \frac{(y - Vt)^2}{4D_y t} \right] \right\} \quad (6.5)$$

where m is an arbitrary constant.

Since the total mass input M must be conserved over time, we have,

$$M = \int_{-\infty}^{\infty} \int_0^{\infty} C(x, y, t) \cdot h_0 \cdot dx dy \quad (6.6)$$

which readily gives,

$$m = M/h_0 \quad (6.7)$$

If the mass input M is extended to a continuous discharge from time instant

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zero to t , in terms of mass conservation, we have,

$$M = C_0 Q t \quad (6.8)$$

where C_0 is the volumetric solute concentration (i.e., excess salinity) of the inject source, and Q is the brine discharge flow rate.

Assuming that the flow rate Q holds constant, we define the mass inject rate M^* as,

$$M^* = \frac{dM}{dt} = C_0 Q \quad (6.9)$$

Based on Eq. 6.7, the effective mass inject rate per unit depth m^* satisfies,

$$m^* = \frac{M^*}{h_0} = \frac{C_0 Q}{h_0} \quad (6.10)$$

The continuous source solution can then be derived from Eq. 6.5 by replacing m with $m^* d\tau$, t with $t - \tau$, and integrating from $\tau = 0$ to $\tau = t$ (Hunt, 1978). By means of this temporal convolution, we obtain,

$$C_c(x, y, t) = \frac{m^*}{4\pi\sqrt{D_x D_y}} \int_0^t \left\{ \exp \left[-\frac{\frac{(x-x_0)^2}{D_x} + \frac{[y-V(t-\tau)]^2}{D_y}}{4(t-\tau)} \right] + \exp \left[-\frac{\frac{(x+x_0)^2}{D_x} + \frac{[y-V(t-\tau)]^2}{D_y}}{4(t-\tau)} \right] \right\} \frac{d\tau}{t-\tau} \quad (6.11)$$

where C_c is the volumetric solute concentration due to the continuous injection. Manipulating the integrand leads to

$$C_c(x, y, t) = \frac{m^* \cdot \exp \left[\frac{yV}{2D_y} \right]}{4\pi\sqrt{D_x D_y}} \cdot \int_0^t \left\{ \exp \left[-\frac{\frac{(x-x_0)^2}{D_x} + \frac{y^2}{D_y}}{4(t-\tau)} - \frac{V^2(t-\tau)}{4D_y} \right] + \exp \left[-\frac{\frac{(x+x_0)^2}{D_x} + \frac{y^2}{D_y}}{4(t-\tau)} - \frac{V^2(t-\tau)}{4D_y} \right] \right\} \frac{d\tau}{t-\tau} \quad (6.12)$$

An integral of the form similar to Eq. 6.12 was derived in Hantush and Jacob (1955) as the leaky aquifer function, W , and further depicted in Hunt (1978).

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The final solution is thus,

$$C_c(x, y, t) = \frac{C_0 Q \cdot \exp\left[\frac{yV}{2D_y}\right]}{4\pi h_0 \sqrt{D_x D_y}} \cdot \left\{ W\left[\frac{R_1^2}{4D_y t}, \frac{VR_1}{2D_y}\right] + W\left[\frac{R_2^2}{4D_y t}, \frac{VR_2}{2D_y}\right] \right\} \quad (6.13)$$

where $R_1 = \sqrt{(x - x_0)^2(D_y/D_x) + y^2}$ and $R_2 = \sqrt{(x + x_0)^2(D_y/D_x) + y^2}$ are weighted radii from the real and image sources to the point of interest, respectively.

As time increases, the rate of salinity advects and disperses out of and the rate of salinity injects into a confined region around the outfall will approach a balance, hence a quasi-steady state can be reached therein. The discussion of the size of the region corresponding to the time of interest will be given in the next section. Upon reaching steady state, Eq. 6.13 can be simplified to (Hunt, 1978),

$$C_c(x, y, \infty) = \frac{C_0 Q \cdot \exp\left[\frac{yV}{2D_y}\right]}{2\pi h_0 \sqrt{D_x D_y}} \cdot \left\{ K_0\left(\frac{VR_1}{2D_y}\right) + K_0\left(\frac{VR_2}{2D_y}\right) \right\} \quad (6.14)$$

where K_0 = zero-order, modified Bessel function of the second kind.

To facilitate the presentation of results, we define the non-dimensional quantities as $x^* = x/h_0$, $x_0^* = x_0/h_0$, $y^* = y/(Vh_0^2/D_y)$, $t^* = tV^2/\sqrt{D_x D_y}$ and $C^* = C/(C_0 Q/Vh_0^2)$. Assuming further that $D_x = D_y = D$, the transient and steady-state solutions are reduced to,

$$\begin{aligned} C_c^*(x^*, y^*, t^*) &= \frac{\mu}{4\pi} \cdot \exp\left[\frac{\mu^2}{2} \cdot y^*\right] \\ &\cdot \left\{ W\left[\frac{\mu^2(x^* - x_0^*)^2 + \mu^4 y^{*2}}{4t^*}, \frac{\mu\sqrt{(x^* - x_0^*)^2 + \mu^2 y^{*2}}}{2}\right] \right. \\ &+ \left. W\left[\frac{\mu^2(x^* + x_0^*)^2 + \mu^4 y^{*2}}{4t^*}, \frac{\mu\sqrt{(x^* + x_0^*)^2 + \mu^2 y^{*2}}}{2}\right] \right\} \end{aligned} \quad (6.15)$$

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and

$$C_c^*(x^*, y^*, \infty) = \frac{\mu}{2\pi} \cdot \exp\left[\frac{\mu^2}{2} \cdot y^*\right] \cdot \left\{ K_0 \left[\frac{\mu \sqrt{(x^* - x_0^*)^2 + \mu^2 y^{*2}}}{2} \right] + K_0 \left[\frac{\mu \sqrt{(x^* + x_0^*)^2 + \mu^2 y^{*2}}}{2} \right] \right\} \quad (6.16)$$

respectively, in which μ is a dimensionless number defined as $\mu = Vh_0/D$. Following Wilson and Miller (1978), the leaky aquifer function and the modified Bessel function can be approximated by asymptotic expansion as,

$$\begin{aligned} W(a, b) &\cong \left(\frac{\pi}{2b}\right)^{1/2} \exp(-b) \cdot \operatorname{erfc}\left(-\frac{b-2a}{2a^{1/2}}\right) \\ K_0(b) &\cong \left(\frac{\pi}{2b}\right)^{1/2} \exp(-b) \end{aligned} \quad (6.17)$$

It is apparent that μ is the only control parameter remained in Eq. 6.15 and Eq. 6.16. As discussed in Kay (1987), the longitudinal (y - direction in the present case) length scale is greater than the lateral (x - direction in the present case) length scale by a factor of μ as the plume is elongated in the direction of the longshore current.

6.3 Practical Application

6.3.1 Shoreline discharges

In the first application, we will consider the pattern of temporal buildup of salinity around a surface outfall at the shore, i.e., $x_0^* = 0$. Subject to this assumption, the salinity profile is determined by reducing Eq. 6.15 as,

$$C_c^*(x^*, y^*, t^*) = \frac{\mu}{2\pi} \cdot \exp\left[\frac{\mu^2}{2} \cdot y^*\right] \cdot W\left[\frac{\mu^2 x^{*2} + \mu^4 y^{*2}}{4t^*}, \frac{\mu \sqrt{x^{*2} + \mu^2 y^{*2}}}{2}\right] \quad (6.18)$$

The salinity excess contours of $C_c^* = 0.01$ at five growing dimensionless time instances are plotted in Fig. 6.2. The growth and eventual steady state (when $t^* > t_5$) of the salinity buildup are depicted in the figure. It can be observed that the extent of the affected area increases with time as expected, and the influence is expanding faster in the y - than in the x -direction in this case due to the residual current. Moreover, the upstream intrusion is found to be suppressed, which verifies that the longshore current will play a stronger role in affecting the

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transport.

Figure 6.2: Salinity contour for $C_c^* = 0.01$ at times $t^* = t_1 < t_2 < t_3 < t_4 < t_5$ ($\times 10^6$)

In the second application, we will consider the extent of the region around the outfall where a quasi-steady salinity distribution is reached corresponding to the time of interest. Again, assuming $x_0^* = 0$, Eq. 6.15 and Eq. 6.16 give,

$$\frac{C_c^*(x^*, y^*, t^*)}{C_c^*(x^*, y^*, \infty)} = \frac{W \left[\frac{\mu^2 x^{*2} + \mu^4 y^{*2}}{4t^*}, \frac{\mu \sqrt{x^{*2} + \mu^2 y^{*2}}}{2} \right]}{2K_0 \left[\frac{\mu \sqrt{x^{*2} + \mu^2 y^{*2}}}{2} \right]} \quad (6.19)$$

Eq. 6.19 can be solved numerically for the relationship between the normalized geometrical and temporal quantities defined as, $R^* = \mu \sqrt{x^{*2} + \mu^2 y^{*2}}$ and t^* which makes $C_c^*(x^*, y^*, t^*)/C_c^*(x^*, y^*, \infty) = 0.99$. Hence, by simplifying Eq. 6.19, we have,

$$\operatorname{erfc} \left(-\frac{\sqrt{t^*}}{2} + \frac{R^*}{2\sqrt{t^*}} \right) = 1.98 \quad \text{i.e.} \quad t^* = 2c^2 + R^* - 2\sqrt{c^4 + c^2 R^*} \quad (6.20)$$

where $c = \operatorname{erfc}^{-1}(1.98)$. The results are plotted in Fig. 6.3.

The results in Fig. 6.3 can also be inversely interpreted as the critical time required for any arbitrary point in the domain to reach a quasi-steady state given the coordinates of the point. Based on this threshold value of time, we

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Figure 6.3: The extent of the region, R^* , around the outfall where a quasi-steady equilibrium (99% of steady-state) is reached at t^*

can justify when it is reasonable to use the simplified steady-state solution to predict the salinity given the location. It is noteworthy that, the shape of the predicted curve is very similar to the case of aquifer dispersion reported in Hunt (1978).

As mentioned in previous sections, the steady-state features draw more attention commonly. When $x_0^* = 0$, the steady-state salinity distribution is described by reducing Eq. 6.16 as,

$$C_c^*(x^*, y^*, \infty) = \frac{\mu}{\pi} \cdot \exp \left[\frac{\mu^2}{2} \cdot y^* \right] \cdot K_0 \left[\frac{\mu \sqrt{x^{*2} + \mu^2 y^{*2}}}{2} \right] \quad (6.21)$$

Contours of salinity excess varying between 0.01 up to 1.0 are plotted in Fig. 6.4. Due to the effect of the residual longshore current pointing upward, the contour generally expands in that direction, while the upstream intrusion is completely suppressed as in Purnama et al. (2003).

6.3.2 Offshore discharges

In disposal practices, the salinity level at the shore is usually of particular environmental concern due to the presence of recreational beaches and shoreline intakes. Therefore, a prediction of the level of increase in salinity at the shore

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(a) Contours 0.01 – 0.02

(b) Contours 0.05 – 0.2

(c) Contours 0.5 – 1.0

Figure 6.4: Steady-state salinity contours around the outfall

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under a prolonged desalination discharge scenario would be of high practical importance. It is also necessary to know quantitatively how the shoreline salinity will be affected by the offshore placement of the outfall, so that an assessment on the length of outfall pipe can be made.

First, we consider the overall transient behavior associated with the offshore discharges. Assume $x_0^* = 40$, i.e., the source situates at $40h_0$ away from the shore, and substitute into Eq. 6.15, the growth of the spatial extent of saline plume is shown in Fig. 6.5. Compared with Fig. 6.2, it is apparent that the affected downstream shorelines have shrunk substantially (from $0 \sim 3200y^*$ to $400 \sim 2200y^*$). This application is of particular significance when the placement of the outfall is being considered to ensure certain part of the beach is avoided of intrusion of excessive salinity. Also, due to the reduced propagating distance, the critical time to reach steady state has also decreased (from 8 unit to 7 unit). More notably, as the outfall is moved away from the shoreline, the level of salinity excess to which the beach is exposed has declined considerably. As revealed in Fig. 6.6(a), the shore is covered by non-dimensional salinity excess of only 0.01.

Figure 6.5: Salinity contour for $C_c^* = 0.01$ when outfall situates at $x_0 = 40h_0$ at times $t^* = t_1 < t_2 < t_3 < t_4 < t_5$ ($\times 10^6$)

We then investigate how the shoreline salinity varies with time. Substitution of $x^* = 0$ into Eq. 6.15 leads to,

$$C_c^*(0, y^*, t^*) = \frac{\mu}{2\pi} \cdot \exp \left[\frac{\mu^2}{2} \cdot y^* \right] \cdot W \left[\frac{\mu^2 x_0^{*2} + \mu^4 y^{*2}}{4t^*}, \frac{\mu \sqrt{x_0^{*2} + \mu^2 y^{*2}}}{2} \right] \quad (6.22)$$

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(a) Contours 0.01 – 0.02

(b) Contours 0.05 – 0.2

(c) Contour 0.5

Figure 6.6: Steady-state salinity contours around the outfall situated at $x_0 = 40h_0$

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The curves of the shoreline salinity corresponding to different times are plotted in Fig. 6.7. The trend of the salinity propagation is clearly shown in the figure. In the beginning, the magnitude of peak salinity increases significantly as time increases. This represents the transient period when the salinity is accumulating near the shore area. Meanwhile, the location of the peak moves downstream at a steady pace. Beyond $t^* = t_2$, the salinity peak ceases to grow and move. As shown in the figure, the downstream sides of the different transient curves descend abruptly, which indicates the salinity gradients in the downstream plume front are high. Due to the residual longshore current, the salinity excess never propagates upstream throughout the period. As the plume expands further downstream over time, the group of transient curves is enveloped by the steady-state curve. Note also that the maximum salinity excess under the current discharge setting is only 0.12.

Figure 6.7: Shoreline salinity when outfall situates at $x_0=40h_0$ at times $t^* = t_1 < t_2 < t_3 < t_4 < t_5$ ($\times 10^6$)

We then consider the effect of the offshore location of the outfall on the shoreline salinity. To facilitate the presentation, the steady-state solution is applied herein. Substitution of $x^* = 0$ into Eq. 6.16 gives,

$$C_c^*(0, y^*, \infty) = \frac{\mu}{\pi} \cdot \exp \left[\frac{\mu^2}{2} \cdot y^* \right] \cdot K_0 \left[\frac{\mu \sqrt{x_0^{*2} + \mu^2 y^{*2}}}{2} \right] \quad (6.23)$$

The salinity at the shore is derived from the equation and plotted in Fig. 6.8. The curves presented reveal how the salinity at the shore is reduced as the

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Figure 6.8: Shoreline salinity as a function of distance along the shoreline for various outfall locations

outfall is moved further offshore. As can be seen from Fig. 6.8, when the source is moved offshore to a small distance (to $5h_0$), the peak salinity at the shore declines drastically. The movement of the peak salinity location as well as the upstream reach of the affected shoreline towards the downstream direction is also clearly shown in the figure. It is noted that the salinity curves collapse downstream at large y^* in Fig. 6.8, implying that the salinity increase far away from the outfall is not sensitive to the offshore location of the outfall.

6.3.3 Discussion on μ

In a steady current V , the value of μ has been suggested to be ~ 50 (i.e., $D_y \sim 0.02hV$) based on a widely accepted empirical formula of longitudinal diffusivity (Kay, 1987). However, in the present configuration, the value of μ depends on the association of the dispersivity with the residual current and thus it can vary substantially with respect to the local conditions.

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Employing the approximation proposed in Eq. 6.17, Eq. 6.18 is expanded as,

$$\begin{aligned}
 C_c^*(x^*, y^*, t^*) &= \frac{\mu}{2\pi} \cdot \exp\left[\frac{\mu^2}{2} y^*\right] \cdot \left(\frac{\pi}{\mu \sqrt{x^{*2} + \mu^2 y^{*2}}}\right)^{1/2} \cdot \exp\left[-\frac{\mu \sqrt{x^{*2} + \mu^2 y^{*2}}}{2}\right] \\
 &\quad \cdot \operatorname{erfc}\left[-\frac{\frac{\mu \sqrt{x^{*2} + \mu^2 y^{*2}}}{2} - \frac{\mu^2 x^{*2} + \mu^4 y^{*2}}{2t^*}}{\sqrt{\frac{\mu^2 x^{*2} + \mu^4 y^{*2}}{t^*}}}\right] \\
 &= \frac{1}{2\sqrt{\pi y^*}} \cdot \left(1 + \frac{x^{*2}}{\mu^2 y^{*2}}\right)^{-1/4} \cdot \exp\left[\frac{\mu^2}{2} y^* \left(1 - \sqrt{1 + \frac{x^{*2}}{\mu^2 y^{*2}}}\right)\right] \\
 &\quad \cdot \operatorname{erfc}\left[-\frac{\sqrt{t^*}}{2} + \frac{\mu^2 y^*}{2\sqrt{t^*}} \sqrt{1 + \frac{x^{*2}}{\mu^2 y^{*2}}}\right] \quad (6.24)
 \end{aligned}$$

For typical cases where the longitudinal extent is much larger than the transverse extent,

$$\frac{x^*}{\mu y^*} \ll 1 \quad \text{or} \quad \mu \gg \frac{x^*}{y^*} \quad \text{or} \quad y^* \gg \frac{x^*}{\mu} \quad (6.25)$$

Eq. 6.24 is further reduced to,

$$\begin{aligned}
 C_c^*(x^*, y^*, t^*) &= \frac{1}{2\sqrt{\pi y^*}} \cdot \left(1 - \frac{1}{4} \frac{x^{*2}}{\mu^2 y^{*2}}\right) \cdot \exp\left[\frac{\mu^2}{2} y^* \left(1 - \left(1 + \frac{1}{2} \frac{x^{*2}}{\mu^2 y^{*2}}\right)\right)\right] \\
 &\quad \cdot \operatorname{erfc}\left[-\frac{\sqrt{t^*}}{2} + \frac{\mu^2 y^*}{2\sqrt{t^*}} \left(1 + \frac{1}{2} \frac{x^{*2}}{\mu^2 y^{*2}}\right)\right] \\
 &= \frac{1}{2\sqrt{\pi y^*}} \exp\left[-\frac{1}{4} \frac{x^{*2}}{y^*}\right] \cdot \operatorname{erfc}\left[-\frac{\sqrt{t^*}}{2} + \frac{\mu^2 y^*}{2\sqrt{t^*}} + \frac{1}{4} \frac{x^{*2}}{y^* \sqrt{t^*}}\right] \quad (6.26)
 \end{aligned}$$

In a similar way, quasi-steady state solution (Eq. 6.21) is reduced to,

$$C_c^*(x^*, y^*, \infty) = \frac{1}{\sqrt{\pi y^*}} \exp\left[-\frac{1}{4} \frac{x^{*2}}{y^*}\right] \quad (6.27)$$

Following Eq. 6.27, the quasi-steady salinity contour would be independent of μ at locations whereby $y^* \gg x^*/\mu$. Based on the numerical evaluation of Eq. 6.21, the planar boundary contour of $C_c^* = 0.01$ is indeed found to be independent of the μ value when $\mu \in (0.1, 10)$. Nevertheless, from Eq. 6.26, it is obvious that μ would still have influence on the temporal development of the salinity diffusion, and that the critical period of time to achieve a quasi-steady state increases as μ increases within the range (which is also reflected in the numerical evaluation).

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6.4 Summary

A two-dimensional mathematical model simulating the long-term build-up of salinity around the brine outfall is developed in this chapter. A flat seabed and steady longshore current are assumed as a first step towards modelling the actual scenario. Transient and steady-state analytical solutions for continuous point source condition are derived. These solutions are then applied to assess shoreline/offshore discharge. Characteristic features such as the temporal buildup of salinity excess and the variation of the shoreline salinity with respect to time and outfall location are investigated. The effect of the advection-to-diffusion ratio μ in the modelling results is also discussed.

Chapter 7

Salinity Buildup due to Continuous Brine Discharge under Oscillatory Tidal Currents

7.1 Introduction

In the last chapter, we consider the process of continuous brine discharge into the sea, in which the receiving seawater is idealized to possess a constant long-shore current that is averaged over a tidal cycle, i.e., the residual current. The simplified analysis allows the development of analytical solutions, and provides important insight into the situation. However, the omission of the tidal oscillation does not allow the assessment of the temporal evolution of the salinity build-up and fluctuations within the oscillatory tidal cycles. In this chapter, we extend the previous analysis by including the combined effect of the mean and oscillatory currents.

The layout of the brine discharge is identical to what we assumed in the last chapter for the mean tidal currents. The desalination plant considered situated off an idealized straight shoreline in a coastal region where the water depth, h_0 , is assumed to be constant. During a tidal cycle, sea water flushes back and forth along the shore direction within a limited distance (normally referred to as the “tidal excursion”), and assists in spreading the salinity excess due to the brine discharges in the coastal region. We assume the presence of an alongshore tidal current, $U(t)$, which consists of a small constant residual or drift current, V (i.e., the V assumed in the last chapter), plus a periodic component, $U_0 \sin \omega t$, i.e.,

$$U(t) = V + U_0 \sin \omega t \quad (7.1)$$

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where U_0 is the amplitude of the oscillatory current and is typically much larger than the magnitude of the residual current V , $\omega = 2\pi/T$ (T is the tidal period) is the angular frequency of the oscillatory current, and t denotes time. In the present study, U_0 is assumed to be invariant in the domain of analysis. x and y axes are taken to be perpendicular to and coincident with the shoreline, respectively. The brine outfall is deployed at a distance of x_0 off shore, and acts like a point source of concentrated brine injection.

It is noted that Purnama and Al-Barwani (2006) extended their original study on the steady-state effect of brine discharges on local salinity (Purnama et al., 2003) to the effects of an oscillatory tidal flow in dispersing the brine discharge occurring in the Gulf of Oman. More recently they showed that the maximum shoreline salinity would remain constant throughout the tidal cycles and thus can be used as an indicator for regulatory purpose (Al-Barwani and Purnama, 2008). Despite these studies, the temporal evolution and the ultimately persistent fluctuation in salinity in the quasi-steady state are not reported in the literature so far.

In the next section (Section 7.2), we present the process of the model development. Subsequently, we investigate the salinity build-up processes due to the continuous brine discharge, focusing particularly on the salinity fluctuations in the presence of the oscillatory tidal currents, as well as the effects of other relevant parameters including the anisotropy and possible time dependency of the dispersivities (Section 7.3). On the whole, we demonstrate the applicability of the developed model to the ‘practical’ discharge problem. Note that the ‘practical’ problem is again hypothesized but with physical relevance.

7.2 Model Construction

Again, for shallow coastal waters, the dispersion in the vertical direction occurs much faster than the horizontal directions. Hence, the transient salinity advection-diffusion equation can be derived in the following two-dimensional form,

$$\begin{aligned} \frac{\partial C}{\partial t} &= D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} - U(t) \frac{\partial C}{\partial y} \\ 0 \leq x &< \infty, \quad -\infty < y < \infty \end{aligned} \quad (7.2)$$

where C denotes the salinity excess above the ambient level, and D_x and D_y are the eddy dispersivities in the x and y directions, respectively.

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The boundary conditions applied herein are identical to that specified in the last chapter, i.e., 6.2 and 6.3.

Referring to the general solution of the one-dimensional advection-diffusion equation with time-varying flow and diffusivity derived by Holley (1969), the solution to Eq. 7.2 can be written in the form of a convolution integral as,

$$\begin{aligned}
 C_c(x, y, t) = & \frac{C_0 Q}{4\pi h_0 \sqrt{D_x D_y}} \cdot \int_0^t \left\{ \exp \left[-\frac{(x - x_0)^2}{4D_x(t - t_0)} \right. \right. \\
 & - \left. \frac{\left[y - V(t - t_0) + \frac{U_0}{\omega}(\cos \omega t - \cos \omega t_0) \right]^2}{4D_y(t - t_0)} \right] + \exp \left[-\frac{(x + x_0)^2}{4D_x(t - t_0)} \right. \\
 & \left. \left. - \frac{\left[y - V(t - t_0) + \frac{U_0}{\omega}(\cos \omega t - \cos \omega t_0) \right]^2}{4D_y(t - t_0)} \right] \right\} \frac{dt_0}{t - t_0} \quad (7.3)
 \end{aligned}$$

where C_0 is the volumetric solute concentration (i.e., salinity excess) at the source, Q is the brine discharge flow rate, C_c is the resulting volumetric solute concentration due to the continuous injection from time zero to time t , and t_0 is a dummy variable.

To facilitate the computation and presentation of results, dimensionless variables are defined as follows,

$$\begin{aligned}
 \tau &= \omega t, & \tau_0 &= \omega(t - t_0) \\
 \xi &= \frac{\omega x}{U_0}, & \xi_0 &= \frac{\omega x_0}{U_0}, & \eta &= \frac{\omega y}{U_0} \\
 C^* &= C / (C_0 Q / 4\pi h_0 \sqrt{D_x D_y}) \quad (7.4)
 \end{aligned}$$

Substitution of these variables into Eq. 7.3 yields,

$$\begin{aligned}
 C_c^*(\xi, \eta, \tau) = & \int_0^\tau \frac{d\tau_0}{\tau_0} \left\{ \exp \left[-\lambda \alpha^2 \frac{(\xi - \xi_0)^2}{\tau_0} \right] + \exp \left[-\lambda \alpha^2 \frac{(\xi + \xi_0)^2}{\tau_0} \right] \right\} \\
 & \cdot \exp \left[-\lambda \frac{[\eta - \nu \tau_0 + \cos \tau - \cos(\tau - \tau_0)]^2}{\tau_0} \right] \quad (7.5)
 \end{aligned}$$

where we have introduced three dimensionless parameters characterizing the advection-diffusion process, namely, the dispersivity ratio,

$$\alpha = \left(\frac{D_y}{D_x} \right)^{1/2} \quad (7.6)$$

which compares the longitudinal dispersivity to the lateral dispersivity, the ve-

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locity ratio,

$$\nu = \frac{V}{U_0} \quad (7.7)$$

which compares the residual flow to the amplitude of the oscillatory tidal flow, and finally the Li and Kozlowski's (1974) parameter,

$$\lambda = \frac{U_0^2}{4\omega D_y} \quad (7.8)$$

which compares the longitudinal transport due to advection to that by dispersion in one tidal cycle.

It is noted that Eq. 7.5 is usually amenable only by means of numerical integration.

7.3 Practical Applications

7.3.1 Nearshore discharges

In the first application, we investigate the salinity build-up due to a nearshore discharge.

Substituting $\xi = 0$ into Eq. 7.5, the salinity profile along the shoreline is derived as,

$$C_c^*(0, \eta, \tau) = 2 \int_0^\tau \frac{d\tau_0}{\tau_0} \exp \left[-\frac{\lambda \alpha^2 \xi_0^2}{\tau_0} \right] \cdot \exp \left[-\lambda \frac{[\eta - \nu \tau_0 + \cos \tau - \cos(\tau - \tau_0)]^2}{\tau_0} \right] \quad (7.9)$$

It is noted that the build-up will fluctuate periodically even in the quasi-steady state due to the presence of the oscillatory alongshore current. As discussed previously, the expression can only be resolved through numerical integration. The dimensionless parameters would have different site-specific values at different locations around the world. As an illustration, we adopt a set of values suggested in Purnama and Al-Barwani (2006) for the case of the Oman Gulf, namely,

$$\alpha^2 = 20, \quad \nu = 0.4, \quad \lambda = 10, \quad \xi_0 = 0.1 \quad (7.10)$$

The temporal salinity variation was computed over a period of 25 lunar days, i.e., $\tau = 100\pi$ as one tidal period T is typically adopted as half a lunar day for semi-diurnal fluctuations and meanwhile equivalent to a dimensionless time of 2π . Fig. 7.1 shows the temporal pattern of salinity build-up with its maximum

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and minimum envelopes at $1L$ and $10L$ (i.e., $\eta = 2$ and 20), which are two locations chosen to be relatively near and far from the source, respectively.

Comparing Fig. 7.1a with Fig. 7.1c, it is clear that the amplitude of the salinity oscillation when reaching the quasi-steady state is much greater at $1L$ than at $10L$. The salinity excess fluctuates between 0.4 and 1.3 at $1L$, while at $10L$, the amplitude is much less than 1.0. It is also found that the salinity excess at the near source location of $1L$ approaches the quasi-steady state much faster than $10L$ as demonstrated in the close-up of the initial stage of the salinity growth together with the thick solid envelopes shown in Fig. 7.1b and 7.1d. From Fig. 7.1b, the salinity excess reaches a quasi-steady state after 0.75 lunar day, i.e., one and a half tidal cycles, within one tidal excursion distance, while in Fig. 7.1d, the salinity build-up only appears significantly after three lunar days from the initiation of the brine discharge, and converges to the quasi-steady state in another two lunar days.

The quasi-steady brine contours is plotted in Fig. 7.2 based on the above assessment of the convergence to the quasi-steady state beyond 5 lunar days (i.e., $\tau \geq 20\pi$). The longitudinal and lateral extents of the analysis domain were chosen to follow Purnama and Al-Barwani (2006) to facilitate the comparison. It is noted that the contours reported in Purnama and Al-Barwani (2006) were based on $\tau = 11\pi$ and 10π . As a result, the results in Purnama and Al-Barwani (2006) were different from the quasi-steady state contours shown in Fig. 7.2a and 7.2b, particularly for the levels lower than 0.5. Nevertheless, for the higher salinity levels in the range of $0.5 - 1$, the contours in the present study compare very well with that in Purnama and Al-Barwani (2006).

7.3.2 Offshore discharges

In disposal practices, the salinity level at the shore can be reduced by an offshore placement of the outfall. It is therefore necessary to have a quantitative assessment on the relationship between the salinity build-up and the offshore placement location.

First, we consider how the shoreline salinity varies with different offshore locations of the outfall. As an illustration, we adopt the dimensionless parameters in Purnama and Al-Barwani (2006) with a tidal excursion approximately equal to $4.8km$. The offshore location of the outfall, ξ_0 , can thus be readily non-dimensionalized using this excursion distance.

The shoreline salinity corresponding to the different outfall locations at $\tau = 20\pi$ and 21π are plotted in Fig. 7.3. They reveal how the salinity at the shore is

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a. $\eta = 2$

b. Close-up of initial development at $\eta = 2$

c. $\eta = 20$

d. Close-up of initial development at $\eta = 20$

Figure 7.1: Temporal pattern of shoreline salinity build-up

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Figure 7.2: Quasi-steady state salinity contours

reduced as the outfall is placed further offshore. As can be seen from Fig. 7.3a, when the source is moved a small distance further offshore (from $\xi_0 = 0.1$ to $\xi_0 = 0.2$), the dominant peaks upstream and downstream of the source decline substantially while the other downstream peaks are reduced to a much lesser degree. When the outfall is moved further offshore to $\xi_0 = 0.5$, however, a drastic reduction for all peaks occurs and the maximum location is shifted towards the downstream direction. Same tendency can be observed in Fig. 7.3b for $\tau = 21\pi$ which is half a tidal cycle beyond Fig. 7.3a, except for the suppression of the upstream peak when the tidal current reverses its direction.

Fig. 7.4 shows the distribution of salinity excess at the near source location of $1L$ at $\tau = 20\pi$ and 21π with the same set of outfall locations. It is evident that as the outfall is placed further offshore, the center of the saline plume is shifted offshore accordingly. As a result, the shoreline impact is to some extent decreased. Thus, the shoreline impact can be minimized to an acceptable level if the outfall is sufficiently far from the shore which is logical. It is also observed that, while the maximum salinity excess at the shoreline is reduced as a result of the offshore placement of outfall, the extent of the salinity excess in the offshore region remains similar. This is again reasonable since the total salt input must

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Figure 7.3: Shoreline salinity as a function of distance along the shoreline for various outfall locations

be conserved. In reality, however, the water depth typically increases in the offshore direction, and the local rise in salinity excess in the offshore region can be easily dampened by an enlarged diffusion capacity thereby. From both figures, it is interesting to note that, regardless of the tidal flow reversal, the magnitude of the peak salinity remains invariant when the outfall is shifted from $\xi_0 = 0.2$ to $\xi_0 = 0.5$. In general, the overall salinity excess cross the transect is greater under the high-water slack (HWS) (Fig. 7.4a) than under the low-water slack (LWS) (Fig. 7.4b).

7.3.3 Effects of varying ν

To investigate the effects of varying ν , we adopt the same set of parameters for the shoreline discharge configuration that was investigated previously. The shoreline salinity excess profiles are plotted in Fig. 7.5 for both HWS (at $\tau = 20\pi$) and LWS (at $\tau = 21\pi$) over a wide range of ν values from 0.05 to 1.0.

Comparing the different profiles, it is evident that, the general effect of increasing ν and thus the intensity of the residual current is to decrease the magnitude of the maximum salinity excess at the shore. The resulting series of

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Figure 7.4: Salinity excess distribution at the cross section of $\eta = 2$ for various outfall locations

peaks demands special consideration when assessing local salinity excess. As ν is decreased gradually, the adjacent peaks distant from the source will overlap each other and become less discernable as previously mentioned. As shown in Fig. 7.5, the numbers of distinct peaks decrease from 5 for $\nu = 0.5$ to 3 for $\nu = 0.4$. When ν is further decreased to 0.2, there is only one clearly visible peak within one tidal excursion downstream from the source, and the profile appears fairly smooth beyond about $\eta = 4$, i.e., twofold tidal excursion distance. When $\nu = 0.05$, which falls in the range of the single-peak profile, a hike of the maximum salinity excess to 3.3 for HWS and 3.6 for LWS is noted in Fig. 7.5a and 7.5b, respectively. Furthermore, it is noted that based on the discussion in Kay (1997), he suggested that the peaks would overlap immediately after they are created when,

$$\nu \leq \left(\frac{1}{4\pi\lambda} \right)^{\frac{1}{2}} \quad (7.11)$$

In the present scenario, this will be the case when $\nu \leq 0.089$. The computed results in Fig. 7.5 are consistent with Kay's prediction.

It is of interest to study if ν would play a significant role in the convergence

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a. $\tau = 20\pi$

b. $\tau = 21\pi$

Figure 7.5: Shoreline salinity as a function of distance along the shoreline for various velocity ratio ν

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of the salinity profile to the quasi-steady state. The temporal patterns of salinity build-up at $1L$ corresponding to two specific values of ν , namely 0.05 and 0.2, are depicted in Fig. 7.6. From the figures, as ν increases from 0.05 to 0.2, the salinity excess would reach the quasi-steady state more rapidly. Further computation with additional ν values ($\nu = 0.6$ and 1.0 shown in Fig. B.32) suggests that the growth would stabilize and the quasi-steady state would be reached within $0.5 - 0.75$ lunar day when $\nu \geq 0.4$. Note also that the decrease in salinity excess level with increasing ν as mentioned earlier has also been verified herein.

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a. $\nu = 0.05$

b. Close-up of initial development for $\nu = 0.05$

c. $\nu = 0.2$

d. Close-up of initial development for $\nu = 0.2$

Figure 7.6: Temporal pattern of salinity build-up at $\eta = 2$ corresponding to various values of ν

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7.3.4 Comparison of time-dependent dispersivity and constant dispersivity

In previous sections, the dispersivities in both the longitudinal and lateral directions are assumed constant for the computations. In actual turbulent coastal flows, however, eddy diffusivities and shear dispersivities both scale as the product of seawater depth and friction velocity, while the friction velocity is widely assumed to be proportional to the mean flow speed. Based on a study of the literature, it is found that several authors studying one-dimensional dispersion in oscillatory flows have compared the concentration distributions obtained using a time-dependent dispersivity with those obtained under the assumption of a constant dispersivity (Holley, 1969; Macdonald and Weisman, 1977). The dispersivity varies in proportion to the absolute value of the velocity as,

$$D_{x,y}(t) = D_{x,y} \frac{|U|}{\bar{U}} = D_{x,y} \frac{|V + U_0 \sin \omega t|}{V} \quad (7.12)$$

in which the vertical bars indicate the absolute value and the over-bar indicates the average during a tidal cycle, i.e., the residual current.

Following Macdonald and Weisman (1977), we define θ as,

$$\theta = \int_{t_0}^t \frac{D_{x,y}(t')}{D_{x,y}} dt' = \int_{t_0}^t \left| 1 + \frac{1}{\nu} \sin \omega t' \right| dt' \quad (7.13)$$

The solution associated with time-dependent dispersivities therefore reads,

$$\begin{aligned} C_c(x, y, t) &= \frac{C_0 Q}{4\pi h_0 \sqrt{D_x D_y}} \cdot \int_0^t \left\{ \exp \left[-\frac{(x - x_0)^2}{4D_x \theta} \right] + \exp \left[-\frac{(x + x_0)^2}{4D_x \theta} \right] \right\} \\ &\cdot \exp \left[-\frac{\left[y - V(t - t_0) + \frac{U_0}{\omega} (\cos \omega t - \cos \omega t_0) \right]^2}{4D_y \theta} \right] \frac{dt_0}{\theta} \end{aligned} \quad (7.14)$$

Employing the same non-dimensional parameters defined in Eq. 7.4 yields,

$$\begin{aligned} C_c^*(\xi, \eta, \tau) &= \int_0^\tau \frac{d\tau_0}{\theta^*} \left\{ \exp \left[-\lambda \alpha^2 \frac{(\xi - \xi_0)^2}{\theta^*} \right] + \exp \left[-\lambda \alpha^2 \frac{(\xi + \xi_0)^2}{\theta^*} \right] \right\} \\ &\cdot \exp \left[-\lambda \frac{[\eta - \nu \tau_0 + \cos \tau - \cos(\tau - \tau_0)]^2}{\theta^*} \right] \end{aligned} \quad (7.15)$$

in which $\theta^* = \int_{\tau-\tau_0}^\tau \left| 1 + \frac{1}{\nu} \sin \tau' \right| d\tau'$, and t' and τ' are both dummy variables of integration.

In engineering practice, tidally-averaged dispersivities are often assumed to

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approximate the overall transport over a tidal cycle, and the tidally-averaged dispersivity is defined as,

$$\begin{aligned}\overline{D_{x,y}} &= D_{x,y} \frac{1}{T/2} \int_0^{T/2} \frac{(V + U_0 \sin(2\pi t/T))}{V} dt \\ &= D_{x,y} \left(1 + \frac{2}{\pi} U_0/V\right)\end{aligned}\quad (7.16)$$

For $\nu = V/U_0 = 0.4$, the tidally-averaged dispersivity would thus be roughly 2.59 times of the assumed constant dispersivity.

A comparison of the shoreline salinity corresponding to the constant dispersivities, $D_{x,y}$, the time-varying dispersivities proportional to the flow speed, $D_{x,y}(t)$ and the tidally-averaged dispersivities, $\overline{D_{x,y}}$, are plotted in Fig. 7.7 at $\tau = 20$ and 21π . The salinity corresponding to the time-varying dispersivity (shown in solid line) is smaller than its counterpart for the constant dispersivity in the proximity of the outfall, and the distribution has a tendency to be smoother (Macdonald and Weisman, 1977). This is a reasonable outcome as the time-varying dispersivities introduce a larger dispersive effect than the constant dispersivities. Contrary to Holley (1969) and Macdonald and Weisman (1977), the difference in the present case remains considerable rather than negligible further downstream. Note also that, the upstream portions under the high-water slack (HWS) (Fig. 7.7a) coincide each other indicating that the upstream intrusion at this time is mainly due to the advective effect. Compared to the constant dispersivities, the effect of the tidally-averaged dispersivities that accounts for both the residual and oscillatory currents is enhanced considerably as illustrated by the much lowered salinity profile (the dotted line). At the same time, the salinity profiles are similar between the time-varying and tidally-averaged dispersivities particularly near the source, which indicates that both approximations are valid for the range of the model parameters.

Fig. 7.8 shows the comparison of the convergence of salinity excess to quasi-steady state for constant, time-varying and tidally-averaged dispersivities. The time dependency of the dispersivities under the current setting reduces the overall salinity excess level due to the larger dispersive effect. The tidally-averaged dispersivities produce the lowest level of salinity and also tends to smooth out the variations within a tidal cycle. Nevertheless, the temporal pattern remains nearly unchanged.

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Figure 7.7: Shoreline salinity as a function of distance along the shoreline for constant, time-varying and tidally-averaged dispersivities (model parameters same as Eq. 7.10)

Figure 7.8: Temporal pattern of shoreline salinity build-up at $\eta = 2$ for constant, time-varying and tidally-averaged dispersivities (model parameters same as Eq. 7.10)

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7.4 Summary

The development of a mathematical model on the cumulative effects due to brine discharges into shallow coastal waters with a flat seabed is conducted in this study. The model incorporates the effects of tidal currents which are commonly encountered in the natural coastal environment. The tidal currents are represented by a small constant component, V (normally referred as residual or drift current), plus a periodic part, $U_0 \sin \omega t$. Anisotropic eddy dispersivities in the alongshore and cross-shore directions are also incorporated. The convergence to the quasi-steady state for the salinity excess due to the continuous brine input has been studied for the first time. The application of the mathematical model to assess a hypothetically practical discharge is also performed. Model predictions for representative velocity ratios of ν ($= V/U_0$) are obtained. In general, the placement of the outfall further offshore has been shown to reduce the shoreline impact as expected. A comparison of the results between constant and time-dependent dispersivities has been conducted.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

Specific findings and conclusions have been provided in the individual chapters. The major conclusions of the present study are summarized as follows.

For desalination discharge with initial angle of discharge smaller than 60° , e.g., 30° and 45° as considered in the present study, if the nozzle is kept sufficiently away from the lower boundary, i.e., no boundary effect or Coanda effect was observed in the flow development, from the analysis of the experimental results, the gross geometrical features and the mixing behavior of the brine plume, i.e., the terminal rise height, the horizontal distance of the return point, the return point dilution, the centerline peak location and the corresponding dilution were found to correlate with the densimetric Froude number as is the case for 60° . Proportionality coefficients were derived and showed to compare well with published results. Through the comparison of the results between two experimental series with distinct z_0/D but overlapping z_0/L_M , z_0/L_M proved to be the controlling parameter for the bed influence and not z_0/D . Therefore, the adequacy of the clearance can be assessed from this dimensionless parameter.

For 30° , it was found that the bed influence became significant when $z_0/L_M < 0.2$, while for 45° , the boundary effect was considerably weaker and did not seem to occur even for z_0/L_M down to the smallest tested value of 0.05. For 30° , the slope of the ascending trajectory for the boundary-affected flows (i.e., $z_0/L_M < 0.2$) appeared to be milder. However, the terminal rise height and the centerline peak were almost unchanged compared to other tests with similar Fr but larger z_0/L_M value. As a result of the combined effect, the horizontal

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location to reach the centerline peak was pushed downstream. At the same time, the slope of the descending trajectory was steeper for the boundary-affected flows and the return point was upstream of their free jet counterparts. The dilutions at the centerline peak and return point were also affected, though to a lesser degree than the geometric features. As noted above, this boundary effect was not observed in the 45° tests.

The decay profiles of the centerline maximum concentration for 30° were found to collapse onto the typical dense jet behavior after normalization, with an initial flat portion corresponding to the potential core, followed by a drastic drop until the impingement points and a subsequent level-off along the bed. For 45° , the potential core region is significantly shorter as the concentration appears to start decaying immediately off the nozzle. The decay of the centerline maximum velocity magnitude was observed to follow a similar pattern. The cross sectional concentration and axial velocity component profiles at various downstream locations followed the transition from an axisymmetric Gaussian, to an asymmetric Gaussian with a much wider lower spread, and finally to the wall-jet pattern. Beyond the centerline peak, the concentration axis began to deviate from the velocity axis presumably due to the existence of the buoyancy-induced instabilities at the lower portion of the dense jet.

The offset horizontal dense jet would undergo a transition from the initial momentum dominated jet regime to the boundary attached dense wall-jet regime. Unlike plane offset jets, the present flow demonstrates strong three-dimensionality, and only weak reverse flow exists underneath the nozzle exit. The normalized horizontal distance of the impingement point, x_{ip}/L_M , is found to correlate well with the bed proximity parameter, z_0/L_M , and the minimum dilution at the impingement point increases linearly with increasing Fr for a particular z_0 , for the covered experiment range. The velocity and concentration axes coincide initially but deviate from each other when the impingement occurs. The concentration axis then descends to the wall due to the zero-gradient boundary condition dictating the maximum concentration to occur right at the boundary, whereas the no-slip condition for the velocity forces the maximum velocity point to be away from the boundary. With the same z_0 , the axes with lower Fr tend to descend faster. Conversely, when Fr is held constant, the initially separated axes with different z_0 appear to converge downstream before impingement. The axes under different combinations of z_0 and Fr but identical z_0/L_M are found to collapse nicely and lie below the reference axis free of boundary effect.

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For horizontal dense jet, the decay of the centerline maximum concentration would go through three regions, namely the potential core region, the rapidly descending region and the transition to dense wall-jet region. The potential core region lasts approximately $5D$. The transition to wall-jet region starts from the impingement point and approaches the dense wall-jet pattern at the downstream end. Beyond the potential core region and before the impingement, the concentration profiles in the lower half deviate considerably from the Gaussian distribution while the streamwise velocity profiles follow the Gaussian satisfactorily for both halves. However, after the impingement, while the concentration profiles match the half Gaussian almost immediately, the velocity distributions do not follow closely the Verhoff profile which is a characteristic of the wall jet until some distance downstream. Meanwhile, the profiles of the vertical velocity component suggest that the net flow is always directed towards the bed before the impingement occurs. As expected, the concentration spread is wider than the velocity counterpart. The spreading rate for both concentration and velocity are however found to be lower than a non-buoyant jet initially but accelerate after the impingement point.

The cross sectional profiles of the streamwise turbulence intensity, u'/U_0 , are bimodal and characterized by a higher peak in the lower half of the jet. In the dense-jet regime, the various turbulence intensities and Reynolds shear stress are mostly shown to be less than previously reported level for vertical buoyant jets. Further downstream, the profiles are yet to achieve self-similarity during the transition to the wall-dense-jet regime but show significantly greater peak value at the centerline, which are also larger than vertical buoyant jets but comparable with three-dimensional wall jets. Contrary to u'/U_0 , the bimodal profiles of streamwise Reynolds flux, $\overline{u'c'}/(U_0C_0)$, show a primary peak above the centerline. The diminishment of the lower peak shows the effect of the bed confinement on the mass transport. The centerline values of $\overline{u'c'}$ and the peak values of $\overline{u'c'}$ are found to be much lower than that of the vertical buoyant jets, while further downstream, the profiles of $\overline{u'c'}$ peak at lower values than reported results for three-dimensional wall jets. The flux vectors in the upper half are observed to align around 30 degree, whereas the fluxes in the lower half are directed around -30 degree. After the impingement, both flux vectors turn to horizontal where a transition to the wall-dense-jet regime takes over. A evaluation of the turbulent viscosity, ν_t , turbulent diffusivity, D_t , and turbulent Schmidt number, Sc_t , has also been performed in the present study, and Sc_t is found to vary in the range 0.4-1 in the present flow.

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In terms of the Coanda effect, a complete Coanda attachment, defined as the effluent adhering to the seabed immediately after the discharge, did not occur for all test conditions even at the minimum bed proximity parameter of $z_0/L_M = 0.12$. It is thus recommended that a minimum clearance of such magnitude be implemented to avoid such adverse scenario for horizontal discharge.

An analytical study for the 2-D salinity excess distribution associated with the continuous discharges of brine into coastal waters from a point source has been conducted. The analytical solution accounts for the transient and steady-state behavior of the salinity advection and dispersion in a hypothetical scenario, i.e., flat seabed and steady longshore current. To generalize the model applicability, analytical solutions in dimensionless form are derived and numerically evaluated. The salinity excess along the shore is proven to be significantly lessened by placing the outfall further offshore. The advection-to-diffusion ratio μ is found to play a stronger role in the buildup process than in the steady-state behavior.

An extension of the model to further incorporate the oscillatory tidal currents has been conducted. The results demonstrate the convergence towards the quasi-steady state and the subsequent fluctuating behavior. In general, while the salinity distribution near the source experiences strong fluctuation, far away from the source the excess only oscillates slightly after converging to the quasi-steady state. It is also shown that, even in the presence of oscillatory tidal currents, the salinity excess along the shore can be significantly lessened by placing the outfall further offshore. The effects on the salinity profile due to the velocity ratio, ν , and the time-dependent dispersivity were also investigated. It was found that the increase in the velocity ratio suppresses the overall salinity level and accelerates the convergence to the quasi-steady state. The time dependency of the dispersivities has a significant impact on the salinity level, at the same time, it shows no obvious effect on the temporal fluctuation pattern. Tidally-averaged dispersivities were also attempted in the modeling and the salinity profiles were found to compare favorably with the profiles with the time-dependent dispersivities. Both approaches are thus valid in terms of their applicability in modeling the tidal transport of brine discharges.

8.2 Recommendations

Multiple-window measurements were extensively used in the experiments performed in the present study. Despite the fact that the piecing of the neighbor-

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ing windows was performed in the best manner as described in Appendix A, the smoothness of the combined fields is imperfect to some extent. This was primarily due to the uncertainties in the test conditions since the measurements were repeated at different time. Although the presented results are still largely useful in terms of determining the gross behavior of the dense jet, further effort to improve the data continuity seems desirable and necessary.

The present study was focused on the vertical plane of symmetry of the flow, and measurements on spanwise sections were not attempted. It would be of interest to resolve the different spanwise sections and explore the potential effects in a future study. It is also worth noting that in some previous studies concerned with a similar but dynamically inverted process of horizontal buoyant jets in the presence of bed and free surface boundaries (e.g. Sobey et al., 1988; Johnston and Volker, 1993), the spreading of the buoyant flow in the vertical and lateral directions have been examined and compared by traversing the point-based measurements of the temperature and velocity across different downstream cross sections. The enhancement in the lateral growth while the suppression in the vertical growth beyond the point of attachment to the bed or free surface when the flow is transiting to buoyant wall jet or surface jet is a well known phenomenon. A comparative study on the difference in the lateral and vertical growths for the dense flow is thus of interest.

The experiments conducted to study the potential Coanda effect are characterized by discrete controlling parameters, z_0/L_M . It would help to design an experiment to move the Perspex false floor up or down in a precisely controlled manner in the future, such that z_0/L_M to the bottom could vary incrementally, and verify the present results in such a case.

The present analytical and semi-analytical models are subject to the basic assumptions of flat seabed in the entire domain. A further study to incorporate a sloping seabed into the model, which will reflect the actual situation in a better manner, will be desirable in the future. By the same token, the present experiments focused on the interaction of the inclined and horizontal dense jets with a flat bed, and further study incorporating the sloping bed is of interest.

While the existence and influence of the buoyancy-induced instability on the dense jets are now well documented, e.g., asymmetry of the cross-sectional distributions of the velocity and concentration. As a direct consequence of this anomaly, the use of the conventional integral models to resolve the inclined dense jets is seriously challenged as the existing models are all based on the assumption of axisymmetric Gaussian distribution. Thus, it is of interest to modify the

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original Gaussian profile to incorporate the asymmetry appropriately.

References

- Abraham, G. (1963), “Jet Diffusion in Stagnant Ambient Fluid”, Tech. Rep. Publication No. 29, Delft Hydraulics Lab.
- Abraham, G. (1965), “Horizontal Jets in Stagnant Fluid of Other Density”, Journal of the Hydraulics Division, Vol. 91, No. HY4, pp. 139–154.
- Abraham, G. (1967), “Jets with Negative Buoyancy in Homogeneous Fluid”, Journal of Hydraulic Research, Vol. 5, No. 4, pp. 235–248.
- Al-Barwani, H. H. and Purnama, A. (2008), “Simulating Brine Plumes Discharged into the Seawaters”, Desalination, Vol. 221, pp. 608–613.
- Alameddine, I. and El-Fadel, M. (2007), “Brine Discharge from Desalination Plants: A Modeling Approach to an Optimized Outfall Design”, Desalination, Vol. 214, pp. 241–260.
- Arya, S. P. (1999), Air Pollution Meteorology and Dispersion, Oxford University Press.
- Balasubramanian, V. and Jain, S. C. (1978), “Horizontal Buoyant Jets in Quiescent Shallow Water”, Journal of the Environmental Engineering Division, Vol. 104, No. EE4, pp. 717–730.
- Bear, J. (1972), Dynamics of Fluids in Porous Media, American Elsevier Pub. Co. New York.
- Berlman, I. B. (1971), Handbook of Fluorescence Spectra of Aromatic Molecules, 2nd ed., Academic Press, New York.
- Bleninger, T. and Jirka, G. H. (2008), “Modelling and Environmentally Sound Management of Brine Discharges from Desalination Plants”, Desalination, Vol. 221, pp. 585–597.

REFERENCES

- Bloomfield, L. J. and Kerr, R. C. (2000), “A Theoretical Model of a Turbulent Fountain”, Journal of Fluid Mechanics, Vol. 424, pp. 197–216.
- Bloomfield, L. J. and Kerr, R. C. (2002), “Inclined Turbulent Fountains”, Journal of Fluid Mechanics, Vol. 451, pp. 283–294.
- Borg, A., Bolinder, J. and Fuchs, L. (2001), “Simultaneous Velocity and Concentration Measurements in the Near Field of a Turbulent Low-Pressure Jet by Digital Particle Image Velocimetry–Planar Laser-Induced Fluorescence”, Experiments in Fluids, Vol. 31, pp. 140–152.
- Brooks, N. H. (1960), “Diffusion of sewage effluent in an ocean current”, in Proceedings of the 1st International Conference on Waste Disposal in the Marine Environment, Pergamon, Oxford, pp. 246–267.
- Buros, O. K. (2000), “The ABCs of Desalting (Second Edition)”, International Desalination Association, [Online]. Available: <http://www.idadesal.org/pdf/ABCs1.pdf>.
- California Coastal Commission (2004), “Seawater Desalination and the California Coastal Act”, Tech. rep., California Coastal Commission.
- Carazzo, G., Kaminski, E. and Tait, S. (2006), “The Route to Self-similarity in Turbulent Jets and Plumes”, Journal of Fluid Mechanics, Vol. 547, pp. 137–148.
- Chang, K.-A. and Cowen, E. A. (2002), “Turbulent Prandtl Number in Neutrally Buoyant Turbulent Round Jet”, Journal of Engineering Mechanics, Vol. 128, No. 10, pp. 1082–1087.
- Chin, D. A. and Roberts, P. J. W. (1985), “Model of Dispersion in Coastal Waters”, Journal of Hydraulic Engineering, Vol. 111, No. 1, pp. 12–28.
- Cipollina, A., Bonfiglio, A., Micale, G. and Brucato, A. (2004), “Dense Jet Modelling Applied to the Design of Dense Effluent Diffusers”, Desalination, Vol. 167, pp. 459–468.
- Cipollina, A., Brucato, A., Grisafi, F. and Nicosia, S. (2005), “Bench-scale Investigation of Inclined Dense Jets”, Journal of Hydraulic Engineering, Vol. 131, No. 11, pp. 1017–1022.

REFERENCES

- Cooley, H., Gleick, P. H. and Wolff, G. (2006), “Desalination, with a Drain of Salt: A California Perspective”, Tech. rep., Pacific Institute for Studies in Development, Environment, and Security.
- Cowen, E. A., Chang, K.-A. and Liao, Q. (2001), “A Single-camera Coupled PTV–LIF Technique”, Experiments in Fluids, Vol. 31, pp. 63–73.
- Cowen, E. A. and Monismith, S. G. (1997), “A Hybrid Digital Particle Tracking Velocimetry Technique”, Experiments in Fluids, Vol. 22, No. 3, pp. 199–211.
- Dantec Dynamics (1998), Dantec FlowMap® PIV Instrumentation Installation & User’s guide.
- Dasi, L. P. (2000), “Statistical Characteristics of Turbulent Chemical Plumes”, Master’s thesis, Georgia Institute of Technology.
- Del Bene, J. V., Jirka, G. and Largier, J. (1994), “Ocean Brine Disposal”, Desalination, Vol. 97, pp. 365–372.
- Del-Pilar-Ruso, Y., De-la-Ossa-Carretero, J. A., Giménez-Casaldueiro, F. and Sánchez-Lizaso, J. L. (2008), “Effects of a Brine Discharge over Soft Bottom Polychaeta Assemblage”, Environmental Pollution, Vol. 156, No. 2, pp. 240–250.
- Doneker, R. L. and Jirka, G. H. (2001), “CORMIX-GI Systems for Mixing Zone Analysis of Brine Wastewater Disposal”, Desalination, Vol. 139, pp. 263–274.
- Doneker, R. L. and Jirka, G. H. (2002), “Boundary Schematization in Regulatory Mixing Zone Analysis”, Journal of Water Resources Planning and Management, Vol. 128, No. 1, pp. 46–56.
- Einav, R., Harussi, K. and Perry, D. (2002), “The Footprint of the Desalination Processes on the Environment”, Desalination, Vol. 152, pp. 141–154.
- Einav, R. and Lokiec, F. (2003), “Environmental Aspects of a Desalination Plant in Ashkelon”, Desalination, Vol. 156, pp. 79–85.
- Fan, L.-N. and Brooks, N. H. (1966), “Discussion of Horizontal Jets in Stagnant Fluid of Other Density by Gerrit Abraham”, Journal of the Hydraulics Division, Vol. 92, No. HY2, pp. 423–429.
- Fan, L.-N. and Brooks, N. H. (1969), “Numerical Solutions of Turbulent Buoyant Jet Problems”, Tech. Rep. KH-R-18, W. M. Keck Laboratory of Hydraulics

REFERENCES

- and Water Resources, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California.
- Feng, H., Olsen, M. G., Hill, J. C. and Fox, R. O. (2007), “Simultaneous Velocity and Concentration Field Measurements of Passive-scalar Mixing in a Confined Rectangular Jet”, Experiments in Fluids, Vol. 42, pp. 847–862.
- Fernández-Torquemada, Y., Sánchez-Lizaso, J. L. and González-Correa, J. M. (2005), “Preliminary Results of the Monitoring of the Brine Discharge Produced by the SWRO Desalination Plant of Alicante (SE Spain)”, Desalination, Vol. 182, pp. 395–402.
- Ferrari, S. and Querzoli, G. (2004), “Sea Discharge of Brine from Desalination Plants: A Laboratory Model of Negatively Buoyant Jets”, in MWWD 2004-The 3rd International Conference on Marine Waste Water Disposal and Marine Environment, Catania, Italy.
- Fischer, H. B., List, E. J., Koh, R. C. Y., Imberger, J. and Brooks, N. H. (1979), Mixing in Inland and Coastal Waters, Academic Press, New York, USA.
- Fukushima, C., Aanen, L. and Westerweel, J. (2000), “Investigation of the Mixing Process in an Axisymmetric Turbulent Jet Using PIV and LIF”, in The 10th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal.
- Global Water Intelligence editorial team (2004), Desalination Markets: 2005-2015, Media Analytics Ltd, Oxford, UK.
- Global Water Intelligence (GWI) and International Desalination Association (IDA) (2008), “Desalination in 2008 – Global Market Snapshot”, [Online]. Available: https://www.idadesal.org/PDF/ida%20desalination%20snapshot_october%202008.pdf.
- Hantush, M. S. and Jacob, C. E. (1955), “Non-steady Radial Flow in an Infinite Leaky Aquifer”, Transactions of the American Geophysical Union, Vol. 36, No. 1, pp. 95–100.
- Herlina and Law, A. W.-K. (2002), “Measurements of Turbulent Mass Transport of a Circular Wall Jet”, International Journal of Heat and Mass Transfer, Vol. 45, pp. 4899–4905.

REFERENCES

- Hodges, B. R., Kulis, P. S. and David, C. H. (2006), “Desalination Brine Discharge Model Final Report”, Tech. rep., Cernter for Research in Water Resources, University of Texas at Austin.
- Hoepner, T. (1999), “A Procedure for Environmental Impact Assessments (EIA) for Seawater Desalination Plants”, Desalination, Vol. 124, pp. 1–12.
- Hoepner, T. and Lattemann, S. (2002), “Chemical Impacts from Seawater Desalination Plants — A Case Study of the Northern Red Sea”, Desalination, Vol. 152, pp. 133–140.
- Holley, E. R. (1969), “Discussion of Difference Modeling of Stream Pollution by David A. Bella and William E. Dobbins”, Journal of the Sanitary Engineering Division, Vol. 95, No. SA5, pp. 968–972.
- Höpner, T. and Windelberg, J. (1996), “Elements of Environmental Impact Studies on Coastal Desalination Plants”, Desalination, Vol. 108, pp. 11–18.
- Hu, H., Saga, T., Kobayashi, T., Taniguchi, N., Chen, Y., Chio, S. and Nara-hara, K. (2000), “Simultaneous Velocity and Concentration Measurements in a Turbulent Jet Flow by Using PIV-PLIF Combined System”, in The 4th JSME-KSME Thermal Engineering Conference, Kobe, Japan.
- Hunt, B. (1978), “Dispersive Sources in Uniform Ground-water Flow”, Journal of the Hydraulics Division, Vol. 104, No. HY1, pp. 75–85.
- Iso, S., Suizu, S. and Maejima, A. (1994), “The Lethal Effect of Hypertonic Solutions and Avoidance of Marine Organisms in Relation to Discharged Brine from Desalination Plant”, Desalination, Vol. 97, pp. 389–399.
- Jaime Sadhwani, J., Veza, J. M. and Santana, C. (2005), “Case Studies on Environmental Impact of Seawater Desalination”, Desalination, Vol. 185, pp. 1–8.
- James, W. P., Vergara, I. and Kim, K. (1983), “Dilution of a Dense Vertical Jet”, Journal of Environmental Engineering, Vol. 109, No. 6, pp. 1273–1283.
- Jenkins, S. A. and Wasyl, J. (2005), “Oceanographic Considerations for Desalination Plants in Southern California Coastal Waters”, Tech. Rep. No. 54, Marine Physical Laboratory, Scripps Institution of Oceanography, University of California, San Diego.

REFERENCES

- Jirka, G. H. (1982), Turbulent buoyant jets and plumes, HMT, The Science and Applications of Heat and Mass Transfer, chap. Turbulent buoyant jets in shallow fluid layers, Pergamon Press, New York, pp. 69–119.
- Jirka, G. H. (2004), “Integral Model for Turbulent Buoyant Jets in Unbounded Stratified Flows. Part I: Single Round Jet”, Environmental Fluid Mechanics, Vol. 4, pp. 1–56.
- Jirka, G. H. (2008), “Improved Discharge Configurations for Brine Effluents from Desalination Plants”, Journal of Hydraulic Engineering, Vol. 134, No. 1, pp. 116–120.
- Jirka, G. H. and Doneker, R. L. (1991), “Hydrodynamic Classification of Submerged Single-port Discharges”, Journal of Hydraulic Engineering, Vol. 117, No. 9, pp. 1095–1128.
- Johnston, A. J., Phillips, C. R. and Volker, R. E. (1994), “Modeling Horizontal Round Buoyant Jets in Shallow Water”, Journal of Hydraulic Engineering, Vol. 120, No. 1, pp. 41–59.
- Johnston, A. J. and Volker, R. E. (1993), “Round Buoyant Jet Entering Shallow Water”, Journal of Hydraulic Research, Vol. 31, No. 1, pp. 121–138.
- Kaminski, E., Tait, S. and Carazzo, G. (2005), “Turbulent Entrainment in Jets with Arbitrary Buoyancy”, Journal of Fluid Mechanics, Vol. 526, pp. 361–376.
- Kay, A. (1987), “The Effect of Cross-stream Depth Variations upon Contaminant Dispersion in a Vertically Well-mixed Current”, Estuarine, Coastal and Shelf Science, Vol. 24, No. 2, pp. 177–204.
- Kay, A. (1997), “Advection-diffusion in Reversing and Oscillating Flows: 2. Flows with Multiple Reversals”, IMA Journal of Applied Mathematics, Vol. 58, pp. 185–210.
- Kikkert, G. A. (2006), “Buoyant Jets with Two and Three-Dimensional Trajectories”, Ph.D. thesis, University of Canterbury, New Zealand.
- Kikkert, G. A., Davidson, M. J. and Nokes, R. I. (2007), “Inclined Negatively Buoyant Discharge”, Journal of Hydraulic Engineering, Vol. 133, No. 5, pp. 545–554.

REFERENCES

- Knudsen, M. and Wood, I. R. (1990), "The Interaction between a Boundary and a Horizontal Buoyant Jet", Journal of Hydraulic Research, Vol. 28, No. 3, pp. 375–385.
- Koh, R. C. Y. and Brooks, N. H. (1975), "Fluid Mechanics of Waste-water Disposal in the Ocean", Annual Review of Fluid Mechanics, Vol. 7, pp. 187–211.
- Lai, C.-S. (2002), "An Experimental Study of Discharge Angle and Boundary Effect on Buoyant Jets", Master's thesis, National Central University, Taiwan, in Chinese.
- Lane-Serff, G. F., Linden, P. F. and Hillel, M. (1993), "Forced, Angled Plumes", Journal of Hazardous Materials, Vol. 33, pp. 75–99.
- Latorre, M. (2005), "Environmental Impact of Brine Disposal on Posidonia Seagrasses", Desalination, Vol. 182, pp. 517–524.
- Lattemann, S. and Höpner, T. (2008), "Environmental Impact and Impact Assessment of Seawater Desalination", Desalination, Vol. 220, pp. 1–15.
- Launder, B. E. and Rodi, W. (1983), "The Turbulent Wall Jet: Measurements and Modeling", Annual Review of Fluid Mechanics, Vol. 15, pp. 429–459.
- Law, A. W.-K. (2006), "Velocity and Concentration Distribution of Round and Plane Turbulent Jets", Journal of Engineering Mathematics, Vol. 56, pp. 69–78.
- Law, A. W.-K. and Herlina (2002), "An Experimental Study on Turbulent Circular Wall Jets", Journal of Hydraulic Engineering, Vol. 128, No. 2, pp. 161–174.
- Law, A. W.-K., Ho, W. F. and Monismith, S. G. (2004), "Double Diffusive Effect on Desalination Discharges", Journal of Hydraulic Engineering, Vol. 130, No. 5, pp. 450–457.
- Law, A. W.-K. and Wang, H. (2000), "Measurement of Mixing Processes with Combined Digital Particle Image Velocimetry and Planar Laser Induced Fluorescence", Experimental Thermal and Fluid Science, Vol. 22, pp. 213–229.
- Law, A. W.-K., Wang, H. and Herlina (2003), "Combined Particle Image Velocimetry/Planar Laser Induced Fluorescence for Integral Modeling of Buoyant Jets", Journal of Engineering Mechanics, Vol. 129, No. 10, pp. 1189–1196.

REFERENCES

- Li, K.-S. (1997), “A study of Boundary Effect on Buoyant Jets Using Laser Induced Fluorescence”, Master’s thesis, National Central University, Taiwan, in Chinese.
- Li, W.-H. and Kozlowski, M. E. (1974), “DO-sag in Oscillating Flow”, Journal of the Environmental Engineering Division, Vol. 100, No. EE4, pp. 837–854.
- List, E. J. and Imberger, J. (1973), “Turbulent Entrainment in Buoyant Jets and Plumes”, Journal of the Hydraulics Division, Vol. 99, No. HY9, pp. 1461–1474.
- Mabrook, B. (1994), “Environmental Impact of Waste Brine Disposal of Desalination Plants, Red Sea, Egypt”, Desalination, Vol. 97, pp. 453–465.
- Macdonald, G. J. and Weisman, R. N. (1977), “Oxygen-sag in a Tidal River”, Journal of the Environmental Engineering Division, Vol. 103, No. EE3, pp. 473–488.
- Madni, I. K. and Ahmad, S. Z. (1989), “Prediction of Turbulent, Axisymmetric, Dense Jets Discharged to Quiescent Ambients”, Mathematical and Computer Modelling, Vol. 12, No. 3, pp. 363–370.
- Malfeito, J. J., Díaz-Caneja, J., Fariñas, M., Fernández-Torrequemada, Y., González-Correa, J. M., Carratalá-Giménez, A. and Sánchez-Lizaso, J. L. (2005), “Brine Discharge from the Javea Desalination Plant”, Desalination, Vol. 185, pp. 87–94.
- Mauguin, G. and Corsin, P. (2005), “Concentrate and Other Waste Disposals from SWRO Plant: Characterization and Reduction of Their Environmental Impact”, Desalination, Vol. 182, pp. 355–364.
- McLellan, T. N. and Randall, R. E. (1986), “Measurement of Brine Jet Height and Dilution”, Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 112, No. 2, pp. 200–216.
- Meerganz von Medeazza, G. L. (2005), ““Direct” and Socially-induced Environmental Impacts of Desalination”, Desalination, Vol. 185, pp. 57–70.
- Mi, J., Nathan, G. J. and Nobes, D. S. (2001a), “Mixing Characteristics of Axisymmetric Free Jets From a Contoured Nozzle, an Orifice Plate and a Pipe”, Vol. 123, pp. 878–883.

REFERENCES

- Mi, J., Nobes, D. S. and Nathan, G. J. (2001b), "Influence of jet exit conditions on the passive scalar field of an axisymmetric free jet", Journal of Fluid Mechanics, Vol. 432, pp. 91–125.
- Miller, B. M. (2005), "Desalination Planning Study Ocean Modelling Report", Tech. rep., Water Research Laboratory, The University of New South Wales.
- Morton, A. J., Callister, I. K. and Wade, N. M. (1996), "Environmental Impacts of Seawater Distillation and Reverse Osmosis Processes", Desalination, Vol. 108, pp. 1–10.
- Morton, B. R. (1959), "Forced Plumes", Journal of Fluid Mechanics, Vol. 5, pp. 151–163.
- Nasr, A. and Lai, J. C. S. (1998), "A Turbulent Plane Offset Jet with Small Offset Ratio", Experiments in Fluids, Vol. 24, pp. 47–57.
- Nemlioglu, S. and Roberts, P. J. W. (2006), "Experiments on Dense Jets Using Three-Dimensional Laser-induced Fluorescence (3DLIF)", in MWWD 2006-The 4th International Conference on Marine Waste Water Disposal and Marine Environment, Antalya, Turkey.
- Newman, B. G., Patel, R. P., Savage, S. B. and Tjio, H. K. (1972), "Three-Dimensional Wall Jet Originating from a Circular Orifice", Aeronautical Quarterly, Vol. 23, pp. 188–200.
- Okely, P., Antenucci, J. P., Imberger, J. and Marti, C. L. (2007), "Field Investigations into the Impact of the Perth Seawater Desalination Plant Discharge on Cockburn Sound", Tech. rep., Center for Water Research, University of Western Australia.
- Oliver, C. J., Davidson, M. J. and Nokes, R. I. (2008), "k- ϵ Predictions of the Initial Mixing of Desalination Discharges", Environmental Fluid Mechanics, Vol. 8, pp. 617–625.
- Papanicolaou, P. N. (1984), "Mass and momentum transport in a turbulent buoyant vertical axisymmetric jet.", Ph.D. thesis, California Institute of Technology.
- Papanicolaou, P. N. and List, E. J. (1988), "Investigations of Round Vertical Turbulent Buoyant Jets", Journal of Fluid Mechanics, Vol. 195, pp. 341–391.

REFERENCES

- Papanicolaou, P. N., Papakonstantis, I. G. and Christodoulou, G. C. (2008), "On the Entrainment Coefficient in Negatively Buoyant Jets", Journal of Fluid Mechanics, Vol. 614, pp. 447–470.
- Pérez Talavera, J. L. and Quesada Ruiz, J. J. (2001), "Identification of the Mixing Processes in Brine Discharges Carried Out in Barranco del Toro Beach, south of Gran Canaria (Canary Islands)", Desalination, Vol. 139, pp. 277–286.
- Pincince, A. B. and List, E. J. (1973), "Disposal of Brine into an Estuary", Journal of Water Pollution Control Federation, Vol. 45, No. 11, pp. 2335–2344.
- Priestley, C. H. B. and Ball, F. K. (1955), "Continuous Convection from an Isolated Source of Heat", Quarterly Journal of the Royal Meteorological Society, Vol. 81, No. 348, pp. 144–157.
- Purnama, A. and Al-Barwani, H. H. (2006), "Spreading of Brine Waste Discharges into the Gulf of Oman", Desalination, Vol. 195, pp. 26–31.
- Purnama, A., Al-Barwani, H. H. and Al-Lawatia, M. (2003), "Modeling Dispersion of Brine Waste Discharges from a Coastal Desalination Plant", Desalination, Vol. 155, pp. 41–47.
- Purnama, A., Al-Barwani, H. H. and Smith, R. (2005), "Calculating the Environmental Cost of Seawater Desalination in the Arabian Marginal Seas", Desalination, Vol. 185, pp. 79–86.
- Rajaratnam, N. and Pani, B. S. (1974), "Three-Dimensional Turbulent Wall Jets", Journal of the Hydraulics Division, Vol. 100, No. HY1, pp. 69–83.
- Rajaratnam, N. and Subramanya, K. (1968), "Plane Turbulent Reattached Wall Jets", Journal of the Hydraulics Division, Vol. 94, No. HY1, pp. 95–112.
- Roberts, P. J. W. (1999), "Modeling Mamala Bay Outfall Plumes. II: Far Field", Journal of Hydraulic Engineering, Vol. 125, No. 6, pp. 574–583.
- Roberts, P. J. W., Ferrier, A. and Daviero, G. (1997), "Mixing in Inclined Dense Jets", Journal of Hydraulic Engineering, Vol. 123, No. 8, pp. 693–699.
- Roberts, P. J. W. and Toms, G. (1987), "Inclined Dense Jets in Flowing Current", Journal of Hydraulic Engineering, Vol. 113, No. 3, pp. 323–341.

REFERENCES

- Roberts, P. J. W. and Webster, D. R. (2002), Environmental Fluid Mechanics: Theories and Application, chap. Turbulent diffusion, American Society of Civil Engineers (ASCE), pp. 7–46.
- Sajwani, A. A. (1998), “The Desalination Plants of Oman: Past, Present, and Future”, Desalination, Vol. 120, pp. 53–59.
- Sánchez-Lizaso, J. L., Romero, J., Ruiz, J., Gacia, E., Buceta, J. L., Invers, O., Fernández-Torquemada, Y., Mas, J., Ruiz-Mateo, A. and Manzanera, M. (2008), “Salinity Tolerance of the Mediterranean Seagrass *Posidonia oceanica*: Recommendations to Minimize the Impact of Brine Discharges from Desalination Plants”, Desalination, Vol. 221, pp. 602–607.
- Shams El Din, A. M., Aziz, S. and Makkawi, B. (1994), “Electricity and Water Production in the Emirate of Abu Dhabi and Its Impact on the Environment”, Desalination, Vol. 97, pp. 373–388.
- Shao, D. and Law, A. W.-K. (2009), “Boundary Interactions of Horizontal Desalination Discharges”, Submitted to Environmental Fluid Mechanics.
- Smith, R. and Scott, C. F. (1997), “Mixing in the Tidal Environment”, Journal of Hydraulic Engineering, Vol. 123, No. 4, pp. 332–340.
- Sobey, R. J., Johnston, A. J. and Keane, R. D. (1988), “Horizontal Round Buoyant Jet in Shallow Water”, Journal of Hydraulic Engineering, Vol. 114, No. 8, pp. 910–929.
- Su, L. K. and Mungal, M. G. (2004), “Simultaneous Measurements of Scalar and Velocity Field Evolution in Turbulent Crossflowing Jets”, Journal of Fluid Mechanics, Vol. 513, pp. 1–45.
- Tennekes, H. and Lumley, J. L. (1983), A first course in turbulence, MIT Press.
- Tsiourtis, N. X. (2001), “Desalination and the Environment”, Desalination, Vol. 141, pp. 223–236.
- Tsunoda, H., Shimizu, Y. and Kashiwagi, T. (2006), “Plane Offset Jet Discharged into Water of Finite Depth”, JSME International Journal Series B, Vol. 49, No. 4, pp. 1111–1117.
- U.S. Bureau of Reclamation and Sandia National Laboratories (2003), “Desalination and Water Purification Technology Roadmap: A Report of the Execu-

REFERENCES

- tive Committee”, Tech. rep., U.S. Bureau of Reclamation and Sandia National Laboratories.
- van Cruyningen, I., Lozano, A. and Hanson, R. K. (1990), “Quantitative Imaging of Concentration by Planar Laser-Induced Fluorescence”, Experiments in Fluids, Vol. 10, pp. 41–49.
- Wang, H. (1999), “Investigations of Buoyant Jet Discharges Using Digital Partical Image Velocimetry (DPIV) and Planar Laser Induced Fluorescence (PLIF)”, Ph.D. thesis, Nanyang Technological University.
- Wang, H. and Law, A. W.-K. (2002), “Second-order Ingegral Model for a Round Turbulent Buoyant Jet”, Journal of Fluid Mechanics, Vol. 459, pp. 397–428.
- Webster, D. R., Roberts, P. J. W. and Ra’ad, L. (2001), “Simultaneous DPTV/PLIF Measurements of a Turbulent Jet”, Experiments in Fluids, Vol. 30, pp. 65–72.
- Wikipedia (2009), [Online]. Available: <http://en.wikipedia.org/wiki/Desalination> (last modified on 20 December 2009).
- Willert, C. E. and Gharib, M. (1991), “Digital Particle Image Velocimetry”, Experiments in Fluids, Vol. 10, pp. 181–193.
- Wilson, J. L. and Miller, P. J. (1978), “Two-Dimensional Plume in Uniform Ground-water Flow”, Journal of the Hydraulics Division, Vol. 104, No. HY4, pp. 503–514.
- Wood, I. R., Bell, R. G. and Wilkinson, D. L. (1993), Ocean Disposal of Wastewater, World Scientific, Singapore.
- Wood, M. J. (2002), “The Behaviour of Dense Plumes near Boundaries and an Evaluation of Modelling Approaches”, Master’s thesis, University of Manchester, UK.
- World Health Organization (2007), “Desalination for Safe Water Supply: Guidance for the Health and Environmental Aspects Applicable to Desalination”, Tech. rep., World Health Organization.
- Wright, S. J. (1977), “Mean Behavior of Buoyant Jets in a Crossflow”, Journal of the Hydraulics Division, Vol. 103, No. 5, pp. 499–513.

REFERENCES

- Yannopoulos, P. C. (2006), “An Improved Integral Model for Plane and Round Turbulent Buoyant Jets”, Journal of Fluid Mechanics, Vol. 547, pp. 267–296.
- Zeitoun, M. A., McHilheny, W. F. and Reid, R. O. (1970), “Conceptual Designs of Outfall Systems for Desalination Plants”, Tech. Rep. Research and Development Progress Report No. 550, Office of Saline Water, United States Department of the Interior.
- Zeitoun, M. A., Reid, R. O., McHilheny, W. F. and Mitchell, T. M. (1972), “Model Studies of Outfall Systems for Desalination Plants. Part III Numerical Simulations and Design Considerations”, Tech. Rep. Research and Development Progress Report No. 804, Office of Saline Water, United States Department of the Interior.
- Zhang, H. and Baddour, R. E. (1998), “Maximum Penetration of Vertical Round Dense Jets at Small and Large Froude Numbers”, Journal of Hydraulic Engineering, Vol. 124, No. 5, pp. 550–553.

Appendix A

Experimental Data

Postprocessing Routines

A.1 Multiple-window stitching program

```
clc;
clear;
close all;

xoffset1=75; % x-direction offset between x1y1 and x2y1
yoffset1=80; % y-direction offset between x2y1 and x2y2

%-----

load x1y1.dat x1y1; % load all x1y1 data
x11 = x1y1(:,1); % specify which column contains x coordinates
x_matrix11 = reshape(x11,[62,62]);
% reshape the original dataset to a 62-by-62 matrix
y11 = x1y1(:,2); % y coordinates
y_matrix11 = reshape(y11,[62,62]);
c11 = x1y1(:,3); % concentration at each point
c_matrix11 = reshape(c11,[62,62]);

% note: all x1y1 data kept as original

figure(); % concentration contours of x1y1
v = [0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0];
```

Appendix A. Experimental Data Postprocessing Routines

```

% specify the contour values displayed
[C,h] = contourf(x_matrix11,y_matrix11,c_matrix11);
colormap jet;
colorbar('North');

%-----

hold on

load x2y1.dat x2y1;
x21 = x2y1(:,1)+xoffset1; % add offset to x2y1 x-coordinates
x_matrix21 = reshape(x21,[62,62]);
[i,j]=find(x_matrix21>x11(end));
% pick the non-overlapping x-coordinates, i and j record the row and column
% number in the matrix respectively
x_21_new=x_matrix21(find(x_matrix21>x11(end)));
% save the non-overlapping x-coordinates to a new data array
x_matrix21_new=reshape(x_21_new,[length(i)/62,62]);
% reshape to a n (less than 62)-by-62 matrix
y_21_new=y_matrix11(find(x_matrix21>x11(end)));
% y-coordinates borrow x1y1's to make them consistent
y_matrix21_new=reshape(y_21_new,[length(i)/62,62]);
c21 = x2y1(:,3);
% concentration at subsequent windows need to be normalized (neglect here,
% same in the following)
c_matrix21 = reshape(c21,[62,62]);
c_21_new=c_matrix21(find(x_matrix21>x11(end)));
% pick concentration data corresponding to non-overlapping area
c_matrix21_new=reshape(c_21_new,[length(i)/62,62]);

% note: for additional downstream windows, carry on the same procedure

figure(); % concentration contours of x2y1
v = [0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0];
% specify the contour values displayed
[C,h] = contourf(x_matrix21_new,y_matrix21_new,c_matrix21_new);
colormap jet;

```

Appendix A. Experimental Data Postprocessing Routines

```

colorbar('North');

%-----

x_matrix1=[x_matrix11; x_matrix21_new];
% combine x-coordinates for 1st floor
y_matrix1=[y_matrix11; y_matrix21_new];
% combine y-coordinates for 1st floor
c_matrix1=[c_matrix11; c_matrix21_new];
% combine concentration data for 1st floor

% data from additional downstream windows can be added to the bracket,
% separated by semicolon

figure(); % concentration contours of 1st floor
[C,h] = contourf(x_matrix1,y_matrix1,c_matrix1);
colormap jet;
colorbar('North');

%-----

load x2y2.dat x2y2;
x22 = x2y2(:,1)+xoffset1; % add offset to x2y2 x-coordinates
x_matrix22 = reshape(x22,[62,62]);
y22 = x2y2(:,2)+yoffset1; % add offset to x2y2 y-coordinates
y_matrix22 = reshape(y22,[62,62]);
c22 = x2y2(:,3);
c_matrix22 = reshape(c22,[62,62]);

x_matrix2=[x_matrix22]; % combine x-coordinates for 2nd floor
y_matrix2=[y_matrix22]; % combine y-coordinates for 2nd floor
c_matrix2=[c_matrix22]; % combine concentration data for 2nd floor

%note: for additional downstream windows in this floor, just follow the
%procedure for 1st floor and combine together

figure(); % concentration contours for raw 2nd floor block

```

Appendix A. Experimental Data Postprocessing Routines

```

v = [0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0];
% specify the contour values displayed
[C,h] = contourf(x_matrix2,y_matrix2,c_matrix2);
colormap jet;
colorbar('North');

%-----

x_matrix2_new=x_matrix1;
% adjust the 2nd floor x-coordinates to make them consistent with 1st floor
[m,n]=size(x_matrix1);
% m and n represent the row and column number of the combined 1st floor
% block
y_matrix2_new=ones(m,1)*y_matrix2(1,:);
% expand the 2nd floor y-coordinates to cover the same x range as 1st floor

[i,j]=find(x_matrix2_new<x_matrix2(1,1));
% identify the blank area on the left edge, i and j record the row and
% column numbers
[p,q]=size(x_matrix2);
% p and q represent the row and column numbers of the raw 2nd floor raw
% block
c_matrix2_new=[zeros(length(i)/62,62); c_matrix2; zeros(m-length(i)/62-p,62)];
% fill the blank area on the left and right edges with zero concentration

figure(); % concentration contours for x-adjusted 2nd floor
[C,h] = contourf(x_matrix2_new,y_matrix2_new,c_matrix2_new);
colormap jet;
colorbar('North');

%-----

[i,j]=find(y_matrix2_new>y_matrix1(end,end));
% pick the non-overlapping y-coordinates in the untrimmed 2nd floor, i and
% j record the row and column numbers
x2_new=x_matrix2_new(y_matrix2_new>y_matrix1(end,end));
% save the x-coordinates in the non-overlapping area to a new data array

```

Appendix A. Experimental Data Postprocessing Routines

```

x_matrix2_newnew=reshape(x2_new,[m,length(i)/m]);
% reshape to m-by-less-than-n matrix

y2_new=y_matrix2_new(y_matrix2_new>y_matrix1(end,end));
y_matrix2_newnew=reshape(y2_new,[m,length(i)/m]);

c2_new=c_matrix2_new(y_matrix2_new>y_matrix1(end,end));
c_matrix2_newnew=reshape(c2_new,[m,length(i)/m]);

figure(); % concentration contours for y-adjusted 2nd floor
[C,h] = contourf(x_matrix2_newnew,y_matrix2_newnew,c_matrix2_newnew);
colormap jet;
colorbar('North');

%-----

x_matrix=[x_matrix1 x_matrix2_newnew]; % combine x for all
y_matrix=[y_matrix1 y_matrix2_newnew]; % combine y for all
c_matrix=[c_matrix1 c_matrix2_newnew]; % combine c for all

[index_i index_j]=size(x_matrix); % the total row and column numbers

figure(); % complete concentration contours
[C,h] = contourf(x_matrix,y_matrix,c_matrix);
colormap jet;
colorbar('North');

set(gca,'XLim',[0 200],'YLim',[0 220]);

%-----

x=reshape(x_matrix,[index_i*index_j,1]);
% change back to single column vector
y=reshape(y_matrix,[index_i*index_j,1]);
c=reshape(c_matrix,[index_i*index_j,1]);

export = [x y c]; % export data to external data file

```

Appendix A. Experimental Data Postprocessing Routines

```
fname=['combined.dat']; % file name
fid = fopen(fname,'wt');
fprintf(fid,'VARIABLES=x-pos\t y-pos\t S\n'); % file header
fprintf(fid,'Zone T = "Zone 1"\n');
fprintf(fid,['I=' num2str(index_i) ',J=' num2str(index_j) ',K=1,F=POINT\n']);
fprintf(fid,'%12.8f\t %12.8f\t %12.8f\n',export');
fclose(fid);

hold off;
```

The various figures that are referred to in the stitching program are attached in the next page.

Appendix A. Experimental Data Postprocessing Routines

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure A.1: Sample images of the multiple-window stitching program (in the order of appearance in the Matlab script)

Appendix A. Experimental Data Postprocessing Routines

A.2 trajectory.m

trajectory.m was developed to derive the streamline starting from the center of the nozzle tip from the obtained velocity vector map, which was then used to approximate the centerline trajectory for the inclined dense jets.

```

clc;
clear;
close all;

cd('D:\Thesis\inclined_dense_jet\centerline_trajectory\H2');
% specify which directory contains data file

load velocityh2.dat velocityh2;
% load data
vel_x = velocityh2(:,1);
% specify which column contains x coordinates
vel_x_matrix = reshape(vel_x,[62,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_y = velocityh2(:,2); % y coordinates
vel_y_matrix = reshape(vel_y,[62,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_u = velocityh2(:,3); % horizontal velocity components
vel_u_matrix = reshape(vel_u,[62,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_v = velocityh2(:,4); % vertical velocity components
vel_v_matrix = reshape(vel_v,[62,330]);
% reshape original dataset to [62 62*number_of_zone]
vel = velocityh2(:,11); % normalized velocity magnitude
vel_matrix = reshape(vel,[62,330]);
% reshape original dataset to [62 62*number_of_zone]
%-----

hold on

v = [0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0];
[C,h] = contour(vel_x_matrix,vel_y_matrix,vel_matrix,v);
colormap gray;

```

Appendix A. Experimental Data Postprocessing Routines

```
% contours of the normalized velocity magnitude

h = streamline(vel_x_matrix,vel_y_matrix,vel_u_matrix,vel_v_matrix,1.24,1.38);
set(h,'Color','k','LineWidth',2);
% streamline derived from velocity map, (1.24,1.38) is the starting point
% based on experimental settings

legend('Contours of velocity magnitude','Centerline','Location','East');

set(get(gca,'XLabel'),'String','x/D');
set(get(gca,'YLabel'),'String','z/D');
set(gca,'XLim',[0 50],'XTick',0:10:50,'YLim',[0 10],...
    'Box','on','PlotBoxAspectRatio',[1 1/3 1]); %set x,y limit

hold off
```

Appendix A. Experimental Data Postprocessing Routines

A.3 combined_cross_section.m

combined_cross_section.m was developed to plot the various cross-sectional concentration profiles at different downstream locations in the same figure.

```

clc;
clear;
close all;

x_cor=3:3:42;
int_point=20;
scale=3;
cd('D:\Thesis\inclined_dense_jet\centerline_trajectory\H1');
% specify which directory contains data file

load velocityh1.dat velocityh1;
% load data
vel_x = velocityh1(:,1)-1.24;
% specify which column contains x coordinates
vel_x_matrix = reshape(vel_x,[119,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_y = velocityh1(:,2)-1.38; % y coordinates
vel_y_matrix = reshape(vel_y,[119,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_u = velocityh1(:,3); % horizontal velocity components
vel_u_matrix = reshape(vel_u,[119,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_v = velocityh1(:,4); % vertical velocity components
vel_v_matrix = reshape(vel_v,[119,330]);
% reshape original dataset to [62 62*number_of_zone]

verts = stream2(vel_x_matrix,vel_y_matrix,vel_u_matrix,vel_v_matrix,0,0);
h=streamline(verts);
set(h,'Color','k','LineWidth',2);
% plot centerline streamline as the trajectory

hold on

```

Appendix A. Experimental Data Postprocessing Routines

```

load concentrationh1.dat concentrationh1;
con_x = concentrationh1(:,1)-1.24;
% specify which colume contains x coordinates
con_x_matrix = reshape(con_x,[119,330]);
% reshape original dataset to [62 62*number_of_zone]
con_y = concentrationh1(:,2)-1.38; % y coordinates
con_y_matrix = reshape(con_y,[119,330]);
% reshape original dataset to [62 62*number_of_zone]
con = concentrationh1(:,3); % concentration
con_matrix = reshape(con,[119,330]);
% reshape original dataset to [62 62*number_of_zone]

tra=cell2mat(verts);
% extract the coordinates along the centerline

tra_x=tra(:,1);
tra_y=tra(:,2);

for i=1:length(x_cor)

cpp = spline(tra_x,tra_y);
% spline-fitting the discrete centerline coordinates

dcpp=fnder(cpp); % generate first direvative

slope=ppval(dcpp,x_cor(i));
% evaluate the tangent of the fitted centerline at x_cor

y0=ppval(cpp,x_cor(i)); % evaluate the y coordinate at x_cor

ya = linspace(con_y(1),y0,int_point);
% generate a number (int_point) of equally spaced points from lowest layer
% to center point

x_lim = (con_y(end)-y0)/(-1/slope)+x_cor(i);
if (x_lim < con_x(1))
    y_lim = -1/slope*(con_x(1)-x_cor(i))+y0;

```

Appendix A. Experimental Data Postprocessing Routines

```

elseif (x_lim > con_x(end))
    y_lim = -1/slope*(con_x(end)-x_cor(i))+y0;
else
    y_lim = con_y(end);
end

yb = linspace(y0,y_lim,int_point);
% generate a number (int_point) of equally spaced points from center point
% to assigned upper limit

y = [ya yb(2:end)];
% combine y coordinate and eliminate the repeating center point

x = (y-y0)/(-1/slope)+x_cor(i);
% calculate back to obtain the respective x values along the normal line

Labs = sqrt((x-x_cor(i)).^2+(y-y0).^2);
% calculate the absolute distances from the center point to the respective
% points

L = [Labs(1:length(ya)) -Labs(length(ya)+1:end)];
% set the distance to be negative for the upper portion and positive for
% the lower portion

[X,Y] = meshgrid(x,y);
% [Xu,Yu]=meshgrid(concentration(:,1),concentration(:,2));

c = griddata(con_x,con_y,con,X,Y,'cubic',{'QJ'});
% interpolate to obtain the horizontal projection of the concentration

C=diag(c,0);
C_nor=C/C(length(ya));

theta=atan(slope);
xx=x_cor(i)+L*sin(theta)+scale*C_nor'*cos(theta);
yy=y0-L*cos(theta)+scale*C_nor'*sin(theta);
plot(xx,yy,'k-');

```


Appendix A. Experimental Data Postprocessing Routines

end

```
set(get(gca,'XLabel'),'String','(x-x_0)/D');  
set(get(gca,'YLabel'),'String','(z-z_0)/D');  
set(gca,'XLim',[0 50],'YLim',[0 15],...  
    'Box','on','PlotBoxAspectRatio',[1 1/3 1]); %set x,y limit
```

hold off

Appendix A. Experimental Data Postprocessing Routines

A.4 axislength.m

axislength.m was developed to calculate the length of the curved jet centerline from the starting point to the point of interest.

```
function len=axislength(x_cor)
% axislength calculates the length of the curve from the starting point to
% the point of interest
% x_cor is the x coordinate of the point of interest

cd('D:\Thesis\inclined_dense_jet\centerline_trajectory\H1');
% specify which directory contains data file

load velocityh1.dat velocityh1;
% load data
vel_x = velocityh1(:,1)-1.24;
% specify which column contains x coordinates
vel_x_matrix = reshape(vel_x,[119,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_y = velocityh1(:,2)-1.38; % y coordinates
vel_y_matrix = reshape(vel_y,[119,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_u = velocityh1(:,3); % horizontal velocity components
vel_u_matrix = reshape(vel_u,[119,330]);
% reshape original dataset to [62 62*number_of_zone]
vel_v = velocityh1(:,4); % vertical velocity components
vel_v_matrix = reshape(vel_v,[119,330]);
% reshape original dataset to [62 62*number_of_zone]

cd('D:\Thesis\inclined_dense_jet\concentration_cross_section\H1');

verts = stream2(vel_x_matrix,vel_y_matrix,vel_u_matrix,vel_v_matrix,0,0);
tra=cell2mat(verts);

tra_x=tra(:,1);
tra_y=tra(:,2);

cpp = spline(tra_x,tra_y);
```

Appendix A. Experimental Data Postprocessing Routines

```

dcp = fnder(cpp); % generate first derivative
L(1)=0;
%
if (x_cor <= 0) | (x_cor > dcp.breaks(dcp.pieces+1))
    error('x coordinate out of limit.')
end

for k=1:dcp.pieces
    F=@(x) (sqrt((dcp.coefs(k,1)*(x-cpp.breaks(k)).^2+dcp.coefs(k,2)...
        *(x-cpp.breaks(k))+dcp.coefs(k,3)).^2+1));
    % using the fundamental line integral
    % delta_L=sqrt(delta_x^2+delta_y^2)=sqrt(1+(dy/dx)^2)*dx
    L(k+1) = quadl(F,dcp.breaks(k),dcp.breaks(k+1));
    % calculate length of each segment
end

for j=1:dcp.pieces
    if (dcp.breaks(j)<x_cor) & (x_cor<dcp.breaks(j+1))
        G=@(x) (sqrt((dcp.coefs(j,1)*(x-cpp.breaks(j)).^2+dcp.coefs(j,2)...
            *(x-cpp.breaks(j))+dcp.coefs(j,3)).^2+1));
        len=sum(L(1:j))+quadl(G,dcp.breaks(j),x_cor);
    end
end
end

```

Appendix B

More Graphical Illustrations

B.1 Figures related to Chap. 4

(a) N2

(b) N3

(c) N4

Figure B.1: Cross-sectional concentration distributions at various downstream locations

Appendix B. More Graphical Illustrations

Figure B.1: Cross-sectional concentration distributions at various downstream locations (cont)

Appendix B. More Graphical Illustrations

(a) N2

(b) N3

(c) N4

(d) N5

Figure B.2: Cross-sectional axial velocity component distributions at various downstream locations

Appendix B. More Graphical Illustrations

B.2 Figures related to Chap. 5

Figure B.3: Radial profiles of the axial mean velocity U at the nozzle exit (H2)

Figure B.4: Radial profiles of the axial rms velocity fluctuation $\sqrt{u'^2}$ at the nozzle exit (H2)

Appendix B. More Graphical Illustrations

Figure B.5: Radial profiles of the axial mean velocity U at the nozzle exit (H3)

Figure B.6: Radial profiles of the axial rms velocity fluctuation $\sqrt{u'^2}$ at the nozzle exit (H3)

Figure B.7: Radial profiles of the axial mean velocity U at the nozzle exit (H4)

Appendix B. More Graphical Illustrations

Figure B.8: Radial profiles of the axial rms velocity fluctuation $\sqrt{u'^2}$ at the nozzle exit (H4)

Figure B.9: Radial profiles of the axial mean velocity U at the nozzle exit (H5)

Figure B.10: Radial profiles of the axial rms velocity fluctuation $\sqrt{u'^2}$ at the nozzle exit (H5)

Appendix B. More Graphical Illustrations

Figure B.11: Radial profiles of the axial mean velocity U at the nozzle exit (H6)

Figure B.12: Radial profiles of the axial rms velocity fluctuation $\sqrt{u'^2}$ at the nozzle exit (H6)

Figure B.13: Radial profiles of the axial mean velocity U at the nozzle exit (H7)

Appendix B. More Graphical Illustrations

Figure B.14: Radial profiles of the axial rms velocity fluctuation $\sqrt{u'^2}$ at the nozzle exit (H7)

Appendix B. More Graphical Illustrations

Figure B.15: Radial profiles of the mean concentration C at the nozzle exit (H2)

Figure B.16: Radial profiles of the rms concentration fluctuation $\sqrt{c'^2}$ at the nozzle exit (H2)

Appendix B. More Graphical Illustrations

Figure B.17: Radial profiles of the mean concentration C at the nozzle exit (H3)

Figure B.18: Radial profiles of the rms concentration fluctuation $\sqrt{c'^2}$ at the nozzle exit (H3)

Figure B.19: Radial profiles of the mean concentration C at the nozzle exit (H4)

Appendix B. More Graphical Illustrations

Figure B.20: Radial profiles of the rms concentration fluctuation $\sqrt{c'^2}$ at the nozzle exit (H4)

Figure B.21: Radial profiles of the mean concentration C at the nozzle exit (H5)

Figure B.22: Radial profiles of the rms concentration fluctuation $\sqrt{c'^2}$ at the nozzle exit (H5)

Appendix B. More Graphical Illustrations

Figure B.23: Radial profiles of the mean concentration C at the nozzle exit (H6)

Figure B.24: Radial profiles of the rms concentration fluctuation $\sqrt{c'^2}$ at the nozzle exit (H6)

Figure B.25: Radial profiles of the mean concentration C at the nozzle exit (H7)

Appendix B. More Graphical Illustrations

Figure B.26: Radial profiles of the rms concentration fluctuation $\sqrt{c'^2}$ at the nozzle exit (H7)

Appendix B. More Graphical Illustrations

(a) H2

(b) H3

(c) H4

Figure B.27: Superimposed mean velocity vector and concentration contour maps

Appendix B. More Graphical Illustrations

(d) H5

(e) H6

(f) H7

Figure B.27: Superimposed mean velocity vector and concentration contour maps (cont)

Appendix B. More Graphical Illustrations

(a) H1

(b) H2

(c) H3

Figure B.28: Boundary streamwise velocity and concentration profile

Appendix B. More Graphical Illustrations

(d) H4

(e) H5

(f) H7

Figure B.28: Boundary streamwise velocity and concentration profile (cont)

Appendix B. More Graphical Illustrations

(a) H2

(b) H3

(c) H4

(d) H5

Figure B.29: Concentration and velocity axes superimposed by the contour of $\Omega_y = 0$

Appendix B. More Graphical Illustrations

(e) H6

(f) H7

Figure B.29: Concentration and velocity axes superimposed by the contour of $\Omega_y = 0$ (cont)

Appendix B. More Graphical Illustrations

(a) H1 (jet regime)

(b) H1 (transition to wall-jet regime)

(c) H2 (jet regime)

Figure B.30: Vertical streamwise turbulence intensity profiles at various downstream locations

Appendix B. More Graphical Illustrations

(d) H2 (transition to wall-jet regime)

(e) H3 (jet regime)

(f) H3 (transition to wall-jet regime)

Figure B.30: Vertical streamwise turbulence intensity profiles at various downstream locations (cont)

Appendix B. More Graphical Illustrations

(g) H4 (jet regime)

(h) H4 (transition to wall-jet regime)

(i) H6 (jet regime)

Figure B.30: Vertical streamwise turbulence intensity profiles at various downstream locations (cont)

Appendix B. More Graphical Illustrations

(j) H6 (transition to wall-jet regime)

(k) H7 (jet regime)

(l) H7 (transition to wall-jet regime)

Figure B.30: Vertical streamwise turbulence intensity profiles at various downstream locations (cont)

Appendix B. More Graphical Illustrations

(a) H1 (jet regime)

(b) H1 (transition to wall-jet regime)

(c) H2 (jet regime)

Figure B.31: Vertical normal turbulence intensity profiles at various downstream locations

Appendix B. More Graphical Illustrations

(d) H2 (transition to wall-jet regime)

(e) H3 (jet regime)

(f) H3 (transition to wall-jet regime)

Figure B.31: Vertical normal turbulence intensity profiles at various downstream locations (cont)

Appendix B. More Graphical Illustrations

(g) H4 (jet regime)

(h) H4 (transition to wall-jet regime)

(i) H6 (jet regime)

Figure B.31: Vertical normal turbulence intensity profiles at various downstream locations (cont)

Appendix B. More Graphical Illustrations

(j) H6 (transition to wall-jet regime)

(k) H7 (jet regime)

(l) H7 (transition to wall-jet regime)

Figure B.31: Vertical normal turbulence intensity profiles at various downstream locations (cont)

Appendix B. More Graphical Illustrations

B.3 Figures related to Chap. 7

a. $\nu = 0.6$

b. Close-up of initial development for $\nu = 0.6$

c. $\nu = 1.0$

d. Close-up of initial development for $\nu = 1.0$

Figure B.32: Temporal pattern of salinity build-up at $\eta = 2$ corresponding to various values of ν

Appendix C

Numerical Integration Routines

C.1 build.m

build.m was developed to compute the temporal pattern of the shoreline salinity build-up as shown in Fig. 7.1.

```
function build(eta,xi0,alp,lam,nu,N)
% compute temporal pattern of shoreline salinity build-up
% xi0: dimensionless offshore location of the source
% alp: the dispersivity ratio alpha (fixed as sqrt(20))
% lam: the Li and Kozlowski's parameter (fixed as 10)
% nu: the velocity ratio
% N: number of quadrature points (64 gives reasonable results after trial
% and error)

t = 0:pi*0.01:100*pi; % dimensionless time (one tidal cycle = 2*pi)

[x,w] = gquad('PG',N); % invoke 'gquad' quadrature algorithm

NC = 2048;

[x1,w1] = gquad('PG',NC);

for i = 1:length(t)
    t1 = min(t(i),12*pi);

    y(i) = buildquad(0,t1,t(i),xi0,eta,alp,lam,nu,x1,w1);
```


Appendix C. Numerical Integration Routines

```

% use dense quadrature points for initial stage (<12pi)

y(i) = y(i)+buildquad(t1,t(i),t(i),xi0,eta,alp,lam,nu,x,w);

end

[up,down] = envelope(t,y,'cubic');
% Call function envelope to extract the envelope

plot(t,y,'g-');

hold on;

plot(t,up,'r-.');
% plot upper envelope

plot(t,down,'r-.');
% plot lower envelope

hold off;

set(gca,'xlim',[0 100*pi],'ylim',[0 1.5],...
    'PlotBoxAspectRatio',[1 0.3 1],'Box','on')
set(get(gca,'XLabel'),'String','Time')
set(get(gca,'YLabel'),'String','Concentration')

return;

function y = buildquad(t0,t1,t,xi0,eta,alp,lam,nu,x,w)
if t==t0, y=0; return; end

s = 0.5*(t1-t0)*(x+1)+t0;
% assign quadrature points between integration interval (t0,t1)

y = func(s,t,xi0,eta,alp,lam,nu);
% compute the value of the integrand at the quadrature points

```

Appendix C. Numerical Integration Routines

```

y = sum(y.*w)*(0.5*(t1-t0));
% summation using 0.5*(t1-t0)*w quadrature weights

function y = func(t0,t,xi0,eta,alp,lam,nu)
% compute the integrand
y(t0<=eps) = 0;
I = (t0>eps);

alp = lam * alp* alp;

y(I) = exp(-lam*(eta-nu*t0(I)+cos(t)-cos(t-t0(I))).^2./t0(I));

y(I) = 2*y(I)./t0(I).*exp(-alp*xi0^2./t0(I));

return;

```

Appendix C. Numerical Integration Routines

The envelope function invoked in build.m was adapted from the original script developed by Lei Wang (developer information included in the file below).

```
function [up,down] = envelope(x,y,interpMethod)

%ENVELOPE gets the data of upper and down envelope of the known input (x,y).
%
%   Input parameters:
%   x               the abscissa of the given data
%   y               the ordinate of the given data
%   interpMethod    the interpolation method
%
%   Output parameters:
%   up             the upper envelope, which has the same length as x.
%   down           the down envelope, which has the same length as x.
%
%   See also DIFF INTERP1

%   Designed by: Lei Wang, <WangLeiBox@hotmail.com>, 11-Mar-2003.
%   Last Revision: 21-Mar-2003.
%   Dept. Mechanical & Aerospace Engineering, NC State University.
% $Revision: 1.1 $   $Date: 3/21/2003 10:33 AM $

if length(x) ~= length(y)
    error('Two input data should have the same length.');
```

end

```
if (nargin < 2)|(nargin > 3),
    error('Please see help for INPUT DATA.');
```

elseif (nargin == 2)

```
    interpMethod = 'linear';
end
```

% Find the extreme maxim values
 % and the corresponding indexes
 %-----

Appendix C. Numerical Integration Routines

```

extrMaxValue = y(find(diff(sign(diff(y)))== -2)+1);
extrMaxIndex = find(diff(sign(diff(y)))== -2)+1;

% Find the extreme minim values
% and the corresponding indexes
%-----
extrMinValue = y(find(diff(sign(diff(y)))== +2)+1);
extrMinIndex = find(diff(sign(diff(y)))== +2)+1;

up(1) = extrMaxValue(1);
up_x(1)=x(extrMaxIndex(1));
k = 2;
for i=2:length(extrMaxValue)-1
    if (extrMaxValue(i)>extrMaxValue(i-1)) | (extrMaxValue(i)>extrMaxValue(i+1))
        up(k)=extrMaxValue(i);
        up_x(k) = x(extrMaxIndex(i));
        k = k+1;
    end
end
up = [0, up];
up_x = [0, up_x];
%
down(1) = extrMinValue(1);
% the starting point is adaptive to the specific case
down_x(1)=x(extrMinIndex(1));
k = 2;
for i=2:length(extrMinValue)-1
    if (extrMinValue(i)<extrMinValue(i-1)) | (extrMinValue(i)<extrMinValue(i+1))
        % | and & can bring about different effects
        down(k)=extrMinValue(i);
        down_x(k) = x(extrMinIndex(i));
        k = k+1;
    end
end
end

```

Appendix C. Numerical Integration Routines

```
down    =[0, down];  
down_x  =[0, down_x];
```

```
% Interpolation of the upper/down envelope data  
%-----  
up = interp1(up_x,up,x,interpMethod);  
down = interp1(down_x,down,x,interpMethod);
```

Appendix C. Numerical Integration Routines

C.2 planar.m

beach.m was developed to compute the salinity contours in the x-y plane as shown in Fig. 7.2.

```
function beach(t,xi0,alp,lam,nu,N)
% compute salinity distribution along the shoreline
% variables and functions same as planar.m unless otherwise stated

eta = -4:0.1:20;
for j = 1: length(eta)
    y(j) = beachquad(t,xi0,eta(j),alp,lam,nu,N);
end

plot(eta,y);
set(gca,'xlim',[-4 20],'ylim',[0 2.0],...
    'PlotBoxAspectRatio',[1 0.3 1],...
    'Box','on')
set(get(gca,'XLabel'),'String','Distance along the beach')
set(get(gca,'YLabel'),'String','Concentration at the beach')

return;

function y = beachquad(t,xi0,eta,alp,lam,nu,N)

[x,w] = gquad('PG',N);

s = 0.5*t*(x+1);

y = func(s,t,xi0,eta,alp,lam,nu);

y = sum(y.*w)*(0.5*t);

return
```

Appendix C. Numerical Integration Routines

```
function y = func(t0,t,xi0,eta,alp,lam,nu)

alp = lam * alp* alp;

y = exp(-lam*(eta-nu*t0+cos(t)-cos(t-t0)).^2./t0);

y = 2*y./t0.*exp(-alp*xi0^2./t0);

return;
```

Appendix C. Numerical Integration Routines

C.3 beach.m

beach.m was developed to compute the salinity distribution along the shoreline as shown in Fig. 7.3.

```
function beach(t,xi0,alp,lam,nu,N)
% compute salinity distribution along the shoreline
% variables and functions same as planar.m unless otherwise stated

eta = -4:0.1:20;
for j = 1: length(eta)
    y(j) = beachquad(t,xi0,eta(j),alp,lam,nu,N);
end

plot(eta,y);
set(gca,'xlim',[-4 20],'ylim',[0 2.0],...
    'PlotBoxAspectRatio',[1 0.3 1],...
    'Box','on')
set(get(gca,'XLabel'),'String','Distance along the beach')
set(get(gca,'YLabel'),'String','Concentration at the beach')

return;

function y = beachquad(t,xi0,eta,alp,lam,nu,N)

[x,w] = gquad('PG',N);

s = 0.5*t*(x+1);

y = func(s,t,xi0,eta,alp,lam,nu);

y = sum(y.*w)*(0.5*t);

return
```


Appendix C. Numerical Integration Routines

```
function y = func(t0,t,xi0,eta,alp,lam,nu)

alp = lam * alp* alp;

y = exp(-lam*(eta-nu*t0+cos(t)-cos(t-t0)).^2./t0);

y = 2*y./t0.*exp(-alp*xi0^2./t0);

return;
```

Appendix C. Numerical Integration Routines

C.4 timed.m

timed.m was modified from beach.m to incorporate a time-dependent dispersivity as shown in Fig. 7.7.

```
function timed(t,xi0,alp,lam,inu,N)
    global nu;
    nu =inu;
    % compute salinity distribution along the shoreline in the case of a
    % time-dependent dispersivity
    % variables and functions same as planar.m unless otherwise stated

    eta = -4:0.1:20;
    for j = 1: length(eta)
        y(j) = timedquad(t,xi0,eta(j),alp,lam,N);
    end

    plot(eta,y);
    set(gca,'xlim',[-4 20],'ylim',[0 2.0],...
        'Box','on')
    set(get(gca,'XLabel'),'String','Distance along the beach')
    set(get(gca,'YLabel'),'String','Concentration at the beach')

    return;

function y = timedquad(t,xi0,eta,alp,lam,N)

    [x,w] = gquad('PG',N);

    s = 0.5*t*(x+1);

    y = func(s,t,xi0,eta,alp,lam);

    y = sum(y.*w)*(0.5*t);

    return
```

Appendix C. Numerical Integration Routines

```
function y = func(t0,t,xi0,eta,alp,lam)
global nu;

alp = lam * alp* alp;
for i = 1: length(t0)
    theta(i) = quadl(@Dintegrand,t-t0(i),t);
end
%by integration, theta is a function of local t0

y = exp(-lam*(eta-nu*t0+cos(t)-cos(t-t0)).^2./theta);

y = 2*y./theta.*exp(-alp*xi0^2./theta);

return
```

```
function u = Dintegrand(tau)
global nu;
% define integrand for theta

u = abs(1+1/nu*sin(tau));

return
```