Mixing of non-swirling and swirling inclined dense jets

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NANYANG
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**MIXING OF NON-SWIRLING AND
SWIRLING INCLINED DENSE JETS**

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MIXING OF NON-SWIRLING AND SWIRLING INCLINED DENSE JETS

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TABLE OF CONTENTS

Table of Contents

Acknowledgements.....	i
Table of Contents	iv
Summary.....	viii
List of Tables	xi
List of Figures.....	xii
List of Symbols	xvii
List of Abbreviations	xxii
Chapter 1 Introduction.....	1
1.1 Background	1
1.2 Objectives and Scope	6
1.3 Outline.....	8
Chapter 2 Literature Review	10
2.1 Seawater Desalination and Brine Discharges	10
2.2 Environmental Impacts of Brine Effluents	14
2.3 Submerged Inclined Dense Jets in Stagnant Ambient	16
2.4 Submerged Inclined Dense Jets in Currents	23
2.4.1 Dimensional analysis	25
2.4.2 Length scale method	29
2.4.3 Influence of density difference	30
2.5 Turbulence Characteristics of Dense Jet.....	32
2.5.1 Different scale motions in turbulent flows	32
2.5.2 Energy spectrum for turbulent flows	33
2.6 Swirling Jets.....	36
2.6.1 Swirl generators	36
2.6.2 Swirl Number G	37

TABLE OF CONTENTS

2.6.3 Flow structure of non-buoyant swirling jets	39
2.6.4 Numerical studies on swirling jets	41
Chapter 3 Experimental Methodology	45
3.1 PLIF and PIV systems	45
3.2 Experimental Setup	47
3.2.1 Tank facility and discharge system.....	47
3.2.2 Glass flume	49
3.2.3 Discharge nozzle.....	50
3.2.4 Pump	51
3.2.5 Flowmeter	52
3.2.6 Pulsed laser	52
3.2.7 Cameras	53
3.2.8 Towing system.....	54
3.2.9 Centralized control panel.....	55
3.2.10 Calibration box and grid	55
3.2.11 Fluorometer.....	56
3.3 Experimental Procedures	58
3.3.1 Planar Laser Induced Fluorescence (PLIF)	58
3.3.2 Particle Image Velocimetry (PIV)	63
3.3.3 Other optical effects.....	67
Chapter 4 Numerical Methodology	71
4.1 Introduction.....	71
4.2 Composition of CFD model.....	71
4.3 OpenFOAM	73
4.4 Governing Equations	74
4.5 Turbulence Closures	78
4.5.1 Reynolds averaged Navier-Stokes (RANS) model.....	79

TABLE OF CONTENTS

4.5.2 Large Eddy Simulations (LES).....	85
Chapter 5 Mixing Behavior of 45 °Inclined Dense Jets in Currents	91
5.1 Introduction.....	91
5.2 Experimental Procedures	95
5.3 Results and Discussion	96
5.3.1 Jet trajectory.....	96
5.3.2 Cross-sectional concentration distributions	105
5.3.3 Growth rate	112
5.3.4 Dilution and concentration decay	115
5.4 Conclusions.....	121
Chapter 6 Turbulence Characteristics of Inclined Dense Jets	123
6.1 Introduction.....	123
6.2 Experimental Procedures	126
6.3 Experimental Results and Discussion.....	129
6.3.1 Overall flow characteristics and jet trajectory	129
6.3.2 Axial and cross-sectional turbulence intensity	130
6.3.3 Energy spectrum and turbulent kinetic energy (TKE).....	132
6.4 Large Eddy Simulations.....	137
6.4.1 Previous LES modeling work on 45 °inclined dense jet ..	137
6.4.2 LES simulations.....	138
6.4.3 Overall flow characteristics and jet trajectory	142
6.4.4 Velocity decay	143
6.4.5 Velocity fluctuations.....	145
6.4.6 Cross-sectional velocity profile	146
6.4.7 Axial and cross-sectional turbulence intensity	150
6.4.8 Energy spectrum and turbulent kinetic energy	152
6.5 Conclusions.....	157

TABLE OF CONTENTS

Chapter 7 Mixing of Swirling Inclined Dense Jets.....	158
7.1 Introduction.....	158
7.2 Experimental Results	160
7.3 Numerical Simulations.....	161
7.4. Results and Discussion	164
7.5. Conclusions.....	178
Chapter 8 Conclusions and Recommendations.....	184
8.1 Conclusions.....	184
8.1.1 Mixing behaviors of 45 °inclined dense jets in currents ...	184
8.1.2 Turbulence characteristics of inclined dense jets	185
8.1.3 Mixing of swirling inclined dense jets.....	186
8.2 Recommendations and Future Works	187
References	189
Author' s Publications	208
Journal Papers	208
Conference Papers	208
Appendix A.	209
MATLAB Program for Data Processing.....	209
A.1 Jet_trajectory.m.....	209
A.2 Concentration_e-width.m.....	214

SUMMARY

Summary

The high salinity brine discharge from large scale SWRO desalination plants is potentially harmful to the local marine ecosystem and therefore needs to be mixed well with the ambient water to meet the environmental requirements. At present, full submergence of the dense jet is generally targeted as the typical design scenario for brine disposal. Due to its engineering importance, the configuration had also been extensively studied in the past two decades.

In some coastal areas especially with gentle slopes and shallow waters, the brine outfall needs to be located far away from the coast to achieve a full submergence, which will increase the cost for the pipeline construction. With a general desire for cost minimization such that the outfall can be located as close to the shore as environmentally acceptable, highly efficient brine outfalls which can effectively dilute the brine with the ambient water within a short distance are desirable. In order to further optimize the outfall design, a comprehensive understanding on the mixing behaviour of the dense jet under different discharge and ambient conditions is necessary.

In the present study, the mixing behaviour of the 45 °inclined dense jets in both co- and counter-flows were first experimentally investigated using the advanced laser imaging technique of Planar Laser Induced Fluorescence (PLIF) with a wide range of jet exit velocities and flowing current velocities. The investigation covered the concentration and geometrical features of the dense jet in currents. The relationships between the currents and jet spread as well as concentration

SUMMARY

decay were also investigated. The quantitative results are useful to assess the mixing zone compliance for the brine discharge.

In order to further understand the mixing behaviour of inclined dense jets, the spatial and temporal distribution of the turbulence characteristics were investigated. The experimental investigation was based on high sampling-frequency PIV measurements which can resolve the turbulence spectrum at different locations along the jet trajectory. In addition, LES was also performed for turbulence simulations. The results showed that the turbulence energy spectrum evolved and developed along the jet trajectory, and the spread was directly related to the turbulence intensity. The average geometric behaviour and the low frequency range of the turbulence energy spectrum were also simulated reasonable well by LES once the grid spacing was sufficiently small.

With the understanding of the mixing behaviour and turbulence of inclined dense jets, the effect of introducing swirl at the outlet which can potentially enhance the entrainment was numerically explored. The comparison of the two different numerical models of RANS and LES showed that LES simulated the trajectory better for non-swirling and weakly swirling dense jets, while RANS performed better with strong swirl. When $G = 0.33$, the disintegration of the vortical layer into smaller eddies increased the turbulence energy production in the frequency range just before the inertial range. With $G = 0.66$, larger scale eddies also appeared. Both the numerical and experimental results showed that there was an optimum Swirl number G between 0.22 and 0.45, which can lower the rise height as well as increase the return point dilution.

SUMMARY

In summary, detailed information was obtained on the mixing and turbulence characteristics of non-swirling and swirling inclined dense jets and the influence of the flowing current on the mixing behavior. It is hopeful that the benchmark data can enhance the simulation and design of the brine outfalls in the future.

LIST OF TABLES

List of Tables

Table 2.1 Forecast of desalination costs for medium and large size projects	12
Table 2.2 Regulations and salinity limits for selected desalination brine discharges (Jenkins et al., 2012)	16
Table 5.1 Experimental conditions (Inclined dense jet in currents)	97
Table 6.1 Experimental conditions (Turbulence characteristics)	127
Table 6.2 Numerical conditions (Turbulence characteristics)	141
Table 7.1 Numerical conditions (Swirling jets)	161

LIST OF FIGURES

List of Figures

Figure 1.1 Water availability estimates for 2013 (Kucera, 2014)	3
Figure 1.2 Schematic of an inclined dense jet in stagnant ambient.....	4
Figure 2.1 Cumulative capacity of desalination plants (Global Water Intelligence, 2010).....	11
Figure 2.2 Desalination technologies classification based on the separation process adopted (Micale et al., 2009).....	12
Figure 2.3 Global installed desalination capacity by technology for 2011 (Global Water Intelligence, 2012).....	13
Figure 2.4 Annual new contracted capacity of desalination.....	14
Figure 2.5 Sketch of four types of vortices associated with a non-buoyant vertical jet (Fric and Roshko, 1994).....	24
Figure 2.6 Schematic side view of an inclined dense jet discharge into co-flowing currents	27
Figure 2.7 Swirl generators	37
Figure 3.1 Experimental setup with towing system	48
Figure 3.2 Schematic diagram of the glass flume	49
Figure 3.3 Arrangement of the nozzle and nozzle piece	52
Figure 3.4 Calibration box and calibration grid	56
Figure 3.5 Relationship between fluorescence signal and concentration...	58
Figure 3.6 Sample LIF calibration images for different standard dye solutions	61
Figure 3.7 PLIF calibration linear relationship from a sample grid	62
Figure 3.8 Two typical consecutive frames	66

LIST OF FIGURES

Figure 3.9 Displacements of the particles between two consecutive frames	66
Figure 3.10 Optical distortions: Barrel and pincushion distortion	68
Figure 5.1 Schematic diagrams of an inclined dense jet issuing into: (a) co-flows and (b) strong counter-flows	94
Figure 5.2 Time-averaged concentration contours in co-flows	100
Figure 5.3 Trajectories for inclined dense jets in (a) co-flows and (b) counter-flows.....	101
Figure 5.4 Relationship between NFr and: (a) z_m/FrD , (b) x_m/FrD	103
Figure 5.5 Relationship between NFr and: (a) z_m/FrD , (b) x_{cp}/FrD	104
Figure 5.6 Vertical cross-sectional concentration distribution.....	106
Figure 5.7 Cross-sectional concentration profiles at different stream-wise distances in (a) vertical and (b) lateral directions	107
Figure 5.8 Cross-sectional concentration profiles at centerline peak in (a) vertical and (b) lateral directions.....	108
Figure 5.9 Vertical cross-sectional concentration distribution.....	109
Figure 5.10 Cross-sectional concentration profiles at different stream-wise distances in (a) vertical and (b) lateral directions	110
Figure 5.11 Cross-sectional concentration profiles at $s = 7D$ in (a) vertical and (b) horizontal directions	111
Figure 5.12 Growth of b_c in co-flows ($Fr = 21.1$): (a) upper half, (b) lower half and (c) left and right half.....	113
Figure 5.13 Growth of b_c in counter-flows ($Fr = 17.1$): (a) upper half, (b) lower half and (c) left and right half	114
Figure 5.14 Relationship between S_m/Fr and NFr (co-flows)	115
Figure 5.15 Concentration decay along the centerline at: (a) $Fr = 17.1$ and (b) $NFr = 1.5$	116

LIST OF FIGURES

Figure 5.16 Concentration decay along the centerline at various Fr and NFr (co-flows)	118
Figure 5.17 Relationship between NFr and: (a) S_m/Fr , (b) S_{cp}/Fr	119
Figure 5.18 Concentric circles for evaluating the radial concentration decay rate	120
Figure 5.19 Concentration decay at different radial distances from the nozzle tip ($Fr = 17.1$) from: (a) Experiments, (b)VISJET	121
Figure 6.1 Average velocity field of dense jet.....	130
Figure 6.2 Normalised jet trajectories of 45 °inclined dense jet	130
Figure 6.3 Stream-wise turbulence intensity along the centerline.....	131
Figure 6.4 Radial turbulence intensity along the centerline	132
Figure 6.5 Cross-sectional distribution of stream-wise turbulence intensity (Case F3)	132
Figure 6.6 Locations of analysis of turbulent energy spectrum	133
Figure 6.7 Experimental turbulent energy spectrum at centerline peak with different Fr	134
Figure 6.8 Experimental turbulent energy spectrum at different locations (Case F11)	136
Figure 6.9 Computational domain	139
Figure 6.10 Experimental and numerical results for horizontal velocity field.....	143
Figure 6.11 Normalised jet trajectories of 45 °inclined dense jet	143
Figure 6.12 Comparison of velocity decay along the centerline	145
Figure 6.13 Experimental and numerical instantaneous velocities fluctuations at Point 6.....	146
Figure 6.14 Cross-section distribution of stream-wise velocity along the trajectory.....	148

LIST OF FIGURES

Figure 6.15 Cross-section distribution of radial velocity at different $s/D/Fr$ values.....	148
Figure 6.16 Variation of upper spread width along the centreline	149
Figure 6.17 Variation of lower spread width along the centerline	149
Figure 6.18 Variation of stream-wise turbulence intensity along the centreline	151
Figure 6.19 Variation of radial turbulence intensity along the centerline	151
Figure 6.20 Cross-sectional distribution of stream-wise turbulence intensity	152
Figure 6.21 Numerical and experimental turbulent energy spectrum at centerline peak.....	153
Figure 6.22 Experimental and numerical turbulent energy spectrum at different locations (N9C and F9)	155
Figure 6.23 Experimental and numerical turbulent energy spectrum at different locations (N12B and F12)	156
Figure 7.1 Computational domain	162
Figure 7.2 Distribution of tangential and axial velocity at the nozzle exit	163
Figure 7.3 Concentration contours for non-swirling inclined dense jets..	165
Figure 7.4 Concentration contours for swirling inclined dense jets	166
Figure 7.5 Trajectory of non-swirling inclined dense jets.....	168
Figure 7.6 Trajectory of swirling inclined dense jets	168
Figure 7.7 Growth rate of upper half	169
Figure 7.8 Growth rate of lower half	170
Figure 7.9 Normalised concentration distribution at various stream-wise distance from the nozzle.....	171

LIST OF FIGURES

Figure 7.10 Normalised concentration distribution at centerline peak with different G	172
Figure 7.11 Concentration decay along the centerline	175
Figure 7.12 Relationship between centerline peak height and G	175
Figure 7.13 Relationship between dilution at return point and G	176
Figure 7.14 Locations of points for analysis of turbulence kinetic energy spectrum	177
Figure 7.15 Turbulence kinetic energy spectrum at different locations along the trajectory based on LES results: $G =$ (a) 0, (b) 0.33 and (c) 0.66	181

LIST OF SYMBOLS

List of Symbols

A_0, A_s	Coefficients in realizable k - ε closure
A_d	Attenuation coefficient of fluorescent dye
A_s	Attenuation coefficient of salt
A_w	Attenuation coefficient of water
b_e	Velocity e-width
b_c	Concentration e-width
B_0	Buoyancy flux
c	Concentration
c_0	Initial concentration
c_c	Centreline concentration
$C_{1\varepsilon}, C_{2\varepsilon}, C_\mu$	Constants in standard k - ε closure
c_m	Maximum concentration
C_s	Smagorinsky constant
C_k, C_ε	Constant in DKE SGS model
C_ϕ	Correction term in Dynamic Smagorinsky SGS model
D	Nozzle diameter
Fr	Densimetric Froude number
f	External force
g	Gravitational acceleration
g'	Reduced gravitational acceleration
G	Swirl Number
G_b	Turbulence kinetic energy generated by buoyancy
G_k	Turbulence kinetic energy generated by mean velocity gradients

LIST OF SYMBOLS

G_θ	Swirl momentum
G_z	Axial momentum
h	Port height
H	Distance from the port to the water surface
k	Turbulence kinetic energy
k_I	Ambient to jet velocity ratio
k_f	Concentration decay coefficient related to Fr and NFr
k_{sgs}	SGS turbulence kinetic energy
l	Path length of the laser beams
l'	Path length of the fluorescence beams
l_M	Momentum-buoyancy length scale
l_m	Cross-flow momentum length scale
L_Q	Discharge length scale
L	Distance from the port to the back and front vertical boundary
L_M	Jet characteristic length scale
L_{ij}	Resolved turbulent stress
M_0	Kinematic momentum
M_{ij}	Anisotropic part of the turbulent stress
NFr	Nominal Froude number
p	Pressure
Pr	Prandtl Number
Q_0	Volume flux
Q_j	SGS scalar flux or turbulent scalar flux
r	Radial distance
r_I	Square root of the momentum flux ratio
$\vec{r}_c$	Corrected vector
$\vec{r}_d$	Distorted vector

LIST OF SYMBOLS

R	Orifice radius
R_j	Coefficient in Dynamic Smagorinsky SGS model
Re	Reynolds number
Re_t	Coefficient in standard $k-\omega$ closure
s	Stream-wise distance from the nozzle
S_m	Dilution at centreline peak
S_r	Dilution at return point
$\tilde{S}$	Local strain rate
S_{cp}	Dilution at centreline penetration depth
Sc_t	Turbulent Schmidt number
S_{ij}	Rate of strain tensor for the resolved scale
S_R	Non-dimensional swirl number
s_ϕ	Scalar source term
t	Time
t_s	Runtime for a simulation
u, v, w	Velocities in x, y and z direction, respectively
μ_{eff}	Effective viscosity
U	Stream-wise velocity
U_a	Velocity of the ambient water
U'	Fluctuation of stream-wise velocity
U_0	Discharge velocity
U_m	Jet velocity along the centreline
U'_{rms}	Root mean square stream-wise velocity fluctuation
$\bar{u}$	Mean velocity
u'	Fluctuating velocity
u_i, u_j	Velocity in i, j direction, respectively

LIST OF SYMBOLS

u_τ	Friction velocity
V	Radial velocity
V'	Fluctuation of radial velocity
V'_{rms}	Root mean square radial velocity fluctuation
W_0	Initial tangential velocity
W_d	Distance from the nozzle to the left and right vertical boundary
x, y, z	Cartesian Coordinates in the horizontal, lateral and vertical direction, respectively
x_{cp}	Centerline penetration depth
x_m	Horizontal locations of the centreline peak
x_p	Penetration depth
z_m	Centreline peak height
Y_M	Contribution of fluctuating to the dissipation rate
Y_k	Dissipation of the turbulent kinematic energy
Y_ϵ	Dissipation of specific dissipation rate
z_t	Terminal rise
Δ	LES filter width
α	Extinction coefficients of the laser
α'	Extinction coefficients of the fluorescence
α_k	Inverse effective Prandtl numbers for k
α_ϵ	Inverse effective Prandtl numbers for ϵ
β	Coefficient in standard $k-\omega$ model
λ	Second viscosity
ρ	Fluid density
ρ_a	Ambient density
ρ_b	Effluent density

LIST OF SYMBOLS

μ	Fluid viscosity
μ_t	SGS eddy viscosity or turbulent eddy viscosity
ϕ	Scalar concentration
θ	Inclined angle relative to the horizontal plane
σ	Angle between the vertical projection of the jet axis and x-axis
σ_k	Turbulent Prandtl numbers for k
σ_ε	Turbulent Prandtl numbers for ε
δ_{ij}	Kronecker delta
ε	Dissipation rate
ε_j	Coefficient in Dynamic Smagorinsky SGS model
κ	Von Karman constant
ω	Specific dissipation rate
ω_k	Angular velocity
τ	Viscous stresses
τ_{ij}	SGS Reynolds stresses or Reynolds stresses
τ_{kk}	Isotropic part of SGS stress
τ_w	Wall shear stress
Γ	Scalar diffusivity
Γ_t	Turbulent dispersivity
Ω_{ij}	Rate of rotation tensor

LIST OF ABBREVIATIONS

List of Abbreviations

CCD	Charge-Coupled Device
CFD	Computational Fluid Dynamics
CORMIX	Cornell Mixing Zone Expert System
CVP	Counter Rotating Vortex Pair System
DKE	Dynamic Kinetic Energy
DNS	Direct Numerical Simulation
ED	Electro-Dialysis
EIA	Environmental Impact Assessment
ESCWA	Economic and Social development Commission in Western Asia
FEM	Finite Element Method
FVM	Finite Volume Method
GUI	Graphical User Interface
GCI	Grid Convergence Index
GWI	Global Water Intelligence
IDA	International Desalination Association
LA	Light Attenuation
LDA	Laser Doppler Anemometers
LES	Large Eddy Simulations
LIF	Laser Image Fluorescence
LSV	Laser Speckle Velocimetry
MD	Membrane Distillation
MED	Multi-state Effect Distillation
MSF	Multi-Stage Flash
PIV	Particle Image Velocimetry

LIST OF ABBREVIATIONS

PLIF	Planar Laser Induced Fluorescence
PVC	Processing Vortex Core
RANS	Reynolds Averaged Navier Stokes
RO	Reverse Osmosis
SGS	Sub-Grid Scale
S-L	Smagorinsky-Lilly
SPIV	Stereoscopic Particle Image Velocimetry
SWRO	Seawater Reverse Osmosis
WET	Whole Effluent Toxicity

CHAPTER ONE

Chapter 1

Introduction

1.1 Background

With the rapid growth of world population and urbanization, the demand for clean potable water is increasing (Figure 1.1). It has been estimated that almost 20% of the world's population is now facing the shortage of safe drinking water (Danoun, 2007). Moreover, the United Nation's "World Water Development Report" suggests that more than 50% of the countries will experience water shortage by 2025 (United Nations, 2003). Predictions suggest that water withdrawals will increase by 50% in developing countries and 18% in developed countries by 2025, leaving an unsustainable demand for fresh water (United Nations Environment Programme, 2007). Therefore, alternative water supplies are urgently in need. Among them, seawater desalination, especially seawater reverse osmosis (SWRO), is becoming popular for some expanding coastal cities around the world (Global Water Intelligence, 2010). With the development of membrane technology, the capacity of SWRO desalination plants has tripled from 2005 to 2016. It is now nearly 65% of the global desalination capacity, which will further increase in the coming years for alternative portable water supplement. In the last decade alone, SWRO desalination plants had developed quickly in countries including the United States, Australia, and China. SWRO is also being utilised by Singapore to diversify the water supply. Two large RO plants are currently operated in Singapore, which can meet 25% of water demand in total. Two more plants are

CHAPTER ONE

being constructed, and a fifth desalination plant has been proposed which would be installed in Singapore in 2020 with a capacity of 137,000 m³ per day (PUB, 2017).

A byproduct from desalination plants, known as desalination brine, is typically discharged directly back to the sea. Desalination brine contains elevated concentrations of dissolved substances (such as high salinity, pretreatment chemicals and heavy metals), suspended solids as well as waste heat (Morton et al., 1997; Hoepner and Lattemann, 2003) which may be potentially harmful to the local marine ecosystem (Talavera and Ruiz, 2001; Dрами et al., 2011; Yoon and Park, 2011). Mortality rate analysis and Whole Effluent Toxicity (WET) tests had been carried out to assess the impact of the brine on the local marine ecosystem (Pillard et al., 1999; Jenkins and Wasyl, 2001). According to these investigations, different marine species have different salinity tolerances, and a salinity of 40g/L was suggested to be the general threshold for acute toxicity (Yoon and Park, 2011).

As mentioned before, with the advanced membrane technology, the recovery ratio of modern multi-stage SWRO desalination processes is increasing. Thus, the salinity of the brine from SWRO desalination plants is also increasing. Therefore, in order to minimize the potential environmental impact and satisfy the environmental requirements, the brine outfall needs to be designed effectively for a large operating range such that the dense effluent can mix well with the ambient water within the mixing zone. Hence, a comprehensive assessment of the mixing characteristics of the brine under different discharge and ambient flow conditions is essential.

CHAPTER ONE

Figure 1.1 Water availability estimates for 2013 (Kucera, 2014)

So far, a full submergence of the dense jet is typically targeted as the design scenario which can be traced back to the work of Zeitoun et al. (1970). Many subsequent studies were conducted to investigate the mixing of brine discharges into ambient waters (Roberts and Toms, 1987; Roberts et al., 1997; Kikkert et al., 2007; Shao and Law, 2010; Lai and Lee, 2012; Oliver et al., 2013). For submerged buoyant jets, the mixing can be divided into two phases (Malcangio and Petrillo, 2011). The first phase occurs near the discharge exit. It happens in the range which is called “near field”, whereby the mixing and transport depend on the discharge and ambient current conditions. The second phase begins after the jet impacts onto the seabed, and this range is called “far field” which depends on the ambient conditions (e.g. currents, winds, etc).

Figure 1.2 illustrates the schematic diagram of a typical inclined dense jet discharged into a stationary ambient. Here, D is the diameter of the discharge nozzle; z_m is the centerline peak height; x_m is the horizontal displacement of the

CHAPTER ONE

centerline peak; z_t is the terminal rise height; S_m is the dilution at the centerline peak and S_r is the dilution at the return point; and θ is the inclined angle. The brine effluent mixes with the ambient water initially as a negatively buoyant jet, and rises to the peak height due to the initial momentum. After that, it is driven downward and impacts onto the seabed due to its negative buoyancy.

Figure 1.2 Schematic of an inclined dense jet in stagnant ambient

It should be noted that the stagnant ambient may not be the worst design scenario. In coastal waters, the inclined dense jet interacts with ambient currents during flood and ebb tides, and the interactions depend on the relative alignment of the jet discharge with the current direction. The worst scenario may occur in a weak current opposite to the inclined jet (Roberts and Toms, 1987). For dense jet in co-flowing currents, on the other hand, the initial momentum flux “pushes” the jet to rise and move forward. In the process, the ambient water is entrained into the jet. The entrainment can be enhanced by the co-flowing currents, thus increases the dilution of the high salinity discharges (Malcangio and Petrillo, 2011). Therefore, a detailed investigation on the effect

CHAPTER ONE

of both co-flowing and counter-flowing currents on the mixing behavior of inclined dense jets is essential.

In addition to the ambient current conditions, turbulence can also affect the mixing behavior of inclined dense jets. Turbulence encompasses eddies with a wide range of time and length scales. The typical shape of temporal turbulent energy spectrum for turbulence was described by Pope (2002). The low-frequency range of the spectrum represents the production range whereby the shear flows generating larger size eddies that contain bulk of the turbulent kinetic energy. Subsequently, the turbulent kinetic energy produced is transported through the energy cascade to smaller eddies in the inertial sub-range. According to the Kolmogorov's theory, the turbulent energy spectrum of a high Reynolds number flow normally exhibits a $-5/3$ slope in the inertial sub-range (Kolmogorov 1941, Obukhov 1941). Beyond that, a steep slope of -3 might be observed for two-dimensional eddies, before a very steep slope of -7 at the highest frequencies range which represents the viscous dissipation into heat (Heisenberg 1948).

In the previous studies, measurement approaches to quantify the turbulence characteristics of buoyant jets including hot-wire probes (stationary and flying), Laser-Doppler anemometers (LDA) and Particle Image Velocimetry (PIV). (Kotsovinos, 1977; Papanicolaou, 1984; Law and Wang, 2000, Wang and Law, 2002). However, only a few studies analyzed beyond the basic level of velocity fluctuations and turbulent intensities. The second order statistics, especially the turbulence energy spectrum for inclined dense jets, which can reflect the overall development of the turbulence and the turbulent kinetic energy distribution in

CHAPTER ONE

different length and time scales, have not been reported for inclined dense jets so far.

Moreover, in order to reduce the water production cost through the economy of scale, the size of desalination plants around the world is growing rapidly. The higher water production capacities (Global Water Intelligence, 2010; Kavvadias and Khamis, 2010) inevitability generate higher brine flow rates. The flowrate of the brine disposal from the desalination plants is different between regular and standby operation modes. Therefore, the design of brine outfalls that can effectively cope with a wide range of flow rate is now necessary. A possible idea is the adoption of swirling inclined dense jets which have shorter jet trajectory but better mixing with the ambient water. Besides, the swirling intensity G can also be changed according to different flow rates. Therefore, the installation of a swirl valve at the nozzle, which is a potential design of the brine outfall, is investigated in the present study.

1.2 Objectives and Scope

In the present study, the mixing behavior of 45° inclined dense jets in both co-flowing and counter-flowing currents was investigated firstly using the Planar Laser Induced Fluorescence (PLIF) approach. The objective was to understand the changes in the mixing behavior due to different ambient conditions. The experiments were conducted in a towing flume, and the test conditions included a wide range of Densimetric Froude number (Fr), nominal Densimetric Froude number ($NFr > 0$ for co-flowing and < 0 for counter-flowing currents). The jet geometrical features, including the rise height

CHAPTER ONE

and horizontal displacement of the dense jet in flowing current, were investigated. The jet spread, growth of the e-width and decay of the concentration along the jet centerline under different ambient velocities were also studied. The study provided the necessary information to assess the brine disposal in different ambient flow conditions and also the implications for mixing zone compliance.

An extensive laboratory investigation was then carried out to quantify the turbulent characteristics of 45 °inclined dense jets using the technique of Particle Image Velocimetry (PIV) over a range of Densimetric Froude Number (Fr). The study enabled the analysis of turbulence at a deeper level beyond the root-mean-square velocity fluctuations and turbulence intensities reported for the inclined dense jet in the previous studies. In particular, the second-order turbulent characteristics, as well as the spatial and temporal turbulent energy spectrum, were resolved at different locations along the curvilinear jet trajectory. Furthermore, numerical simulations using the approach of Large Eddy Simulations (LES) were performed with the Dynamic Smagorinsky sub-grid model for the specific discharge conditions in the experiments. The capability for LES model to simulate the second order statistics and the energy spectrum of the turbulent dense jet as well as the possible improvement of the present sub-gride model for LES was discussed.

In order to cope with the wide range of flow rate as well as the brine discharging in shallow waters, swirling jets were also studied numerically in the present study. Previous studies with non-buoyant jets showed that the swirl can affect the mixing behaviour and suppress the axial velocity (Gibson and Younis, 1986; Champagne and Kromat, 2000). However, so far there is only limited

CHAPTER ONE

experimental investigation on inclined turbulent swirling dense jets in the literature. Based on the assessment, the mixing behaviour of inclined swirling dense jets with different swirl intensities was investigated. The jet spread, turbulence characteristics and concentration decay under different Swirl Number G were studied by using both the LES and RANS model. The capability of the numerical model to simulate the mixing characteristics of the inclined swirling dense jet as well as the optimal swirling intensity which can lower the centreline peak together with a maximum dilution, were also explored.

1.3 Outline

This thesis is organized into 8 chapters. In Chapter 1, the background information, including the desalination brine discharge, the research gaps and the objectives of the present study are introduced. In Chapter 2 the literature review is presented. Previous studies on the evolution of seawater desalination, the environmental impact of the brine, the near-field mixing and turbulence characteristics of inclined dense jets, the improvement of the brine outfalls and swirling jet are introduced. In Chapter 3, the experimental setup and procedures, including the advanced laser imaging techniques of Planar Laser Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV) are described. In Chapter 4, the numerical methods are introduced. The principle and equations for typical RANS and LES models and the equations for different closures are presented. Chapter 5 presents the experimental observations on the inclined dense jets in co-flowing and counter-flowing currents. The geometrical features and the spread of the dense jet are reported, and the effect of currents with

CHAPTER ONE

different directions are discussed. In Chapter 6, the turbulence characteristics of the inclined 45 °dense jet are investigated. The first and second order statistics, including the turbulence intensity, spatial kinetic energy spectrum of the dense jet are analyzed. Beside, LES simulations are performed and the results are compared with the experimental results. In Chapter 7, experiments and numerical simulations for 45 °inclined swirling dense jet are carried out. The jet spread, turbulent characteristics as well as the optimized swirl intensity for brine disposal are explored by both RANS and LES models. Finally, Chapter 8 summarizes the major findings of the present study and recommendations for possible future work.

Chapter 2

Literature Review

2.1 Seawater Desalination and Brine Discharges

With the rapid population growth, urbanization and industrialization, demand for freshwater will increase and this will further stress the already scarce freshwater supply all over the world. Therefore, freshwater production technologies, such as seawater desalination is gaining popularity in some arid and semi-arid coastal cities around the world (Figure 2.1). The world total desalination capacity has increased rapidly in recent years. According to the 20th International Desalination Association (IDA) Worldwide Desalting Plant Inventory, the total capacity of desalination plants worldwide was 44.1 million m^3 per day in 2006 (IDA and GWI, 2008). The capacity almost reached 130 million m^3 per day in 2017. At present, there are a number of technologies available for seawater desalination (shown in Figure 2.2), such as distillation, electro-dialysis, reverse osmosis membrane separation and membrane distillation (Ali et al., 2011). Distillation is a traditional technique which was mainly used in the past few decades. Modern distillation methods include multi-stage effect distillation (MED), multi-stage flash (MSF) and thermal vapor compression (TVC). These techniques are different in details but are based on the same principle that the freshwater can be separated from the seawater by evaporation and then collecting the cooled and condensed water vapor. Among all the distillation methods, MSF is most widely used which accounts for about 85% of the distillation production in the Economic and Social Development

CHAPTER TWO

Commission in Western Asia (ESCWA) Member countries (Al-Weshahi et al., 2012).

Figure 2.1 Cumulative capacity of desalination plants (Global Water Intelligence, 2010)

With the advance of the membrane technology in recent years, reverse osmosis desalination (RO) is gaining popularity as an alternative to the distillation method. Different from distillation, seawater reverse osmosis (SWRO) is a membrane filtration process that removes the dissolved minerals, including salt, from the solutions by applying high pressure (exceeding the osmotic pressure) on the high solute concentration side of a semi-permeable membrane which only allows water but not the salt molecules to pass through. Since the energy consumption for SWRO is lower than distillation methods, and the cost of membrane has dropped significantly as shown in Table 2.1, it has become the dominant desalination method in recent years. Figure 2.3 shows that SWRO plants took up approximately 60% of the global desalination capacity in 2011,

CHAPTER TWO

and the total contracted RO desalination capacity has tripled in the last decade (Figure 2.4).

Figure 2.2 Desalination technologies classification based on the separation process adopted (Micale et al., 2009)

Table 2.1 Forecast of desalination costs for medium and large size projects (IWA, 2016)

Parameter for Best-in-Class Desalination Plants	Year 2016	Within 5 Years	Within 20 Years
Cost of water (US\$/m ³)	0.8-1.2	0.6-1.0	0.3-0.5
Electrical Energy Use (kWh/m ³)	3.5-4.0	2.8-3.2	2.1-2.4
Membrane Productivity (m ³ /membrane)	28-47	35-55	95-120

The size of seawater desalination is also increasing rapidly. In the year 1969, the water production ability of the world's largest operating RO system was 380 m³ per day in Dallas, Texas, while the capability is over 728,000 m³ per day

CHAPTER TWO

nowadays for the largest RO system (Ras Al Khair Desalination Plant, 2014). According to the investigation (Global Water Intelligence, 2012), RO system takes up the majority part of the installed desalination plants, with 63% of the total capacity, while MSF and MED account for 23% and 8%. The remaining 6% is shared by other minor desalination systems.

Figure 2.3 Global installed desalination capacity by technology for 2011
(Global Water Intelligence, 2012)

In other words, RO is fast becoming the dominant process including the United States, Australia, China and Middle East region. SWRO is also being used by Singapore to diversify the water supply. The two large RO plants (SingSpring and Tuaspring) in Singapore have a total capacity of 448,500 m³ per day, which can meet 25% of water demand for over 20-year period. The recent proposed fifth desalination plant in Singapore will add another 137,000 m³ water per day for the water supply (PUB Singapore's National Water Agency, 2017).

CHAPTER TWO

Figure 2.4 Annual new contracted capacity of desalination
(Global Water Intelligence, 2010)

2.2 Environmental Impacts of Brine Effluents

Although desalination is a useful technology in producing freshwater, it comes with a certain environmental cost which has to be appropriately managed. One major by-product of the desalination process is the highly saline effluent (typically around 75 ppt), which is generally called brine. The brine can result in negative impacts on the marine ecosystem, as demonstrated by previous studies on the influence of the brine discharge on marine communities (Drami et al., 2011; Yoon and Park, 2011). A marine environment that has high salinity and temperature could reduce the cell numbers of chlorophyll-a and Pico-phytoplankton. Heavy metals, including copper, nickel, chromium, molybdenum and iron which can be found in brine, are also potentially harmful to the ecosystem (Malcangio and Petrillo, 2011).

CHAPTER TWO

Mortality rate analysis and Whole Effluent Toxicity (WET) test were carried out to assess the impact of desalination brine on the local marine ecosystem by Voutchkov (2007). Different phytoplankton species were found to have different brine sensitivities. For zooplankton species, over 65 ppt (parts per thousand, 1ppt = 1g/L) of salinity could lead to over 50% mortality, and 40 ppt of salinity was found to be a general threshold concentration to cause acute toxicity (Yoon and Park 2011). Since the desalination brine from SWRO is typically has the salinity around 75 ppt due to the high recovery rate of the advanced multistage SWRO desalination process, it is much higher than the threshold salinity. Therefore, the brine effluents should be diluted with surrounding water within a short distance (Tsiourtis, 2008).

Different environmental requirements were proposed in order to minimize the adverse impacts of the brine discharge. Jenkins et al. (2012) reviewed various regulations and standards (Table 2.2). Two key elements are typically emphasized in these regulations: a salinity limit and a point of compliance (expressed as a distance from the discharge). The salinity limit is usually stated as an increment relative to the ambient and less frequently expressed as an absolute salinity or a minimum level of dilution. The point of compliance for the salinity limit is usually specified in terms of a fixed distance from the discharge that ranges from 50 to 300 m.

Jenkins et al. (2012) recommended that the brine discharge from the desalination plants should be regulated by a mixing zone approach whereby the water quality regulations are met at the mixing zone boundary, and the mixing zone should also encompass the near-field processes.

CHAPTER TWO

Table 2.2 Regulations and salinity limits for selected desalination brine discharges (Jenkins et al., 2012)

Region/Authority	Salinity Limit	Compliance Point	Source
US EPA	Increment ≤ 4 ppt	--	--
Carlsbad, CA	Absolute ≤ 40 ppt	1,000 ft	San Diego Regional Water Quality Control
Huntington Beach, CA	Absolute ≤ 40 ppt salinity	1,000 ft	San Ana Regional Water Quality Control Board
Western Australia guidelines	Increment $< 5\%$	--	--
Oakajee Port, Western Australia	Increment ≤ 1 ppt	--	The Waters of Victoria State Environment
Perth, Australia/Western Australia EPA	Increment ≤ 1.2 ppt at 50 m and ≤ 0.8 ppt at 1,000m	50 m and 1,000 m	Wec, 2002
Sydney, Australia	Increment ≤ 1 ppt	50-75 m	ANZECC (2000)
Gold Coast, Australia	Increment ≤ 2 ppt	120 m	GCD Alliance (2006).
Okinawa, Japan	Increment ≤ 1 ppt	Mixing zone boundary	Okinawa Bureau for Enterprises
Abu Dhabi	Increment $\leq 5\%$	Mixing zone boundary	Kastner (2008)
Oman	Increment ≤ 2 ppt	300 m	Sultanate of Oman (2005)

2.3 Submerged Inclined Dense Jets in Stagnant Ambient

Many investigations had been conducted to develop effective brine outfall designs such that the dense effluent can mix well with the surrounding ambient waters within a short distance. A full submergence of the inclined brine discharge into stationary ambient was commonly recommended for the brine

CHAPTER TWO

outfall configuration (Zeitoun et al., 1970; Roberts and Toms, 1987). The analysis of the inclined dense jet includes parameters such as the z_m , z_t , x_m , S_m and S_r . Dimensional analysis was carried out and the parameters were measured to predict the jet geometrical features and dilution of the inclined dense jet (Turner, 1966; Zeitoun et al., 1970; Roberts and Toms, 1987; Roberts et al., 1997). From the dimensional analysis in Chapter 1, it can be shown that the dilution and jet geometrical features are dependent on the discharge Densimetric Froude number Fr . From the equations, it can be observed that when the discharging angle is fixed, the centerline peak dilution can be enhanced with a larger Densimetric Froude number (Fr). The investigation of full submergence of the inclined dense jet can be traced to Zeitoun et al. (1970), in which the inclined dense jets with various inclined angles above the horizontal, i.e., 30° , 45° , 60° and 90° , were investigated. The inclined angle of 60° was recommended since it produced maximum dilution at the terminal rise height.

Roberts and Toms (1987) also recommended 60° inclined dense jets because of their lower terminal rise and much higher dilution than vertical jets. Apart from the dilution at the terminal rise, they also determined the dilution at the impact point which is an essential parameter for environmental impact assessment (EIA). Herein the impact point was defined as the minimum dilution point along the seabed. Note that in many papers the impact point was used interchangeably as the return point which is defined as the minimum dilution point at the discharge level since the seabed slope and the nozzle height are sometimes relatively small compared to the entire receiving water body. Among the jets with different inclinations, the impact point dilution of the 60° inclined

CHAPTER TWO

dense jet was the largest and twice that of the vertical dense jet. Therefore, the 60° inclined jet was preferable in terms of the environmental impact.

In the early studies, the dilution was measured by probe-based approaches or samples taken from the body of the jet. With the advancement of modern laser imaging techniques in the past two decades, non-intrusive Planar Laser Induced Fluorescence (PLIF) had become popular to investigate the mixing of the dense jet. Roberts et al. (1997) applied the PLIF technique to obtain the instantaneous concentration fields of the fluorescent dye tracer at the centreline plane, illustrating the flow properties in detail. The mixing characteristics, including the impact point dilution and terminal rise height, were measured for 60° inclined dense jets. The concentration distribution along the seabed revealed that the jet flow made a transition to a horizontally spreading layer after the impingement point. The horizontal spreading induced additional mixing and led to a higher dilution beyond the impact point.

Cipollina et al. (2005) conducted an extensive series of experiments on an inclined dense jet in stagnant ambient. Several parameters, such as nozzle diameter, discharge angle, brine density, effluent flow rate and brine viscosity, were studied to quantify their effects on the jet geometry. The normalised geometrical parameters, including the centerline peak location, were all found to be well proportional to the Froude number, which indicated that the dimensional analysis is reasonable.

Kikkert et al. (2007) investigated the concentration field and geometrical features of dense jets with different discharge angles by using both light attenuation (LA) and PLIF techniques. The centerline peak, terminal rise and

CHAPTER TWO

return point as well as return point dilution and their corresponding empirical coefficients were determined with twelve different discharge angles ranging from 0 to 75 °. The relationship between the centerline peak height/horizontal displacement of centerline peak and discharge angles were also demonstrated.

Shao and Law (2010) studied the mixing behaviors of 30 ° and 45 ° inclined dense jets in stationary ambient by employing a combined PLIF and Particle Image Velocimetry (PIV) technique. In their study, the concentration and velocity fields were measured simultaneously to eliminate the potential errors caused by repeating the experiments when the concentration and velocity fields were captured separately. Similar to previous studies, the locations of the return point, jet centerline peak as well as return point dilution were determined and plotted against various Froude numbers. The empirical coefficients for these mixing characteristics were then estimated and compared with the values obtained previously in the literature. Besides, their study revealed the non-dimensional cross-sectional distributions of the axial velocity and concentration that were found to be asymmetric. The upper half of the distribution followed the Gaussian distribution while a distortion was observed for the lower half, which was in good agreement with the observation by Kikkert et al. (2007). Furthermore, the influence of seabed boundary proximity on inclined dense jets was investigated. The mixing characteristics were found to be affected by the seabed when the elevation of the discharge nozzle (h) was sufficiently small. h/l_M (l_M is the momentum-buoyancy length scale) was recommended to be greater than 0.2 and 0.05 for the 30 ° and 45 ° inclinations, respectively, to avoid the Coanda effect due to the proximity to the seabed.

CHAPTER TWO

Ferrari and Querzoli (2010) explored the effects of re-entrainment on the mixing of inclined dense jets from a sharp-edged orifice in stagnant ambient. The concentration fields were captured by PILF. An extensive series of θ from 45 ° to 90 ° and Froude numbers (8, 14.8, 23.8 and 30.8) for each discharge angle were investigated. The normalised geometrical parameters, including the normalised horizontal displacement of the return point and normalised vertical location of the centerline peak were quantified. They found that when the discharge angle exceeded 75 °, the observed trend line deviated from the previous investigations results, which indicated that the re-entrainment became significant in affecting the jet trajectories.

Papakonstantis and Christodoulou (2010) experimentally investigated the mixing behavior of inclined dense jets with four different inclined angles, namely 45 °, 60 °, 75 ° and 85 °. The variation of the dimensionless radial spread of the dense jets on the horizontal seabed with the discharge angle and densimetric Froude number was presented.

Papakonstantis et al. (2011a) investigated the geometrical characteristics of the dense jet with various discharge angles ranging from 45 ° to 90 °. The dense jet was colored with food dye and recorded by a video camera. The steady terminal rise height was found to increase with the discharge angle, achieving a maximum value at an 80 ° inclination and then decreasing after that. The horizontal displacements of the terminal rise and the outer visual boundary at the discharge level both decreased as the discharge angle increased, which was consistent with the findings of Kikkert et al. (2007). Besides, the visual boundaries of the dense jet were normalised by DFr . The boundaries were found to be collapsed onto a single curve, which again proved that the

CHAPTER TWO

dimensional analysis was reasonable. Papakonstantis et al. (2011b) also experimentally studied the mixing characteristics of inclined dense jets at three different discharge angles. The concentration of the brine was measured using a micro-scale conductivity probe. The non-dimensional vertical concentration distributions were observed to be asymmetric. The upper half of the distribution followed the Gaussian profile; the lower half however deviated from the Gaussian profile due to the buoyancy instability. Finally, the empirical correlations for various geometrical parameters as well as the return point and centerline peak dilutions were determined and compared with obtained results in other studies.

Lai and Lee (2012) investigated the jet mixing behaviors of inclined dense jets with various discharge angles (15° ; 30° ; 38° ; 45° ; 52° and 60°) and various Froude numbers (10-40). The PLIF and PIV techniques were adopted to measure the concentration distribution and velocity field, respectively. The asymmetric non-dimensional cross-sectional distributions of the time-averaged concentration implied that the buoyancy-induced instability caused considerable detrainment and mass outflux when the discharge angle exceeded 15° . The jet trajectories and the empirical coefficients for various geometrical features, including the horizontal displacement of the return point, the locations of the jet centerline peak and the terminal rise, as well as the return point dilution and centerline peak dilution were compared with simulation results of a widely used model, VISJET, to validate the model. The model results were found to underestimate the geometrical parameter values by 10-15% and the dilution values by 30%.

CHAPTER TWO

Oliver et al. (2013a) investigated the mixing of inclined dense jets on a sloping seabed. The jet nozzle was inclined at 30°, 45° or 60° above the horizontal, and the seabed with the slopes ranged from 0-20° below the horizontal were tested. The dilution at impact point beyond the return point was obtained and compared with a semi-analytical model. The results indicated that the impact dilution increased with both the jet inclination and the seabed slope. The model prediction was found in good agreement with the experimental data and could be a useful tool for the estimation of mixing properties at the impact point. Oliver et al. (2013b) pointed out that the significant scatter in the dilution data reported in the literature could be attributed to the boundary effect, i.e. the influence of the seabed or the free water surface, especially for the return point dilution since the return point is relatively further away from the discharge nozzle. The jet trajectories and outer boundaries for a specific inclination were normalised by D_{Fr} , as a result, they well collapsed onto two curves representing the normalised trajectory and edge, respectively. This observation agreed well with the findings of Papakonstantis et al. (2011b). The normalised jet trajectories for different inclinations collapsed onto a single curve by further normalizing with the centerline peak height and the horizontal displacement of the return point. Additionally, the various empirical coefficients were again obtained and compared with the data in the literature.

Jiang et al. (2014) experimentally investigated the effect of water depth on the mixing of 30° and 45° inclined dense jets in shallow water. Three different mixing regimes, named full submergence, plume contact, and centerline impingement regimes were identified based on the different relative cover water depths (H/D). The mixing characteristics in these three regimes, including the jet trajectory and minimum dilution at the water surface as well as the dilution

CHAPTER TWO

at the return point near the seabed were quantified. The transitional value of FrD/H among different regimes and the asymptotic limits of the minimum surface dilution at large Fr were also determined. Their study showed that the water surface constrained the plume contact and centerline impingement regimes and reduced the surface dilution, while the bottom dilution remained relatively constant. The comparison indicated that 45° inclined jets were preferable in surface contact scenarios in which the jet could achieve better bottom dilution, which enabled the assessment of the mixing characteristics of the inclined dense jet in shallow coastal waters with possible surface contact for environmental impact assessment.

In summary, fully submerged dense jets in stagnant ambient were recommended as the design scenario in the previous studies. Empirical equations were proposed to predict the jet geometry and dilution. The boundary effects and the detrainment of the jet fluid were also discussed, which is of great value for the design of brine outfalls and environmental impact assessment. The experimental results also facilitated the development of theoretical and numerical models for submerged dense jets in stagnant ambient.

2.4 Submerged Inclined Dense Jets in Currents

Currents can significantly affect the dilution of the jet (Lee and Chu, 2003 and Christodoulou et al. 2015). Therefore, it is important to consider the effect of ambient currents in studying the mixing of the dense jet. As discussed in Chapter 1, the mixing of discharged brine can be divided into two phases (Malcangio and Petrillo, 2011). In the “near field”, the mixing and transport

CHAPTER TWO

mainly depended on the discharge characteristics, while in the “far field”, the mixing depended not only on the discharge but also on the ambient surrounding movement (e.g. wind and density currents). Figure 2.5 shows the flow structure of a non-buoyant jet in cross-flow currents. The jet is distorted in the cross-sectional shape and evolves into a flow field with complex large-scale vortex structure near the jet exit. It is known that the near field entrainment is influenced by vortices, while the far-field entrainment is dominated by the counter-rotating vortex pair system which is named CVP with abbreviations (Coelho and Hunt, 1989).

Figure 2.5 Sketch of four types of vortices associated with a non-buoyant vertical jet (Fric and Roshko, 1994)

However, different from non-buoyant jets, the direction of the initial momentum and buoyancy of the dense jet are opposite along the trajectory for dense jet. The characteristics of dense jets are thus not symmetrical about the centerline as in non-buoyant jet (Law and Wang, 2000). This has led to the complex behaviors of the inclined dense jet reported in the literature, including

CHAPTER TWO

the detrainment process (Kikkert et al. 2007). Therefore, the mixing behavior of inclined dense jet in currents was separately investigated in the previous studies. When the dense jet is discharged into the current, the initial momentum flux “pushes” the jet to rise and move forward. In the process, the ambient water is entrained into the jet, thus expanding the jet boundary. This entrainment can be enhanced by the currents, which can affect the dilution of the high salinity discharges (Malcangio and Petrillo, 2011).

2.4.1 Dimensional analysis

Figure 2.6 shows the inclined discharge of the dense effluent with density ρ_b into the currents with density ρ_a through a round nozzle of diameter D at a velocity of U_0 . The uniform ambient current is U_a . From previous studies (Pincince and List, 1973; Roberts and Toms, 1987), the behavior of the inclined dense jet is characterized by the following basic parameters:

$$\text{Volume flux: } Q_0 = \frac{\pi}{4} D^2 U_0 \quad (2.1)$$

$$\text{Kinematic momentum: } M_0 = \frac{\pi}{4} D^2 U_0^2 \quad (2.2)$$

$$\text{Specific buoyancy flux: } B_0 = Q_0 \frac{\rho_b - \rho_a}{\rho_a} g = Q_0 g' \quad (2.3)$$

A dimensional analysis can be conducted as follows:

$$z_m = f(Q_0, M_0, B_0, U_a, \theta) \quad (2.4)$$

Selecting M_0, B_0 as basic dimension parameters, Equation (1.4) can be transformed into:

CHAPTER TWO

$$\frac{z_m}{M_0^{\frac{3}{4}} B_0^{-\frac{1}{2}}} = f\left(\frac{Q_0}{M_0^{\frac{5}{4}} B_0^{-\frac{1}{2}}}, \frac{U_a}{M_0^{-\frac{1}{4}} B_0^{-\frac{1}{2}}}, \theta\right) \quad (2.5)$$

Equation (1.5) can be further written as:

$$\frac{z_m}{\frac{U_0 \sqrt{D}}{\sqrt{g'}}} = f\left(\frac{\sqrt{\frac{\pi}{4}}}{\frac{U_0}{\sqrt{g'D}}}, \frac{U_a}{\sqrt{g'D}}, \theta\right) \quad (2.6)$$

Here, the Densimetric Froude Number is defined as:

$$Fr = \frac{U_0}{\sqrt{\frac{\rho_b - \rho_a}{\rho_a} g D}} = \frac{U_0}{\sqrt{g'D}} \quad (2.7)$$

With Equation (2.7), Equation (2.6) can be simplified into:

$$\frac{z_m}{Fr D} = f\left(\frac{1}{Fr}, \frac{U_a}{\sqrt{g'D}}, \theta\right) \quad (2.8)$$

Here, the expression of $U_a/\sqrt{g'D}$ is much similar to the jet Froude number, which is referred as the nominal Froude number (NFr) in the present study. Equation (2.8) can then be expressed as:

$$\frac{z_m}{Fr D} = f\left(NFr, \frac{1}{Fr}\right) \quad (2.8)$$

similarly, the jet dilution can also be expressed as:

CHAPTER TWO

$$\frac{S_m}{Fr} = f\left(\frac{U_a Fr}{U_0}, Fr\right) = f\left(NFr, \frac{1}{Fr}\right) \quad (2.9)$$

Equations (2.8) and (2.9) shows that the mixing behavior of inclined dense jet can be affected by both the current and the initial discharge condition.

Figure 2.6 Schematic side view of an inclined dense jet discharge into co-flowing currents

The dense jet can be discharged at various angles to the ambient currents (e.g. cross-flow, co-flow and counter-flow). There are many previous studies on the topic of inclined buoyancy jets in cross-flows with various nozzle inclination angles. Tong and Stolzenbach (1979) experimentally investigated the buoyant jet inclined at 45° and 60° in a plane perpendicular to the cross-flow with NFr ranged from 0.19 to 1.44, by using the thermistor probe heated saline jets. Vertical profiles were also measured, and it was found that the dilutions were relatively insensitive to the upward inclination angle.

Roberts and Toms (1987) investigated the mixing characteristics of inclined and vertical dense jets discharged into a uniform cross flow of different speeds and directions. By analyzing the terminal rise height and minimum dilutions at the

CHAPTER TWO

terminal rise height, empirical prediction equations were proposed. They also recommended aligning the inclined jet in the direction of the current in order to obtain better dilution.

Lindberg (1994) performed experiments on dense jets with various inclination angles to the cross-flowing currents perpendicularly to the jet centreline. The cross-flow Froude number k_1Fr ranged from 0 to 10.6. By analyzing the relationship between k_1Fr and dimensionless dilution/terminal rise, they concluded that the cross-flow can be classified as weak flow for $k_1Fr < 0.7$, and strong flow for $k_1Fr > 0.7$. The study also showed that the ambient velocity has little effect on the rise height when $k_1Fr < 0.7$.

Gungor and Roberts (2009) studied the mixing characteristics of turbulent vertical dense jets in flowing currents by using three-dimensional laser-induced fluorescence (3DLIF) technique. The dilutions at the terminal rise height were investigated in detail. The experiments indicated that the dilutions at the terminal rise height increased as current speeds increased. At higher current speeds, the cross-sectional concentration profiles initially approached radial symmetry, but subsequently developed a kidney shape due to the formation of two counter-rotating vortices.

Lai and Lee (2014) examined the mixing behavior with perpendicular cross flows. By analyzing the geometrical features of 60° inclined dense jets with various jet Froude number and ambient to jet velocity ratio, the influence of k_1Fr was investigated. Their study showed that the mixing patterns could be classified as jet-dominated and cross-flow dominated regimes. The counter-

CHAPTER TWO

rotating vortices similar to Gungor and Roberts (2009) were also reported in their study.

Compared to co- and cross-flows above, studies on inclined dense jets in counter-flows are even fewer, and the reported mixing behavior is more complex with marked instabilities due to the reverse flow (Sivapragasam et al. 2014). Previous studies for non-buoyant jets in counter-flows gave substantial attention on the penetration depth (the definition of penetration depth x_p is referred in Chapter 5). Arendt et al. (1956) used a dimensional analysis to show that x_p was directly proportional to the velocity ratio k_I . Lam and Chan (1995) used an advection hypothesis to derive the relationship between normalised x_p and k_I , and compared their results with previous studies. Yoda and Fiedler (1996) reported that $x_p/D = 2.8k_I$. However, similar study for inclined dense jets in counter-flows again has not been reported in the literature so far.

2.4.2 Length scale method

Except for the dimensionless analysis with Fr and NFr , length scales methods were also employed to investigate the mixing characteristics of the dense jet in flowing currents. Pratte and Baines (1967) proposed that the length scale of $r_I D$ can be used to predict the centerlines of jets with different jet to ambient velocity ratios. The empirical correlation was summarized as Equation (2.10):

$$\frac{y}{r_1 D} = A \left(\frac{x}{r_1 D} \right)^m \quad (2.10)$$

CHAPTER TWO

where A is a parameter with the jet trajectory, and r_l is the square root of the momentum-flux ratio:

$$r_l = \sqrt{\left(\frac{\rho_0 U_0^2}{\rho_a U_a^2}\right)} \quad (2.11)$$

Broadwell and Breidenthal (1984) analyzed the overall mixing characteristics of non-buoyant jets in flowing currents and determined the coefficients of the correlation proposed by Pratte and Baines (1967). Their study concluded that $r_l D$ was the only global length scale needed for predicting the jet trajectory and dilution.

Hasselbrink (1999) studied the mixing characteristics of non-buoyant jets in cross-flowing currents by PLIF. Scaling laws were established to predict the dilution and jet trajectory for both near-field and far field. Another length scale $r_l^2 D$ was also employed by Keffer and Baines (1963) to estimate the trajectories, with r_l ranging from 6 to 10 under eight different nozzle diameters. Unfortunately, the above formulations were only valid for a specific range of velocity ratio. Therefore, the length scale method had not been used extensively for the analysis of the mixing characteristics of dense jets in currents.

2.4.3 Influence of density difference

When an inclined dense jet is discharged into a current, the density gradient may not be uniform along the vertical direction. Kikkert et al. (2007) compared the momentum flux between the positive and negative buoyant jets, and

CHAPTER TWO

concluded that the Boussinesq assumption was valid for small density differences between the jet and ambient water.

Bloomfield and Kerr. (2000) analyzed the entrainment between the upflow and downflow of the dense jet, and developed a theoretical model that can predict the height of a turbulent vertical dense jet in an arbitrary density gradient.

Baddour and Zhang (2009) studied the terminal rise height of the vertical dense jet. They found that the dimensionless centerline peak height was a function of relative density difference, and the Boussinesq's approximation was valid when the relative density difference was typically less than 0.003.

In summary, the geometric and dilution distribution of the dense jet in cross-flowing currents were investigated under various flow conditions. The effects of the current on the mixing characteristics were discussed, and empirical equations have been established based on different theoretic analysis. The influence of the jet inclination and flow direction were also systemically investigated. At the same time, there are few experimental investigations on the three-dimensional flow structures of the jet behaviors in co-flowing currents.

In addition to the experimental studies, Kikkert et al. (2007), Papanicolaou et al. (2008) and Cipollina et al. (2009) developed theoretical models to predict the mixing behaviours of inclined dense. Lee and Chu (2003) and Lai and Lee (2014) employed Lagrangian numerical models to study the behavior of dense jets in currents. Several integral models, such as CORJET (Jirka, 2004) and UM3 (Frick, 2004), are now available to predict the mixing characteristics of submerged inclined dense jets in currents. The governing equations involve the

CHAPTER TWO

conservation of mass, and momentum, buoyancy and scalar fluxes. The main assumption of these integral models is the Boussinesq approximation. Commercial tools, such as CORMIX, VISJET and VISUAL PLUMES are also extensively used to quantify the mixing characteristics of the dense jet in currents.

2.5 Turbulence Characteristics of Dense Jet

Turbulent flows can be commonly observed in many places, such as the smoke from a chimney, waterfalls, or the hot gas from the rocket launching. Turbulent flows are unsteady, irregular, random and chaotic. Therefore, the motion of the eddies in turbulent flow is hard to be predicted. Reynolds (1883) reported that the turbulence has an ability to transport and mix fluid much more effectively than a comparable laminar flow. He later established (Reynolds, 1894) that the flow is characterized by a single non-dimensional parameter, now known as the Reynolds number Re . The effectiveness of turbulence for transporting and mixing fluids is of importance to the mixing of the dense jet. When the brine and the ambient water are brought together to mix, it is generally desirable for this mixing to take place as rapidly as possible. The development of jet turbulence therefore had been investigated by many previous studies.

2.5.1 Different scale motions in turbulent flows

Many different techniques have been used to address different questions concerning turbulence and turbulent flows. The turbulent structures existing in a turbulent flow can be classified into small scale and large scale motions. The large scale motions are strongly influenced by the geometry of the flow (e.g.

CHAPTER TWO

boundary conditions), and they control the transport and mixing. The behavior of the small scale motions, on the other hand, is determined almost entirely by the rate at which they receive energy from the large scales, and also by the viscosity. The small-scale motions have a universal character, independent on the flow geometry. As discussed in Chapter 1, the low-frequency range of the turbulence kinetic energy spectrum represents the production range whereby the shear flows generate the larger scale eddies (motions) that contains bulk of the turbulent kinetic energy. Subsequently, the turbulent kinetic energy produced is transported through the energy cascade to smaller scale eddies in the inertial sub-range.

2.5.2 Energy spectrum for turbulent flows

Attempts to measure the jet energy spectra had mainly been focused in the simple case of non-buoyant jets. Many advanced measurement approaches, including hot-wire probes (stationary and flying), Laser-Doppler anemometers (LDA) and Particle Image Velocimetry (PIV) had been used to investigate the turbulent characteristics of buoyant jets. For example, Kotsovinos (1977) used LDA to quantify the velocity characteristics of a plane vertical buoyant jet with positive buoyancy. The turbulent structures in the transition range from jet-like to plume-like were investigated comprehensively. The results showed that the stream-wise velocity fluctuation increased with the Richardson number. For buoyant jets, the turbulent energy is directly affected by the buoyancy and discharge momentum. The spectrum should thus be different between negative and positive buoyant jets, as well as for inclined dense jets given the oblique angle between the two. It is also expected that the profile of turbulent energy spectrum is different between the jet-like and plume-like stages.

CHAPTER TWO

Papanicolaou (1984) used LDA to investigate the axial and radial velocity fluctuations of a vertical buoyant jet. The cross-sectional distribution of non-dimensional turbulent velocity fluctuations was found to be similar in the jet-like and plume-like ranges. In their study, the sampling duration was more than 100 seconds, and the sampling rate was as high as 200 to 1000 Hz.

Wang and Law (2002) examined the turbulence characteristics of axi-symmetric round buoyant jets in details including the turbulence intensities both in the axial and radial direction using PIV method. However, due to the limitation of laser pulsed rate, images were recorded at a relatively low sampling frequency of 5 Hz and the inertia sub-range of the turbulence spectrum, which extended to higher frequencies and thus required high-frequency measurements, was not resolved.

Deshpande et al. (2009) reported an experimental study to investigate the mean velocity and turbulence characteristics of a jet loop reactors. Measurements were made using PIV, LDA, and Hot Film Anemometry (HFA). However, only HFA and LDA results were used for spectral analysis. Their study showed that the appearance of the inertial sub-range can be delayed when close to the nozzle due to the convective flow generated from the nozzle. Fellouah and Pollard (2009) studied a turbulent round air jet by using the single hot wire technique with $Re = 6000, 10,000$ and $30,000$. The axial velocity spectra were investigated at different locations between $1 < x/D < 20$. Their study showed that the energy spectrum began to display the turbulence cascade when $x/D > 3$.

Integral modeling studies on the turbulence characteristics of inclined dense jets had also been performed in recent years. As mentioned in section 2.4, They reported significant discrepancies in the dilution predictions by these integral

CHAPTER TWO

models, which were attributed to the complex physics involved in the inclined dense jet such as detrainment and boundary effects that were not included.

Vafeiadou et al. (2005) used the software CFX with the Reynolds Averaged Navier Stokes (RANS) model and k- ϵ turbulence closure for the simulations of inclined dense jets. They reported some agreement of the dense jet characteristics compared to the laboratory measurements. However, the terminal rise height was significantly underestimated.

Oliver et al. (2008) conducted a detailed numerical investigation of inclined dense jets using the same numerical approach. They concluded that the simulations provide a more accurate representation of the mixing processes for the inclined dense jet compared to the integral models. Gildeh et al. (2015) used the RANS model with different turbulence closures as well as the Reynolds Stress models (RSMs) (LRR and Launder–Gibson models) to simulate the inclined dense jet. They concluded that the RSMs generally yield better results due to their ability to account for the anisotropic turbulence properties, but they require more computational resources.

More recently, Zhang et al. (2016) used the Large Eddy Simulations (LES) approach with both the Smagorinsky and Dynamic Smagorinsky subgrid models to investigate the mixing behavior for 45 ° inclined dense jets, using GCI as the grid convergence criteria targeting the dilution near the return point. They concluded that LES could reproduce the geometric behaviors of the inclined dense jet in a satisfactory manner. However, the dilution is underestimated which again implies that some aspects of the turbulence mixing are not correctly simulated.

CHAPTER TWO

Overall, experimental studies had shown that the turbulent energy can be directly affected by the buoyancy and discharge momentum, which further affects the mixing behavior of the inclined dense jet. However, experiments on turbulence characteristics of inclined dense jet have not been reported so far. Previous numerical studies also revealed a need to better understand the turbulence characteristics of the inclined dense jets in order to develop more accurate numerical models for the mixing of inclined dense jets.

2.6 Swirling Jets

Previous studies showed that the near field mixing of the inclined dense jet can be affected by the initial discharge characteristics. Therefore, the wide range of discharge flowrate due to the changing needs of desalination with climate fluctuations is a big challenge to the design of brine outfall. In addition, in order to avoid surface interactions, the outfalls need to be located in deeper water, which means an increase in the construction cost due to the stretched pipeline for brine discharging. Previous studies with non-buoyant jets showed that the swirl can affect the mixing behavior and suppress the axial velocity (Gibson and Younis, 1986; Champagne and Kromat, 2000). Based on the assessment, swirl valve for inclined dense jets was proposed. The related literature review is presented in the following.

2.6.1 Swirl generators

Swirl can be generated by different methods:

CHAPTER TWO

1. Rotating mechanical devices, such as rotating pipes or grids: the shear force on the contact surface imports a swirl motion to the fluid (Inoue and Su, 1983; Gallaire et al., 2004).
2. Tangential entry: the fluid injects into the cylindrical chamber or tube through tangential entry, and swirl is generated by its initial momentum (Ichimiya and Tsukamoto, 2010; Zhang et al., 2011; Guo et al., 2011)
3. Use of guide vanes or helical structure in axial tube flows, as shown in Figure 2.7 (Iyogun et al., 2011; Oberleithner et al., 2011; Beaubert et al, 2015; Huang and El-Genk, 1998; Ianiro and Cardone, 2011; Wannassi and Monnoyer, 2014).

Figure 2.7 Swirl generators (Wannassi and Monnoyer, 2014; Beaubert et al, 2015)

2.6.2 Swirl Number G

Previous studies were conducted to investigate the influence of the swirl intensity. Chigier and Chervinsky (1967) conducted theoretical and

CHAPTER TWO

experimental studies of turbulent swirling jets issued from an round orifice. They measured the mean axial velocity and static pressure profiles, and found that the mean tangential velocity was a function of the Swirl Number, G defined as the ratio of maximum mean tangential-to-axial velocity at the nozzle exit as shown in Equation (2.12):

$$G = \frac{W_0}{U_0} \quad (2.12)$$

Here, W_0 is the initial tangential velocity. Gupta et al. (1984) proposed that the degree of swirl also can be characterized by the non-dimensional Swirl Number S_R , representing the ratio of the axial flux of swirl momentum G_θ to the axial flux of axial momentum G_z multiplied by the orifice radius R :

$$S_R = \frac{G_\theta}{G_z R} \quad (2.13)$$

where,

$$G_\theta = 2\pi\rho \int_0^\infty r^2 \overline{v_0 w_0} dr \quad (2.14)$$

G_θ can also be written as:

$$G_\theta = 2\pi\rho \int_0^\infty r \left((\overline{w})^2 - \frac{(\overline{v_0})^2}{2} \right) dr \quad (2.15)$$

Takhar and Halim (1984) built a theoretical model to investigate turbulent buoyant swirling jets in quiescent ambient. The results revealed that the

CHAPTER TWO

behavior of the turbulent swirling buoyant jet depended solely on the initial Swirl Number (G) and Densimetric Froude number (Fr). For a given Froude number, a higher initial swirl number always led to a higher rate of spread. When the initial swirl number increased from 0.1 to 0.3, the spread width growth increased by approximately 33% and 90%, respectively. They also concluded that swirling jets can be classified for different swirl numbers: non-swirling jets ($G = 0$); weak swirling jets ($0 < G \leq 0.2$); moderate swirling jets ($0.2 < G \leq 0.5$) and strong swirling jets ($G > 0.5$).

2.6.3 Flow structure of non-buoyant swirling jets

The flow structure of swirling jets is more complex than non-swirling jets. Batchelor (1967) made an inviscid analysis on a stream of rotating fluid. He found that the swirling fluid which has an initial uniform axial velocity rotates as a rigid body (solid-body rotation). The vortex lines which are initially parallel to the axis gradually turn into spirals when passing through the contraction area. This process causes the axial velocity distribution to become non-uniform and induce a negative value of velocity gradient. Hence, a momentum deficit is generated, which suppressed the axial velocity.

Pratte and Keffer (1972) also concluded that two types of rotation can be observed in a swirling jet, namely solid body forced vortex rotation (Batchelor, 1967) and free vortex. The combination of the forced and free vortex was common in viscous fluids, and was known as the Rankine combined vortex. Downstream of the jet orifice, the swirl distribution rapidly decayed in the form of a Rankine vortex that lost its direct influence on the flow, hence the influence of the swirl was only constrained in the near field.

CHAPTER TWO

Similar findings in the velocity fields of swirling jets were observed by Gadalrab and Seo (2002). In their study, an analytical model was developed to explore the effect of swirl on the mean behaviors of the turbulent jet. The simulated results proved that the initial swirling degree significantly affected the time-averaged jet characteristics. Compared to a non-swirling jet, the growth of jet width was considerably larger, and the velocity field was suppressed. The core length also became shorter.

Park and Shin (1993) investigated the entrainment of a gas jet by using the schlieren flow visualization method. Their study showed that the swirl induced large-scale motions near exit region, which can enhance the entrainment of surrounding air. The study also demonstrated the processing vortex core (PVC) phenomenon, which is excited by strongly swirling jets ($G > 0.6$). Relations between the swirling intensity and entrainment were also explored in their investigation. With $G < 0.6$, the entrainment rate is fairly independent of the Reynolds number. With $G > 0.6$, an intense PVC was developed. With the effect of PVC, the entrainment rate increased as the Reynolds number increased. The entrainment rate also found to increase nearly linearly with the downstream distance in the initial region soon after the nozzle exit.

Gilchrist and Naughton (2005) carried out an experimental study on the effect of swirl on the growth-rate enhancement for incompressible non-buoyant jets using a miniature five-hole probe. The measurements of the velocity fields showed that the Swirl Number had an important effect on enhancement of the jet growth rate. However, the enhancement of growth rates only occurred when the swirl number exceeded a certain value ($G > 0.1$). When $G < 0.1$, there was no enhancement effect; while when $0.1 < G < 0.3$, the enhancement increased

CHAPTER TWO

almost linearly with the increasing of swirl. When the swirl number was sufficiently high, the vortex will break down which can further improve the enhancement. The results also indicated that the enhancement of the growth rate might saturate before the Swirl Number which was sufficient for vortex breakdown was reached. However, the exact swirl level defining the borders of these regions was not determined in their study.

2.6.4 Numerical studies on swirling jets

Detailed velocity measurements can directly illustrate the distribution inside the swirling jet and the mixing process involved. However, such measurements involve the use of high-resolution three-dimensional velocimetry techniques, which are typically complex. Moreover, further information on characteristic eddy length scales and temporal dynamics of coherent structures require the spatial correlation of the velocity measurements which is very difficult to achieve at this point. Thus, Computational Fluid Dynamics (CFD) simulations had also been explored in the literature for the analysis of swirling turbulent non-buoyant jets (Leschziner and Rodi, 1984; Kollmann et al., 2001; Ruith et al., 2003; McIlwain and Pollard, 2002; García-Villalba et al., 2007; Fröhlich et al., 2008; Stoellinger et al., 2017).

Hu et al. (2001) conducted a direct numerical simulation (DNS) of a swirling jet for the effects of swirl on the dynamics of axisymmetric and three-dimensional round non-buoyant jets. The numerical results showed that the evolution of flows in the early stage agreed well with the linear stability theory. In nonlinear stage, pairing of vortex rings and the outward movement of vortex pairs was observed due to the interaction of the primary ring and stream-wise columnar

CHAPTER TWO

vortex. The interaction enhanced the entrainment of the fluid. Their study also found that the shear of the tangential velocity has a significant influence on the dynamics of flows. The stream-wise vortical layer developed in the early stage will rapidly break down into small eddies under the joint stretch of the axial and tangential shear, which can significantly enhance mixing.

Maciel et al. (2008) experimentally and numerically studied the near-field characteristics of a turbulent non-buoyant jet with moderate swirl ($G \leq 0.5$) generated by a fully developed, axially rotating pipe flow. Measurements were made by using LDV and the time-resolved stereoscopic PIV techniques. LES was also applied to simulate the swirling jet. The experimental results showed that large-scale vortical structures with either double, triple or even quadruple-helix configuration existed at the pipe exit but rapidly break down or amalgamate after two jet diameters. LES results agreed well with the experimental observations, which revealed that large-scale vortical structures rapidly break down and amalgamate after two jet diameters. Smaller vortical structures were found further downstream after $8D$, which were usually inclined in the azimuthal–axial plane probably due to the action of the azimuthal shear. Both the experimental and numerical studies showed the rapidly break down of the large scale vortical structures, which can explain the enhancement of the mixing of swirling jets.

Zemtsop et al. (2009) conducted a numerical investigation on swirling and non-swirling turbulent jets by LES. Investigations of the suitability of various SGS closure models showed that the Dynamic Smagorinsky model and Dynamic Kinetic Energy model yielded similar predictions for swirling cases while the latter performed better for the non-swirling cases. The validated LES

CHAPTER TWO

method was used for studying the swirling turbulent jet flows with swirl numbers G ranging from 0 to 1. The dynamics of coherent structures were also demonstrated by analyzing the instantaneous flow fields provided by LES. The results revealed that swirl broke apart into two distinct structures: a helical mode and streamwise braid structures. The interaction of these structures generated unorganized turbulent motions that contributed to the enhancement of the turbulent mixing of the scalars. The mixing efficiency was employed as an indicator to quantify the amount of mixedness related to different swirl cases. Their investigation showed that swirl can increase the mixing efficiency by 21.7% when swirl number increased from 0 to 1.0.

Castro and Demuren (2017) used LES to simulate the behavior of swirling turbulent jets. The standard subgrid-scale Smagorinsky-Lilly model was used for all simulations. The numerical results showed a redistribution of turbulent energy due to the swirl effect on the anisotropic tensor of the Reynolds stress. When the swirl number increased, the suppression of the axial component occurred with corresponding amplification of the tangential component. The swirl was observed to change the characteristics of the flow field, including the increased jet spread, faster velocity decay, and decreased potential core length. Besides, the study also revealed that the axial turbulent intensity component increased with the swirl.

In summary, previous investigations on turbulent swirling jets showed that the swirl can increase the rate of entrainment of the jet. The rapid breakdown of the large-scale vortical structures and amalgamate were observed by many previous studies, which can bring a rapid increase in the jet spread, together with the higher spread width growth rate and higher decay rates for velocity and

CHAPTER TWO

concentration field. Moreover, the studies also revealed that the suppression of the axial velocity component occurred together with corresponding amplification of the tangential velocity. These observations showed the possibility for using the inclined swirling jet in the design for brine disposal, which can potentially cope with the wider range of discharging flow rate and enables shortening of the pipe length, thus reduces the construction cost for the brine disposal.

Nearly all the studies mentioned above were on non-buoyant turbulent swirling jets or gas jets. There were almost no investigations conducted on the inclined swirling dense jet in literature so far. Therefore, the mixing and turbulence characteristics of the inclined swirling dense jet will be explored in the present study. The capability of the two different numerical models of RANS and LES in simulating the mixing behavior of the inclined swirling dense jets will be evaluated.

Chapter 3

Experimental Methodology

3.1 PLIF and PIV systems

The fundamental principle of PLIF is that the intensity of the fluorescent light emitted from the fluorescent dye tracer is proportional to the dye concentration which enables the concentrations fields of liquid flows to be tracked (Law and Wang, 2000). In the early stage, LIF technique was used only for flow visualization, as the boundary of the flow can be clearly resolved in the images. Ferrier et al. (1993) investigated the quantitative statistics for jets in stratified ambient by using PLIF. However, only geometrical features were available in their study, the concentration fields were not included due to the limitations imposed by their instruments. After that, many studies were conducted using PLIF to quantify concentration distributions (Karasso and Mungal, 1997; Webster et al., 2003). These studies showed that PLIF was capable when proper laser intensity and calibration were applied.

In recent years, PLIF has been extensively used as an efficient method to obtain the concentration fields. Comparing to the point-based hot-wire measurements, the main advantage for PLIF is that overall concentration field can be obtained by a single measurement, which can provide abundant concentration information for analysis and visualization. Previous studies on the mixing behavior of dense jets such as Lai and Lee (2012), Shao and Law (2010) and Oliver et al. (2013b) reported the use of PLIF in the concentration

CHAPTER THREE

measurements. In the present study, PLIF method was selected for vertical and cross-sectional measurements of concentration fields.

The fundamental principle of PIV is that, the velocity field can be obtained by comparing the displacements of the seeding particles between two consecutively obtained images. The PIV technique was developed from the Laser speckle velocimetry (LSV) method. Pickering and Halliwell (1984) were the first to highlight the influence of the particle numbers for LSV measurements. They set PIV apart from LSV by reducing the concentration of particles which enabled the traces to be viewed individually. The method was later improved and became the early form of PIV technique.

With PIV method, the fluid is firstly discharged with neutrally buoyant particles. The particles are then illuminated by a thin light sheet and their motion is recorded in a continuous manner to provide a two-dimensional view of the flow velocity field. To determine velocity fields, algorithms are used to identify particles from frame to frame. PIV takes small windows (interrogation areas (IAs)) of the intensity field in the frame and correlates them with similar sized IAs in the next frame. The location of the IA with the maximum correlation determines the new position of the particles. Because the time step between frames is fixed, the velocity of the particle motion can be calculated. The main advantages of PIV technique are that the precise instantaneous fluid velocity field can be obtained. Besides, PIV measurement is nonintrusive comparing to hot-wire method.

Many previous studies on the investigation of the velocity field of the inclined dense jet were conducted by using PIV techniques such as Ferrari and Querzoli

CHAPTER THREE

(2010) and Lai and Lee (2012). Shao and Law (2010) also studied the mixing behaviors of 30° and 45° inclined dense jets in quiescent ambient by employing a combined PLIF and Particle Image Velocimetry (PIV) technique. The combined technique enables the simultaneous measurements for concentration and velocity fields, which can effectively eliminate the potential errors caused by repeating the experiments when measuring the concentration and velocity field separately.

3.2 Experimental Setup

Figure 3.1 shows a schematic view of the major components involved in the experimental setup. The experimental setup included: the source tank where source fluid was stored, the head tank and the nozzle for the jet discharging, the solenoid valve and flowmeter for controlling the discharge, the laser for generating the light sheet, the CCD camera and buffering system for capturing images and a towing carriage system which can be moved using a stepping motor at a constant speed along the flume for simulating the flowing current. A detailed description of each component is provided in the following sections.

3.2.1 Tank facility and discharge system

Experiments were performed in a towing flume with dimensions of 6.4 m (L) $\times$ 1.0 m (W) $\times$ 0.7 (H), at the Environmental Hydraulic Laboratory of Environmental Process Modelling Centre (EPMC)/NEWRI, Nanyang Technological University, Singapore. The flume walls were made of transparent glasses for observation and measurements. The tank was filled with tap water

CHAPTER THREE

and took approximately 1 hour to fill and empty. The source brine solution was prepared with specific amounts of sodium chloride and seeding particles or fluorescent dye tracer (for PIV or PLIF respectively). The water depth of the flume was kept constant by overflowing the excess water from the overflow pipe. The ceiling area above the water surface was masked with black cloth to eliminate the light reflection from the surface. A container with a volume of up to 60 liters was used to store the source fluid. A diaphragm pump was used to deliver the brine to the constant head tank.

Figure 3.1 Experimental setup with towing system

A discharge nozzle, which was attached to a constant head tank, was placed on top of the towing carriage. The constant head tank was elevated at 1.2 meters. Driven by the constant energy head difference, the source solution was discharged into the test tank/flume via the inclined discharge nozzle. The constant head tank was partitioned into two parts. The main chamber was used

CHAPTER THREE

to receive the brine solution from the source container during the experiment. When the main chamber was filled up, the excess brine solution overflow to the secondary chamber which later flew back to the source container. Therefore, the free surface of the source solution in the main chamber of the constant head tank was constantly kept at a certain elevation above the water surface in the glass tank/flume. The discharge flow rate was controlled by a solenoid valve and monitored by a magnetic flow meter thereby maintaining a uniform flow rate for the duration of the experiment. The details of each facility will be introduced in the following sections.

Figure 3.2 Schematic diagram of the glass flume

3.2.2 Glass flume

In the present study, the glass flume was used to conduct both the PLIF and PIV experiments. The bottom of the flume was elevated at 1.2 m above the floor and

CHAPTER THREE

the laser together with a motorized towing system was installed below the flume. This arrangement reduced the penetration length of the laser light and hence reduced the divergence of the laser beam as well as the attenuation of the light intensity in the water. A towing carriage was also installed at the top of the tank, which can be moved using a stepping motor at a constant speed along the flume. The carriages carried the camera and the constant head tank as well as the laser below the flume bottom to move simultaneously. Therefore, different flow velocities can be simulated by the towing system.

3.2.3 Discharge nozzle

The discharge nozzles were generally customized and modified from Perspex tubes with different inner diameters using hot air blower. The nozzle was connected to the pipe which attached to the constant head tank. Because the constant head tank was installed on the towing carriage, the nozzle can be moved along with the head tank and the camera on the upper edge of the flume. The position of the nozzle can be adjusted and fixed by fastening the screws. In experiments for cross-section observations, the distance between the laser sheet and the nozzle can be adjusted. Therefore, the cross-sections at different distances from the nozzle can be observed. The center of the nozzle tip was generally set larger than $0.5DFr$ to the bottom to avoid the Coanda attachment effect by the bottom boundary (Shao and Law, 2010). For dense jet in currents, the discharging nozzle was far away from the nozzle piece (as shown in Figure 3.3). In other words, the nozzle piece and the nozzle were not in the same plane. Therefore, no interference occurred between the nozzle piece and the dense jet during the towing process.

CHAPTER THREE

3.2.4 Pump

A membrane pump (China Nanfang Pump, GM0400PQ4MNN) was used to deliver the brine solution to the head tank. The membrane pump utilized two flexible diaphragms to draw in and expels fluids. The diaphragms worked as a separation wall between the air and the liquid. When the diaphragm moved up, the pressure inside the pump chamber decreased, and fluid was drawn into the chamber. When diaphragm moved down, the pressure increased due to the decreased volume of the pump chamber, and the fluid previously drawn in was forced out. Finally, the diaphragm moved up once again to draw fluid in and complete the cycle. In order to reduce the fluctuation of the flow rate due to the motion of the diaphragms, an air buffer chamber was connected to the membrane pump, which resulted in a steadier discharge flowrate. The efficiency of the membrane pump which can be up to 97% was much higher than the other types of pump. The working noise of the membrane pump was also low, which can work without lubrication or maintenance due to the simple structure. More importantly, for peristaltic pumps, the brine solution was not in direct contact with the pump chambers. Therefore, the pump was not corroded by the saline solution. The flowrate of the pump can be adjusted by the control panel with an increasing step of 1 ml/s, and the maximum flowrate can be up to 1200 ml/s. In the experiments, the flowrate of the membrane pump was generally set to be 10-20% higher than the discharge flow rate so that the free water surface in the constant head tank will not decrease.

CHAPTER THREE

Figure 3.3 Arrangement of the nozzle and nozzle piece

3.2.5 Flowmeter

The electromagnetic flow meter (YOKOGAWA-AXF015G) was installed between the constant head tank and the discharge nozzle to monitor the real-time discharge flowrate. The flow rate of the flow meter can be monitored by the centralized control panel that can control the flowrate of the membrane pump. The inlet flowrate to the constant head tank was set larger than the flowrate of the discharge nozzle to ensure that the feeding brine solution flowrate was sufficient to maintain a constant discharge water head. The stability of the discharge flowrate also can be obtained directly from the control panel.

3.2.6 Pulsed laser

A dual-cavity frequency-doubled pulsed laser (Dantec Dynamics, Class 4 Nd: Yag, DualPower 50-100 Laser) was adopted to illuminate the flow. The laser can emit green light (with the wavelength of 532nm) with a frequency-doubled laser. The laser head had two parallel cavities. Each of them was connected to a

CHAPTER THREE

separate power supply. However, the two cavities shared the same cylindrical light sheet optics. Through careful prior alignment, the two laser beams from the separate cavities were collinear and illuminate the same plane. The duration of each pulse could be as short as 5-8 ns by using the Q-switch, which produced a stroboscopic effect and froze the movement of the illuminated dye tracer and seeding particles. Therefore, the particles can be clearly demonstrated in each image without echo effect. The advantage of the dual-cavity laser was that the maximum frequency of the laser beams can be doubled when conducting PLIF experiments. In the present study, the pulse repetition rate of the double cavities can be up to 100 Hz. Besides, with double cavities, the time interval between two consecutive pulses from the two laser cavities can be extremely short, which can satisfy the requirements of PIV measurements.

3.2.7 Cameras

The Charge-Coupled Device (CCD) camera (Dantec Dynamics, SpeedSense 1040) was installed at the side of the flume, which can be moved along with the towing carriage and capture the flow illuminated by the laser light. The charge-coupled device in the camera can convert the light intensity into electrical charge. Once the light intensity had been converted, the accumulated charge was determined and digitized to produce an intensity value that was assigned to an appropriately located pixel, and the images can then be recorded. The SpeedSense 1040 camera had a maximum resolution of 2320×1726 pixels with a frame rate of up to 193 frames per second. During the PLIF measurements, the cameras were generally installed with low-pass filters. The fluorescent light with wavelengths around 570 nm needed to be separated with the 532nm laser light. Therefore, a 570nm low-pass filter was used for PLIF

CHAPTER THREE

experiments, and only the light emitted by the fluorescent dye can be captured by the camera. For PIV, 532nm low-pass filter was used in order to capture the direct reflected light from the seeding particles which had the same wavelength with the laser light. For both, the images were recorded in 8 bits grayscale and hence were black and white pictures, and the light intensity therefore ranged from 0-255 in decimal value.

3.2.8 Towing system

The towing system contained two different parts. Below the tank, a carriage was placed on the lower parallel precise linear guideways (HIWIN-HGH25) with optical gratings installed. The dual-cavity pulsed laser was installed in the carriage; On the top of the tank, another carriage was placed on the upper guideways, with the constant head tank placed on it. The camera and the nozzle were also attached to the upper carriage, thus they can be towed together. Both carriages were driven using a stepping motor at a constant speed (5-150 mm/s) along the flume for simulating the flowing current. The upper and lower carriages can be moved separately or simultaneously. The movement can be precisely controlled and monitored by a centralized control panel. Since the active turbulence induced by the dense jet discharge was typically much stronger than the ambient turbulence in the near field region, the latter was ignored in the experiments and the towed movement can be effectively used to simulate the action of the current (Tian and Roberts 2003, Saeedi et al. 2012). Similar approach was also reported by Kikkert, et al. (2010) and Abessi, et al. (2012).

CHAPTER THREE

3.2.9 Centralized control panel

The centralized control panel was used to control the towing system and also the flow rate of the pump. The control system was capable of: (1) adjusting the flowrate of the membrane pump which transferred the brine solution from the source container to the constant head tank; (2) displaying the readings from the flow meter and thus monitoring the real time discharge flow rate; (3) sending control signals to the motors of the towing systems and setting the speed, direction, displacement of the towing movements; (4) receiving the real time signal from the optical grating sensors on the platforms and therefore monitoring the positions of the towing platforms to which the camera and laser were attached; (5) plotting the time varied velocity and displacement. (6) indicating the fluctuations of the flowrate; and (7) setting turns of circle movements of the towing system.

3.2.10 Calibration box and grid

A calibration box with inner dimensions of 0.4 m (L) $\times$ 0.05 m (W) $\times$ 0.65(H) was prepared to facilitate the laser imaging techniques as well as determine the scale factor for PIV measurements. The calibration box (as shown in Figure 3.4) was made of transparent Perspex. A perspex board with a well-defined grid on the board surface was placed into the calibration box. The grid enabled the adjustment of the camera and laser, and also used as a reference object for the object-to-image scale factor that converted the image dimensions to the actual physical distances in the flow field, the scale factor was essential for both PLIF and PIV measurements. For PLIF experiments, the calibration box was filled with sample solution which contained the fluorescent dye. The calibration box

CHAPTER THREE

was then illuminated by the laser, and the light intensity was recorded along with corresponding concentration for calibration process. The box was installed on a steel carriage, which can move along the bottom of the flume. The box also can be rotated 90 degrees, which can facilitate the calibration for cross-sections measurements. The cleanliness of the bottom wall of the calibration box was vital to the calibration. Because the laser was shone from below, tiny dust and scratches will project shadows and significantly affect the calibration. Therefore, attention was paid when installing and cleaning the bottom. Special swab was used to clean the surface to avoid scratching the surface of the bottom.

Figure 3.4 Calibration box and calibration grid

3.2.11 Fluorometer

For the PLIF experiments, the concentration of Rhodamine dye in the brine solution and PLIF sample solution can be measured by the fluorometer (Turner Design-Model TD-700). The principle of the fluorometer is that the light

CHAPTER THREE

intensity emitted by the fluorescent dye increases with the dye concentration. The intensity of the fluorescence is recorded by the light detector, which can convert the signal into the digital readout (fluorescence signal) with the unit of RFU (relative fluorescence unit). Therefore, the raw data indicated on the screen is actually the light intensity. In order to obtain the corresponding concentration value, calibration needs to be conducted for the fluorometer. In the present study, a series of Rhodamine dye sample solutions with known concentrations, i.e. 2.5, 5, 10, 20, 30, 50, 100, 200, 250 and 500 $\mu\text{g/L}$, respectively, were prepared and the corresponding fluorescence signal was recorded by the fluorometer to obtain the calibration equation which was saved in the fluorometer. The sample solutions were prepared as the following. The solution of 500 $\mu\text{g/L}$ was prepared by adding 20mg of dye to 40 Litres of water. Subsequently, other solutions were prepared by diluting a specific volume of the 500 $\mu\text{g/L}$ solution.

The relationship between the fluorescence signal and the concentration (shown in Figure 3.5) may not be always in the linear range. The linear range begins with the smallest detectable concentration, and spans to an upper limit. A non-linear relationship can be observed at very high concentrations where the fluorescence signal does not increase at a constant rate in comparison to the change in concentration. For even higher concentrations, the “signal quenching” phenomenon occurs, for which the fluorescence signal decreases even though the sample concentrations continue to increase. Therefore, there is a limitation for the concentration of the samples used for calibration.

CHAPTER THREE

Figure 3.5 Relationship between fluorescence signal and concentration

3.3 Experimental Procedures

3.3.1 Planar Laser Induced Fluorescence (PLIF)

3.3.1.1 Testing procedures

PLIF technique was employed to obtain the concentration distribution of the inclined dense jet. The dye tracer, Rhodamine B, was added to the source brine. The dye can emit fluorescent light with a peak wavelength of 575 nm when excited by the 532 nm laser light. The fluorescent light then passed through the 570 nm low-pass filters and was captured by the cameras, which can convert into concentration field through calibrated relation. The detailed steps of the test are described as follows:

- (1) Preparation works for the setup and testing facilities, which included:
cleaning the tank walls; adjusting the nozzle accurately to the desired

CHAPTER THREE

discharge angle; turning on the laser and aligning the light sheet to the jet centre plane.

- (2) The tank was filled with filtered tap water. Meanwhile, the source solution with table salt (NaCl) and Rhodamine B was prepared. The density of the fluid was measured with the Anton Parr density meter and then the source solution was transferred to the mixing tank located at the top of the control unit. It took approximately 1 hour for the water in the tank to acquire the quiescent state.
- (3) The initial conditions, which included: source pipe diameter (D); source fluid density (ρ), ambient water density (ρ), the temperature (T), and the concentration of the source solution (c_0).
- (4) The main power of the laser system along with the cooling system of the laser was started 15 minutes before the experiment. Meanwhile, the shutters of the laser were closed.
- (5) Background calibration was needed for the camera so that the light intensity was evenly distributed in the image. The image window was adjusted to cover the full range of the jet. Any depositions on the bottom wall which may block the laser sheet in the measurement were cleared.
- (6) The source fluid in the storage tank was well mixed. After the density and concentration were measured, the source solution was pumped the header tank. Air bubbles were expelled from the pipelines by adjusting the solenoid valve to discharge with maximum flow rate.

CHAPTER THREE

- (7) Once the header tank was filled, the solenoid valve was turned on and discharge began. The valve was gradually adjusted until the flowrate reached the desired value. The laser, camera and the towing system were started 1-2 minutes after the discharge. The velocity of the towing carriage was recorded by the central control system.
- (8) When the desired number of images was captured, the laser and the camera stopped automatically. The images were stored in the buffer, which later were written into the hard drive of the computer. The data writing process took 10-15 minutes, which can be done by using software Flow Manager (DynamicStudio version 3.40.28). The images were reviewed and selected for the processing in the next step.

3.3.1.2 Calibration

The images obtained only recorded the information of fluorescent light intensity. In order to convert the recorded light intensity to the concentration field, calibration has to be carried out before the experimental tests. The calibration process was much similar to the calibration of the fluorometer, which included aligning the calibration box with the image window, and filling the box with the solutions of the fluorescent dye tracer of standard concentrations (e.g. approximately 0, 5, 10, 15, 20, 30, 40 and 50 g/L, respectively). The standard sample with known concentrations was measured by the calibrated fluorometer (Turner Design-Model TD-700). The dye concentration was kept within the range of 0~50g/L to minimize the attenuation effect of the laser. For each calibration solution, 30 images were recorded in 6 seconds by using the

CHAPTER THREE

software Flow Manager (DynamicStudio version 3.40.28). By averaging the 30 images, a mean image which represented the corresponding concentration can be obtained. Similarly, a series of sample images can be obtained corresponding to different concentrations and are shown in Figure 3.6.

Figure 3.6 Sample PLIF calibration images for different standard dye solutions

The grayscale value of each pixel in the pictures represented the intensity of emitted fluorescent light. The calibration enabled the conversion of the recorded light intensity to concentrations. Note that the light intensity slightly decreased as the concentration increased due to the attenuation effect (shown in Figure 3.7). The steps of the calibration are described as follows.

CHAPTER THREE

Figure 3.7 PLIF calibration linear relationship from a sample grid

- (1) The physical dimensions of the image were first determined by imaging a submerged grid with known grid size at the position of the laser sheet.
- (2) The water-filled calibration box was placed inside the tank and aligned with the laser sheet.
- (3) 30 images of the calibration box without Rhodamine-B dye were captured and averaged so that the background gray value could be determined. Each image was post-processed by a filtering algorithm which identified and replaced spurious gray value due to the presence of solid particles.
- (5) Rhodamine-B dye of known concentration and volume was added in step to the calibration box. In each step, 30 images were captured and averaged. The corresponding gray value of each grid was determined by a MATLAB code.

CHAPTER THREE

- (7) The grid-by-grid grayscale value could then be related to the Rhodamine concentration by a linear best fit line determined by MATLAB.

3.3.2 Particle Image Velocimetry (PIV)

The Particle Image Velocimetry (PIV) was applied to measure the velocity field and the turbulence properties of the inclined dense jet. The seeding particles were polyamide particles of diameter 50 μm which will scatter the laser sheet with 532 nm wavelength. The concentration of the seeding particles was approximately 0.1 g/L. The cameras were set to the double frame mode. The laser was synchronized with the cameras. Experiments were performed in a dark room in order to eliminate the influence of the background light. The main steps for PIV measurements are described in the following.

3.3.2.1 Testing procedures

- (1) Preparation same as that in 3.3.1.1 was first performed. The seeding particles were mixed evenly in the brine solution. The temperature and density of the source brine solution were adjusted to the desired value by adding a suitable amount of salt and density measured by a density meter.
- (2) The calibration board with known grid size was submerged in the tank and aligned with the laser sheet. The focus of the camera was correctly adjusted when a sharp image of the grid had been seen. Because each grid size on the grid is 2 cm $\times$ 2 cm, the physical size of the image window can also be determined, and the scale factor for PIV measurement can be set correspondingly.

CHAPTER THREE

- (3) A trial test was first conducted. The focusing of the camera was checked again by observing the instantaneous images of the particles. The light intensities between the two consecutive frames should be equally distributed. If the brightness of the two images differed obviously, the difference should be minimized by adjusting the light intensity of the two laser cavities.
- (4) The number of the particles should be within the required number. The displacement of the particles between two consecutive frames was compared. The “time between pulse” was increased/decreased if the displacement was too large/small.
- (5) The brine was discharged at the required flow rate. The jet was illuminated by the laser and images were captured for post-processing.

3.3.2.2 Post Processing

To determine the velocity of the particles, the two consecutive images were divided into a number of interrogation areas (IAs) which had the dimensions of 32×32 pixels in the present study (as shown in Figure 3.8). Each of these areas was cross-correlated from the first frame to the second frame to produce an average particle displacement vector. Repeating this for all the IAs can generate an instantaneous displacement vector map (as shown in Figure 3.9). Transforming these displacements in pixels to physical distances and dividing by the time interval, the displacement vector map can be converted into an instantaneous velocity map. To conduct the post-processing, the experimental

CHAPTER THREE

conditions such as the particle size, particle density and time interval should be carefully determined since the factors can affect the accuracy of the PIV technique.

- (1) Particle size: the size of the particles should be small enough so that they can track the flow motions accurately. On the other hand, the particle size should be big enough to scatter sufficient light and can be detected by the camera. In present post-processing, sub-pixel interpolation method was used to improve the accuracy. Therefore the particle size should be big enough such that it can take up 3 or 4 pixels when focused by the camera. Considering the above requirements, the particle size adopted in the present study was 50 μm .
- (2) The concentration of seeding particles: the concentration should be low enough so that the particles on the average can be separated from each other by particle-diameter equivalents. However, experimental results showed that too low seeding density biased the measured displacements and led to zero velocity value. It was found that at least 5 particles were required in each interrogation area to achieve reliable results (Shao and Law, 2010).
- (3) Noise level: The signal-to-noise ratio was used to evaluate the reliability of PIV results. The signal is represented by the number of correct vectors, while the noise is the number of random correlations vectors. In order to achieve a high signal-to-noise ratio, the particle displacement should not be too small. For an interrogation area size (side length, 32 pixels in this study) of length N , a maximum particle displacement of $N/4$ was recommended to

CHAPTER THREE

ensure a reasonable signal-to-noise ratio. Therefore, the time interval between two frames should be chosen properly to make sure that the maximum particle displacement in the area of interest was around one quarter of the side length of the interrogation area.

Figure 3.8 Two typical consecutive frames

Figure 3.9 Displacements of the particles between two consecutive frames

- (5) Similar to the PLIF procedures, the ambient water in the test tank was also left undisturbed for hours to achieve a quiescent condition. During the experimental runs, the recording was normally started after the discharge was initiated for 2 minutes.

CHAPTER THREE

(6) The function “Adaptive Correlation” in FlowManager was applied to PIV images to produce the instantaneous velocity vector maps. The “Moving Average Validation” was adopted during the adaptive-correlation analysis, while the individual vectors were compared to the neighborhood vectors. Spurious vectors were removed and replaced by the interpolation of three surrounding IAs. If the rejection percentage was high, we would typically repeat the PIV measurements by varying the PIV parameters until the percentage became acceptable. The function “Vector Statistics” was finally applied to obtain the time-averaged velocity vector map.

3.3.3 Other optical effects

3.3.3.1 Optical distortion

Optical distortion may exist in the processing of image capturing. The degree of distortion varies between different camera lenses and depth of the focus. The distortions can be generally classified into barrel distortion and pincushion distortion. As shown in Figure 3.10, both distortions are radially symmetric about the central point. Barrel distortion occurs when the image is captured when using wide angle lenses. Images are magnified and the magnification decreases with distance from the optical axis. Comparing to barrel distortion, pincushion distortion results in the opposite effect where image magnification increases with distance from the optical axis. The distortions can be corrected by the following equation (Ojanen,1999):

$$\vec{r}_c = (c_0 + c_1 \cdot \|\vec{r}_d\| + c_2 \cdot \|\vec{r}_d\|^2 + c_3 \cdot \|\vec{r}_d\|^3) \cdot \vec{r}_d \quad (3.1)$$

CHAPTER THREE

(a) Barrel distortion

(b) Pincushion distortion

Figure 3.10 Optical distortions: Barrel and pincushion distortion

Here, $\vec{r}_d$ is the distorted vector, $\vec{r}_c$ is the corrected vector, c_0 , c_1 , c_2 , and c_3 are the parameters determined by the camera lens and the experimental conditions. What's more, the distortion may also cause the outer parts of the image to be out of focus (Crowe, 2013). The out of focus may cause the light spread over a number of pixels thus change the distribution and the intensity of fluorescent light during the PLIF experiments. However, out of focus in the outer part of the image was negligible for the concentration measurements, because the concentration was converted through the calibrated light-concentration correlation. The influence can be cancelled by the calibration since the distortion was included in the calibration procedures.

Comparing to PLIF, the influence of distortion may be more dominant in PIV experiments. The seeding particles need to be well defined for applying the particle tracking algorithms, thus errors can happen due to out of focus in the outer part of the image. The distortion can also be more obvious when large depth of focus is applied. However, in the present experiments, small image

CHAPTER THREE

windows with shallow depth were used for measuring the velocity field and turbulence characteristics. The focus issue was therefore negligible. Besides, the “online-focus” calibration was also conducted, which can effectively eliminate the out of the focus issue before the PIV measurements were conducted.

3.3.3.2 Laser light attenuation

When the laser light passes through the solution which contains salt and fluorescent dye, the dye and salt molecules can absorb the photons of the laser. Since the initial dye/salt molecules absorb the photons, the photons reaching to fluorescent molecules that lie behind can be reduced. Therefore, the longer the light source travels through the solution, the more obvious attenuation can happen. The attenuation coefficient A_d for the irradiating light after traveling a certain distance of fluorescent dye can be calculated using the following equation (Law and Wang, 2000):

$$A_d = e^{-\alpha \int_0^l c(s)ds - \alpha' \int_0^{l'} c(s')ds'} \quad (3.2)$$

Here, c is the concentration. l and l' are the path lengths of the laser and fluorescence beams; α and α' are the extinction coefficients of the laser and fluorescence; s and s' are the distance along the direction of propagation for laser and fluorescence, respectively. Similarly, the attenuation coefficient also can be applied to water and salt, which can be expressed as A_w and A_s . The total of A_d , A_w and A_s is the attenuation coefficient of the solution.

CHAPTER THREE

When there are few fluorescent molecules in the tank, and the irradiating light intensity is very high, which means there are more photons to be absorbed by the dye/salt molecules. Increasing the laser power cannot further increase the amount of fluorescent light emitted from the dye. In other words, the output signal is not dependent on the input power level, and the attenuation is negligible. However, in most cases, the irradiating light intensity is relatively low, and the molecules number is large in the solution. Attenuation is then more likely to happen in the direction that light photons would be traveling. Regular attenuation is not problematic; water can evenly attenuate the light to some extent. As calibration is performed based on pixels and as the camera remains unmoved between experiment and calibration recording, attenuation by water is accounted automatically. The difficulty however, is due to the changing attenuation levels. When the light passes through the jet with complex fluid structures, attenuation level can be different in the different parts of the flow. Therefore, the attenuation is not constant, and quantitative concentration data can no longer be reliably attained. Prediction model must be developed to correct the attenuation. At the same time, accurately quantifying the attenuation for each image captured during an experiment is too difficult due to the turbulent nature of the flow. Oliver (2012) initially investigated the viability of using a 1 m wide calibration cell. The fluorescence signal along the width of the cell was mapped for various dye concentrations. It was found that using a cell width below 160 mm and dye concentrations below 300 $\mu\text{g/L}$ resulted in a negligible attenuation. This concentration was well within the limits required for a linear response. In the present study, the concentration of the Rhodamine B was controlled below 80-100 $\mu\text{g/L}$, which can satisfy the requirement of the negligible attenuation.

Chapter 4

Numerical Methodology

4.1 Introduction

Different from experimental measurements, numerical simulations with Computational Fluid Dynamics (CFD) approaches to obtain the results by generalizing the problem and solving the fluid mechanic equations. With the development of CFD theory and availability of powerful high-speed supercomputers, CFD has been greatly improved nowadays. The ongoing research develops software that improves the accuracy and speed of complex simulation scenarios such as turbulent flows. Experimental validations and field data are used in validation of such software. In this chapter, typical CFD models and approaches will be discussed

4.2 Composition of CFD model

For a typical CFD model, three main parts are included: a pre-processor, a main solver and a post-processor. The pre-processor includes the setting of the computational domain, physical parameters, mesh construction and initial and boundary conditions. The solver contains the discretized governing equations, discrete methods and algorithm. Besides, the solver also includes other related functions which can be used to control the computing speed and stability. The post-processor includes exporting the concentration contours, velocity vector

CHAPTER FOUR

maps, particle tracking, turbulence characteristics and other results (Versteeg and Malalasekera, 2007).

Among the three parts, the solver is the most important. Numerical methods including the finite volume, finite element, finite difference and other methods can be used by the solver. The Finite Difference Method (FDM) is the common and earliest used numerical method. The method solves the differential equations by approximating them with different equations, which was first proposed by Richardson (1910) and later was used in numerical simulations by Thom (1933). FDM is easy to implement. However, the method only can be applied to simply structured grids. Therefore FDM is not proper for simulating cases with complicated shapes. Moreover, in some cases with coarse grids, non-convergence may happen due to the errors brought by FDM, which can cause improper results.

Different from FDM, the Finite Volume Method (FVM) uses different methods to discretize the partial differential equations and surface integrals to calculate the physical terms surrounding the finite volume. Because the flux entering the volume is identical to that leaving the adjacent volume, these methods are conservative. FVM is now extensively used for flow problems. Many commercial CFD codes, such as Phoenix, Ansys CFX, Ansys CFX and Ansys Fluent have been developed. Other open source codes are also established based on FVM, such as OpenFOAM, which is used by the present study. FVM is more reliable than FDM since the flux is conserved. However, it is more demanding in computational resources.

CHAPTER FOUR

The Finite Element Method (FEM), which is similar to FVM, is also becoming popular with the development of the high capacity computer. FEM was initially developed for structural mechanics (Courant, 1943) and thereafter began to be adopted for fluid flows in the 1970s. Similar to FVM, FEM calculates based on the finite element. The difference is that FEM uses the approximation functions to calculate within the finite elements. Compared to FDM and FVM, FEM is more complicated in equations and has the highest computational complexity. However, FEM is more accurate and can be applied to unstructured grids (Diekmann et al., 1995). With the improvement of computing technique,

4.3 OpenFOAM

OpenFOAM (Open Source Field Operation And Manipulation), which is originally created by Weller et al. (1998), is a C++ toolbox with which the users can create their own applications for the solutions of CFD. Unlike earlier CFD software which commonly uses FORTRAN computer language for coding, OpenFOAM uses C++ and provides a more flexible environment for general use. OpenFOAM is currently released as an open source code under the protection of the GNU General Public License and maintained by OpenFOAM Foundation (Greenshields, 2015). The OpenFOAM provides different solvers which cover incompressible and compressible flows, steady and unsteady flows, multiphase flow, combustion, heat transfer and buoyancy-driven flows as well a series of turbulence closures with the RANS, LES and DNS approaches. OpenFOAM also provides a mesh generating tool “blockMesh” for the structured mesh generation. For objects with more complex geometry, the platform provides “snappyHexMesh” tool for modifying the meshes. Besides,

CHAPTER FOUR

OpenFOAM is also compatible with grids generated by third-party tools. There are now many utilities for pre- and post-processing in OpenFOAM.

As an open source and flexible platform, OpenFOAM provides the embedded utilities, and specific solvers. Users can modify or create utilities or solvers with C++ language. The parameters of the solvers can be directly changed in related files. New coded solvers and boundary types also can be added into the platform after compiling for special problems. A post-processing graphical user interface (GUI) is also provided by OpenFOAM, for users to check and visualize the numerical results.

4.4 Governing Equations

The governing equations can be found in many classical texts (e.g. Pope 2001). A general summary is given in the following. The movement of viscous fluid can be described by the continuity and momentum equations, which can be written as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \quad (4.1)$$

Momentum equation (in x , y and z directions, respectively):

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \quad (4.2)$$

CHAPTER FOUR

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \quad (4.3)$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \quad (4.4)$$

Here, p is the pressure; f is the external force (e.g. gravity force in z direction); u , v and w are the velocities in the x , y and z direction, respectively; τ represents the viscous stresses, which are proportional to the deformation rates of the control volume (Versteeg and Malalasekera, 2007):

$$\tau_{xx} = 2\mu \frac{\partial u}{\partial x} + \lambda \text{div}(u) \quad (4.5)$$

$$\tau_{yy} = 2\mu \frac{\partial v}{\partial y} + \lambda \text{div}(u) \quad (4.6)$$

$$\tau_{zz} = 2\mu \frac{\partial w}{\partial z} + \lambda \text{div}(u) \quad (4.7)$$

$$\tau_{xy} = \tau_{yx} = \mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \quad (4.8)$$

$$\tau_{xz} = \tau_{zx} = \mu \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \quad (4.9)$$

$$\tau_{yz} = \tau_{zy} = \mu \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \quad (4.10)$$

where λ is the second viscosity and μ is the dynamic viscosity. The influence of the second viscosity is typically small. Schlichting (1979) studied the second viscosity of gas flows and suggested $-\frac{2}{3}\mu$ as the value of λ .

For incompressible flows, the continuity equation (4.1) can then be written as:

$$\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + v \frac{\partial \rho}{\partial y} + w \frac{\partial \rho}{\partial z} = 0 \quad (4.11)$$

CHAPTER FOUR

Therefore, $\text{div}(u) = 0$. The term $\lambda \text{div}(u)$ can be deleted from equations (4.5), (4.6) and (4.7). Substituting Equations (4.5)-(4.10) to the Equation (4.2), the following equation can be obtained:

$$\begin{aligned} \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = & -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(2\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) + \\ & \frac{\partial}{\partial z} \left(\mu \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right) + \rho f_x \end{aligned} \quad (4.12)$$

The LHS of equation (4.12) thus can be further extended as:

$$\frac{\partial(\rho u)}{\partial t} + \rho \left(\frac{\partial(u^2)}{\partial x} + \frac{\partial(uv)}{\partial y} + \frac{\partial(uw)}{\partial z} \right) = \frac{\partial \rho u}{\partial t} + \rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) \quad (4.13)$$

For the RHS of Equation (4.12), similarly:

$$\begin{aligned} -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(2\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) + \frac{\partial}{\partial z} \left(\mu \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right) + \rho f_x \\ = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho f_x \end{aligned} \quad (4.14)$$

Therefore, with Equations (4.13) and (4.14), Equation (4.12) can be converted to:

$$\frac{\partial(\rho u)}{\partial t} + \rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho f_x \quad (4.15)$$

Similarly, the momentum equations in y and z direction can be converted to:

$$\frac{\partial(\rho v)}{\partial t} + \rho \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + \rho f_y \quad (4.16)$$

CHAPTER FOUR

$$\frac{\partial(\rho w)}{\partial t} + \rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho f_z \quad (4.17)$$

Equation (4.15) is then converted to Equation (4.18). Similarly, Equations (4.16) and (4.17) are converted to ones for the y, z directions, the equations together constitute the well-known Navier-Stokes (*N-S*) equation.

$$\frac{\partial \rho u}{\partial t} + \rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho f_x \quad (4.18)$$

Similarly, for scalar variable ϕ , the equation can be expressed as:

$$\frac{\partial \rho \phi}{\partial t} + \rho \left(u \frac{\partial \phi}{\partial x} + v \frac{\partial \phi}{\partial y} + w \frac{\partial \phi}{\partial z} \right) = \frac{\partial}{\partial x} \left(\Gamma \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(\Gamma \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left(\Gamma \frac{\partial \phi}{\partial z} \right) + s_\phi \quad (4.19)$$

where, Γ is the scalar diffusivity and ϕ is the scalar concentration.

In theory, all viscous fluid mechanic problems can be directly solved by the above *N-S* and scalar transport governing equations. The method Direct Numerical Simulation (DNS) is the approach based on directly solving the governing equations without any turbulence model. However, the computational cost of DNS is very high as it is very difficult to apply the equations directly in the simulations for turbulent flow. As referred in Section 2.5, the turbulent flow contains many small scale motions (Kolmogorov, 1941), which requires very small grids to resolve them resulting in a large number of grids. This is constrained by the present capacity of the computer resources. For the Reynolds numbers encountered in most industrial applications, the computational resources required by DNS would exceed the capacity of the

CHAPTER FOUR

most powerful computers currently available. Nevertheless, DNS is a useful tool to perform the experiments which is difficult or impossible to be conducted in the laboratory, allowing a better understanding of the physics of turbulence. Also, DNS is useful in the development of turbulence models for practical applications. The results of DNS can also be used for validation of the numerical results from turbulence models.

4.5 Turbulence Closures

As mentioned above, the high computational cost of the numerical model is mainly caused by the simulation of the small-scale motions which exist in turbulence flows. Therefore, many different models were proposed to solve the governing equations by simplifying the turbulent motions. (Launder and Spalding, 1974; Yakhot and Orszag, 1986; Shih et al., 1995, Girimaji, 2000). All the approaches base on one principle: the vector and scalar terms in a turbulent flow can be separated into the mean value and fluctuation value, which can be expressed by equations (4.20) and (4.21), respectively (Munson et al., 2013):

$$u_i = \bar{u}_i + u_i' \quad (4.20)$$

$$\phi = \bar{\phi} + \phi' \quad (4.21)$$

where $\bar{u}_i$ is the mean velocity and u_i' is the fluctuating velocity components, respectively. Similarly, $\bar{\phi}$ is the mean value of the scalar term and ϕ' is the fluctuation of the scalar factor. Substituting the above equations into the continuity and momentum equations for incompressible steady flow, the following equations can be obtained (Launder and Spalding, 1974):

CHAPTER FOUR

$$\frac{\partial \rho \bar{u}}{\partial x} + \frac{\partial \rho \bar{v}}{\partial y} + \frac{\partial \rho \bar{w}}{\partial z} = 0 \quad (4.22)$$

$$\begin{aligned} \rho \left(\bar{u} \frac{\partial \bar{u}}{\partial x} + \bar{v} \frac{\partial \bar{u}}{\partial y} + \bar{w} \frac{\partial \bar{u}}{\partial z} \right) = & -\frac{\partial \bar{p}}{\partial x} + \frac{\partial}{\partial x} \left(\mu \frac{\partial \bar{u}}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial \bar{u}}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial \bar{u}}{\partial z} \right) - \frac{\partial \rho \overline{u'u'}}{\partial x} - \\ & \frac{\partial \rho \overline{u'v'}}{\partial y} - \frac{\partial \rho \overline{u'w'}}{\partial z} + \rho f_x \end{aligned} \quad (4.23)$$

$$\begin{aligned} \rho \left(\bar{u} \frac{\partial \bar{v}}{\partial x} + \bar{v} \frac{\partial \bar{v}}{\partial y} + \bar{w} \frac{\partial \bar{v}}{\partial z} \right) = & -\frac{\partial \bar{p}}{\partial y} + \frac{\partial}{\partial x} \left(\mu \frac{\partial \bar{v}}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial \bar{v}}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial \bar{v}}{\partial z} \right) - \frac{\partial \rho \overline{u'v'}}{\partial x} - \\ & \frac{\partial \rho \overline{v'v'}}{\partial y} - \frac{\partial \rho \overline{v'w'}}{\partial z} + \rho f_y \end{aligned} \quad (4.24)$$

$$\begin{aligned} \rho \left(\bar{u} \frac{\partial \bar{w}}{\partial x} + \bar{v} \frac{\partial \bar{w}}{\partial y} + \bar{w} \frac{\partial \bar{w}}{\partial z} \right) = & -\frac{\partial \bar{p}}{\partial z} + \frac{\partial}{\partial x} \left(\mu \frac{\partial \bar{w}}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial \bar{w}}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial \bar{w}}{\partial z} \right) - \frac{\partial \rho \overline{u'w'}}{\partial x} - \\ & \frac{\partial \rho \overline{v'w'}}{\partial y} - \frac{\partial \rho \overline{w'w'}}{\partial z} + \rho f_z \end{aligned} \quad (4.25)$$

For Equations (4.23) to (4.25), the terms in the RHS, e.g. $-\frac{\partial \rho \overline{u'u'}}{\partial x} - \frac{\partial \rho \overline{u'v'}}{\partial y} - \frac{\partial \rho \overline{u'w'}}{\partial z}$ cannot be solved directly by the continuity and momentum equations.

Additional equations are necessary to obtain the solution of the equations.

4.5.1 Reynolds averaged Navier-Stokes (RANS) model

Replacing the body force term with gravity, Equations (4.22) to (4.25) can be expressed in Cartesian tensor form as the following (Tennekes, 1972):

$$\frac{\partial}{\partial x_i} (\rho \bar{u}_i) = 0 \quad (4.26)$$

$$\frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho \overline{u'_i u'_j} \right] + \bar{\rho} g_i \quad (4.27)$$

and the scalar transport equation:

CHAPTER FOUR

$$\frac{\partial}{\partial t}(\rho\bar{\phi}) + \frac{\partial}{\partial x_j}(\rho\bar{\phi}\bar{u}_j) = \frac{\partial}{\partial x_j}\left[\Gamma\left(\frac{\partial\bar{\phi}}{\partial x_j}\right)\right] + \frac{\partial Q_j}{\partial x_j} \quad (4.28)$$

The nonlinear term $-\rho\overline{u'_i u'_j}$ from the convective acceleration, which effects on the mean flow like a stress, is known as the Reynolds stress (Visscher and Andersson, 2011). The Reynolds stress term in Equation (4.27) is the main difficulty for closing the equation. Therefore, an approximation with Boussinesq hypothesis is applied to model the Reynolds stress term. The Reynolds stress is converted turbulent viscosity or eddy viscosity term μ_t as the following (Launder and Spalding, 1974):

$$-\rho\overline{u'_i u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \rho \delta_{ij} k \quad (4.29)$$

$$k = \frac{\overline{u'_i u'_i}}{2} \quad (4.30)$$

Here, k is the turbulent kinetic energy and δ_{ij} is the kronecker delta. For the scalar transport Equation (4.28), the scalar flux term is proportional to the gradient of the mean quantity. Therefore, Q_j can be represented by the following equation: (Munson et al., 2013)

$$Q_j = -\rho\overline{\phi' u'_j} = \Gamma_t \frac{\partial \bar{\phi}}{\partial x_j} \quad (4.31)$$

where Γ_t is the turbulent diffusivity. The ratio of momentum diffusivity and mass diffusivity can be expressed by Schmidt number (Sc_t), which can be presented as follows:

$$Sc_t = \frac{\mu_t}{\Gamma_t} \quad (4.32)$$

CHAPTER FOUR

Note that Schmidt number is the mass transfer equivalent of Prandtl Number (Pr_t), the value of Sc_t is approximate the same value with Pr_t for flow fluid. Therefore, through the RANS Equations (4.29) to (4.32), the main problem is converted to determining the value of the eddy viscosity μ_t .

Many different turbulence closures for RANS have been proposed to solve μ_t . The selected RANS closures are introduced in the following sections.

4.5.1.1 Standard k - ε closure

In the standard k - ε closure, the molecular viscosity is not taken into account, the flow is assumed to be fully turbulent and isotropic. The dissipation rate (ε) and the turbulence kinetic energy (k) are calculated from the following equations (Launder and Spalding, 1972):

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right) - \rho \varepsilon + G_k + G_b - Y_M + S_k \quad (4.33)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (4.34)$$

Here, G_k is the turbulence kinetic energy which is generated by the mean velocity gradients; G_b is turbulence kinetic energy generated by buoyancy; Y_M is the contribution of fluctuating dilatation in the compressible turbulence to the dissipation rate, which is normally neglected in the modeling of incompressible flows. S_k and S_ε are the source terms, which can be determined by the user.

CHAPTER FOUR

σ_k and σ_ε are the turbulent Prandtl numbers for k and ε , respectively. The expressions of G_k , G_b were as follows:

$$G_k = -\rho \overline{u'_i u'_j} \frac{\partial u'_j}{\partial x_i} \quad (4.35)$$

$$G_b = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right) g_i \frac{\mu_t \partial T}{Pr_t \partial x_i} \quad (4.36)$$

$$Y_M = 2\rho\varepsilon \left(\sqrt{\frac{k}{a^2}} \right)^2 \quad (4.37)$$

where a is the sound speed. With the expression (4.39) to (4.41), k and ε can be solved from Equations (4.33) and (4.34). The turbulent viscosity later can be determined by the following equation:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (4.38)$$

where C_μ is a constant which can be defined by the user.

4.5.1.2 RNG k - ε closure

In the standard k - ε model, the eddy viscosity is calculated by using a single turbulence length scale. However, the turbulent diffusion also can be affected by other scales of motions. In order to account for the effect of different scales of motions, RNG k - ε closure was developed by using the renormalization group (RNG) method (Yakhot and Orszag, 1986). The RNG k - ε closure is much similar to standard closure in terms of the transport equations (Yakhot et al., 1992):

CHAPTER FOUR

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (4.39)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \quad (4.40)$$

where α_k and α_ε are the inverse effective Prandtl numbers, and μ_{eff} is the effective viscosity calculated by RNG theory, which can be determined by the following equation:

$$d \left(\frac{\rho^2 k}{\sqrt{\varepsilon} \mu} \right) = 1.72 \frac{\frac{\mu_{eff}}{\mu}}{\sqrt{\left(\frac{\mu_{eff}}{\mu} \right)^3 - 1 + C_v}} d \left(\frac{\mu_{eff}}{\mu} \right) \quad (4.41)$$

R_ε can be determined by:

$$R_\varepsilon = \frac{c_\mu \rho \left(\frac{SK}{\rho} \right)^3 \left(1 - \frac{SK}{\varepsilon \eta_0} \right) \varepsilon^3}{1 + \beta \left(\frac{SK}{\rho} \right)^3} \frac{1}{k} \quad (4.42)$$

Here, η_0 and β are constant, S is the strain rate. Note that when $S = 0$, from Equation (4.42), R_ε shall be 0. Equation (4.40) then can be converted to Equation (4.34), which means that RNG closure can be converted to the Standard k - ε closure. The conversion also shows that RNG closure is more sensitive to strain rate. By inserting an additional term in the equation and considering the low Reynolds number effects, RNG closure therefore is more accurate in simulating the rapidly strained flows.

CHAPTER FOUR

4.5.1.3 Realizable k - ε closure

Different from the standard k - ε closure, the realizable k - ε closure uses a modified transport equation for the dissipation rate and also contains an alternative formulation for the turbulent viscosity. The equations for Realizable k - ε closure are as follow (Shih et al., 1995)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (4.43)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right) + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \rho \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \quad (4.44)$$

Similar to the standard k - ε closure, the turbulent viscosity is determined by Equation (4.45). Here, A_0 and A_s are constant. C_μ is no longer a constant but determined by Equation (4.46). The expression Ω is presented as the following:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (4.45)$$

$$C_\mu = \frac{1}{A_0 + A_s \frac{k U^*}{\varepsilon}} \quad (4.46)$$

$$U^* = \sqrt{S_{ij} S_{ij} + \tilde{\Omega}_{ij} \tilde{\Omega}_{ij}} \quad (4.47)$$

$$\tilde{\Omega}_{ij} = \Omega_{ij} - 2\varepsilon_{ijk} \omega_k \quad (4.48)$$

$$\Omega_{ij} = \bar{\Omega}_{ij} - \varepsilon_{ijk} \omega_k \quad (4.49)$$

where $\bar{\Omega}_{ij}$ is the mean rate-of-rotation tensor viewed in a rotating reference frame with the angular velocity ω_k .

CHAPTER FOUR

4.5.2 Large Eddy Simulations (LES)

The RANS model referred above requires relatively low computational resources. However, this method cannot predict the flow behaviour accurately for complex flow movements, especially for the small-scale motions in the turbulent flow. As introduced before, the (DNS) approach is the most accurate, while it has the highest computational requirements. Besides, DNS also needs very fine meshes to capture the smallest eddies. Therefore, the alternative numerical method is to combine the DNS and turbulence model.

Observation reveals that in turbulent flows, the transports of mass, momentum, energy, and other quantities are mainly affected by the large-scale motions which contain most of the energy in the flow that are strongly affected by the boundary and flow conditions. (Pope, 2002). Comparing to the anisotropic large-scale motions, the smaller scale motions are more isotropic and rarely affected the flow conditions. Therefore, the isotropic turbulence models can be applied for simulating the small-scale motions. In Large Eddy Simulations (LES), eddies are filtered into large and small scales by a low-pass filtering operation. The filtered large eddies are computed by the instantaneous Navier-Stokes equations, which is similar to DNS while small-scale motions are modeled by turbulence models based on the Boussinesq hypothesis which is similar to RANS closures. By combining direct and subgrid models, LES is expected to simulate the flow motions better than RANS. The computational requirements for LES are lower than DNS, although it is still much higher than RANS model.

CHAPTER FOUR

In LES, a filter is used to split up the variables into filtered and sub-filtered portion. The filtered continuity, momentum and concentration transport equations based on the instantaneous Navier-Stokes equations in Cartesian coordinates are as follows (Smagorinsky, 1963):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \tilde{u}_i) = 0 \quad (4.50)$$

$$\frac{\partial (\rho \tilde{u}_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho \tilde{u}_i \tilde{u}_j) = -\frac{\partial p}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j} \left(\mu \left(\frac{\partial \tilde{u}_i}{\partial x_j} \right) \right) - \frac{\partial \tau_{ij}}{\partial x_j} \quad (4.51)$$

Similarly, the scalar equations can be expressed as:

$$\frac{\partial}{\partial t} (\rho \tilde{\phi}) + \frac{\partial}{\partial x_j} (\rho \tilde{\phi} \tilde{u}_j) = \frac{\partial}{\partial x_j} \left(\Gamma \left(\frac{\partial \tilde{\phi}}{\partial x_j} \right) \right) + \frac{\partial Q_j}{\partial x_j} \quad (4.52)$$

$$\tau_{ij} = \rho \tilde{u}_i \tilde{u}_j - \rho \tilde{u}_i \tilde{u}_j \quad (4.53)$$

$$Q_j = -\rho \tilde{\phi} \tilde{u}_j - \rho \tilde{\phi} \tilde{u}_j \quad (4.54)$$

Where the tilde indicates spatially filtered variables. For equations (4.50) to (4.52), the main difficulty is to determine the value of the Reynolds stresses term τ_{ij} , which is related to the filter term. Therefore, different models have been proposed to closure the equations.

Similar to RANS closures, the subgrid-scale turbulence models are also based on the Boussinesq hypothesis. The turbulent stresses and scalar flux are calculated by subgrid-scale closure using the following equations: (Smagorinsky, 1963)

CHAPTER FOUR

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = 2\mu_t\tilde{S}_{ij} \quad (4.55)$$

$$Q_j = -\frac{\mu_t}{Sc_t} \frac{\partial \tilde{\phi}}{\partial x_j} \quad (4.56)$$

where μ_t is the SGS viscosity, τ_{kk} is the isotropic SGS stresses which can be added to the filtered static pressure term or neglected, Sc_t is the SGS turbulent Schmidt number, which has the value of 0.7 in the present study (Yimer et al., 2002; Law, 2006), and $\tilde{S}_{ij}$ is the strain rate tensor given by:

$$\tilde{S}_{ij} = \frac{1}{2} \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \quad (4.57)$$

Similar to the RANS closure, through Equations (4.55) and (4.56), the problem is converted into solving the SGS viscosity μ_t . Different subgrid closures which were proposed in the previous studies to determine the viscosity μ_t in LES simulations are introduced in the following sections.

4.5.2.1 Smagorinsky SGS model

The Smagorinsky SGS model was developed by Smagorinsky (1963) and was originally applied within the meteorological community. Later, Lilly (1967) further improved the model. Therefore, the Smagorinsky SGS model is also named Smagorinsky-Lilly SGS model. In the Smagorinsky SGS model, the subgrid-scale turbulent viscosity is calculated by the following equations:

$$\mu_t = \rho(C_s \Delta)^2 |\tilde{S}| \quad (4.58)$$

CHAPTER FOUR

$$|\tilde{S}| = \sqrt{2\tilde{S}_{ij}\tilde{S}_{ij}} \quad (4.59)$$

where C_S is the Smagorinsky constant which ranges from 0.1 to 0.2 and Δ is the grid scale. $\tilde{S}_{ij}$ is the resolved-scale strain rate, which is represented by same Equation of (4.57). However, the selection of constant C_S is empirical, which limits the application of the model.

4.5.2.2 Dynamic Smagorinsky SGS model

For Dynamic Smagorinsky SGS model, the parameter C_S is not defined by the users but determined by a dynamic procedure. The value of C_S is defined by a localized dynamic procedure (Germano et al., 1991). The Dynamic Smagorinsky SGS model was further modified by Lilly (1992) as follows:

$$C_S^2 = \frac{\langle L_{ij}M_{ij} \rangle}{2\langle M_{ij}M_{ij} \rangle} \quad (4.60)$$

$$L_{ij} = \widehat{\tilde{u}_j \tilde{u}_i} - \widehat{\tilde{u}_i} \widehat{\tilde{u}_j} \quad (4.61)$$

$$M_{ij} = \Delta^2 |\widehat{\tilde{S}}| \widehat{\tilde{S}_{ij}} - \widehat{\Delta^2 |\tilde{S}|} \tilde{S}_{ij} \quad (4.62)$$

Here, the angular brackets indicate a spatial averaging procedure of the directions of statistical homogeneity, and the caret indicates a spatial filtered quantity on the test-filter. With the similar method, the turbulent Schmidt number for the scalar transport equation can be represented by the following equations (Lilly, 1992)

CHAPTER FOUR

$$Sc_t = \frac{c_s^2}{c_\phi^2} \quad (4.63)$$

$$C_\phi^2 = \frac{\langle \varepsilon_j R_j \rangle}{\langle R_j R_j \rangle} \quad (4.64)$$

$$\varepsilon_j = \widehat{\tilde{u}_j \tilde{\phi}} - \widehat{\tilde{u}_j} \widehat{\tilde{\phi}} \quad (4.65)$$

$$R_j = \Delta^2 \left| \widehat{\tilde{S}} \right| \frac{\partial \tilde{\phi}}{\partial x_j} - \widehat{\Delta^2 \left| \tilde{S} \right|} \frac{\partial \widehat{\tilde{\phi}}}{\partial x_j} \quad (4.66)$$

4.5.2.3 Dynamic Kinetic Energy SGS model

The Dynamic Kinetic Energy SGS model (DKE) was proposed based on the assumed local equilibrium between the transferred energy through the grid-filter scale and the dissipation of kinetic energy at subgrid scales. Therefore, the subgrid-scale turbulence can be better simulated by accounting for the transport of the subgrid-scale turbulence kinetic energy. In the Dynamic Kinetic Energy (DKE) model, the transport of turbulence kinetic energy is calculated by the following equation (Kim et al., 1997)

$$k_{sgs} = \frac{1}{2} (\overline{u_k^2} - \bar{u}_k^2) \quad (4.67)$$

The value of k_{sgs} is obtained by solving the following transport equation:

$$\rho \frac{\partial \bar{k}_{sgs}}{\partial t} + \rho \frac{\partial \bar{u}_j \bar{k}_{sgs}}{\partial x_j} = -\tau_{ij} \frac{\partial \bar{u}_j}{\partial x_j} - C_\varepsilon \rho \frac{k_{sgs}^{3/2}}{\Delta f} + \frac{\partial}{\partial x_j} \left(\frac{\mu_t \partial \bar{k}_{sgs}}{\sigma_k \partial x_j} \right) \quad (4.68)$$

Here, the constant σ_k is equal to 1.0 and C_ε is determined dynamically by localized dynamic k-equation model (LDKM) (Kim et al. 1999). The subgrid-scale turbulent viscosity is thus computed by

CHAPTER FOUR

$$\mu_t = C_k \rho k_{sgs}^{1/2} \Delta \quad (4.69)$$

where C_k is determined dynamically by LDKM, and Δ is the filter-size which is calculated through the following equation

$$\Delta = V^{1/3} \quad (4.70)$$

where V is the volume of the computational cell. The SGS stress in Dynamic Kinetic Energy SGS model is calculated by

$$\tau_{ij} - \frac{2}{3} \rho k_{sgs} \delta_{ij} = -2\mu_t C_k k_{sgs}^{1/2} \Delta \bar{S}_{ij} \quad (4.71)$$

Chapter 5

Mixing Behavior of 45 °Inclined Dense Jets in Currents

5.1 Introduction

In the present study, we performed an experimental investigation of the 45 ° inclined dense jets in both co-flows and counter-flows using the laser imaging approach of Planar Laser Induced Fluorescence (PLIF). The objective was to report more quantitative details on the effect of the current on the mixing behavior of the inclined dense jet beyond what had been reported in the literature, so as to provide additional benchmarking data to aid in the physical understanding as well as the development of numerical models in the future. A series of experiments with a wide range of Fr and NFr were conducted. The analysis of the results covered the axial and cross-sectional concentration distributions, geometric characteristics of the trajectories, as well as centerline peak dilutions. The results were also compared with predictions from the integral model VISJET developed by Lee and Chu (2012). In the following, we shall first present the background of the problem before discussing the results obtained.

Detailed studies had been performed on brine outfalls in the last few decades, and a fully submerged inclined dense jet had been recommended as the design

*This chapter is written based on Jiang, M., Law, A.W.K. and Zhang, S. (2017). Mixing behavior of 45 °inclined dense jets in currents. Journal of Hydro-environment Research, 18: 37-48.

CHAPTER FIVE

configuration (Zeitoun et al. 1970, Roberts and Toms 1987). The mixing characteristics of the inclined dense jet in stagnant ambient had also been well studied both analytically and experimentally (Jirka 2004, Cipollina et al. 2005, Kikkert et al. 2007, Shao and Law 2010, Papakonstantis et al. 2011a, Lai and Lee 2012, Oliver et al. 2013, Jiang et al. 2014). Furthermore, with the advancement in computing technology, numerical studies had also been carried out in recent years with RANS and LES approaches to provide predictions of the mixing of the inclined dense jet (Vafeiadou et al. 2005, Oliver et al. 2008, Gildeh et al. 2015, Zhang et al. 2016).

In coastal waters, the inclined dense jet interacts with ambient currents during flood and ebb tides, and the interactions depend on the relative alignment of the dense jet discharge with the current direction as shown in the schematic diagram in Figure 5.1(a). In the figure, the coordinate system is set up such that the ambient velocity U_a is along the x -axis. θ is the inclined angle relative to the horizontal plane, and σ is the angle between the vertical projection of the dense jet axis and the longitudinal x -axis. We note that, in the literature of buoyant jets, the description of “co-/counter-flow” has been used to describe the situation when the dense jet discharge and ambient current are in the same/opposite direction respectively, while “cross-flow” refers to the two moving perpendicularly to each other. Jirka (2004) defined that the jet is in a longitudinal co-flow when $\theta = 0^\circ$ and $\sigma = 0^\circ$. The same definition was also adopted earlier by Chu et al. (1999) and Davidson and Wang (2002) for non-buoyant jets, and Davidson et al. (2002) for dense jets. However, for inclined dense jets in currents whereby $\sigma = 0^\circ$ but θ is nonzero, the definition of co-/counter-flow is not as straightforward. In the limit when $\theta = 90^\circ$, the discharge is perpendicular to the current and the flow condition becomes a

CHAPTER FIVE

cross-flow. Roberts and Toms (1987) referred to the experiments by Anderson et al. (1973) with $\theta = 45^\circ$ and 60° as inclined dense jets in co-flows, although strictly speaking the effect of the ambient current may be closer to that of a cross-flow with the steeper angle. Thus, the effect of the discharge angle can be complex and three-dimensional in actual configurations (Kikkert et al. 2010), and the description of co-/counter- and cross-flow should be taken for general indication only.

Very few studies had been performed on the mixing characteristics of inclined dense jets in flowing currents so far. As referred in Chapter 2, the dilution and geometrical features of dense jet in current with different inclined angles were investigated by the previous studies. (Roberts and Toms, 1987; Lindberg, 1994; Chu et al., 1999; Lai and Lee, 2014). The studies were mainly on the influence of the jet-to-ambient velocity ratios. Abessi and Roberts (2017) also conducted experimental studies on inclined dense jets discharged from multiport diffusers with flowing ambient water. The results showed that the rise height of the inclined dense jet decreased when the current speed increased, while the impact dilution increased. However, similar studies for 45° inclined dense jets in co-flows have not been reported so far.

Compared to co- and cross-flows above, studies on inclined dense jets in counter-flows are even fewer, and the reported mixing behavior is more complex with marked instabilities due to the reverse flow (Sivapragasam et al. 2014). Figure 5.1(b) shows a schematic diagram of the inclined dense jet issuing into a strong counter-flow. The dense jet penetrates a certain axial distance into the current until a stagnation point, and is then deflected backward to asymptotically approach the velocity of the counter-flow. The horizontal

CHAPTER FIVE

penetration distance from the nozzle to the jet edge and centerline are defined as the penetration depth x_p and x_{cp} , respectively, and S_{cp} is the dilution at x_{cp} . As mentioned in Chapter 2, previous studies for non-buoyant jets in counter-flows paid substantial attention to the penetration depth (Arendt et al., 1956; Lam and Chan, 1995; Yoda and Fiedler, 1996). However, similar study for inclined dense jets in counter-flows again has not been reported in the literature so far.

Figure 5.1 Schematic diagrams of an inclined dense jet issuing into: (a) co-flows and (b) strong counter-flows

CHAPTER FIVE

5.2 Experimental Procedures

The fundamental principle of PLIF is that, upon laser light excitation, the concentration of the dye tracer can be determined by the fluorescence light intensity captured by the camera with calibration. A detailed description of the calibration process can be found in Chapter 3 and Law and Wang (2000).

For the PLIF measurements, the laser sheet was projected through the glass bottom of the flume. The projection was either through the center plane of the inclined dense jet, or rotated 90° to illuminate the vertical cross-section. The source brine solution was prepared by adding dye tracer (Rhodamine B) and sodium chloride to the tap water in the source container. In order to avoid significant attenuation of the light intensity, the source dye concentration c_0 was limited to the range of 80-100 $\mu\text{g/L}$ determined by a fluorometer (Turner Design 1200). The density of the source solution was measured by a density meter (Anton Paar, DMA 35N) and controlled to be within 3.0% to 3.5% heavier than the ambient water. The temperature of both the ambient water and source solution was kept to be approximately $27.5 \pm 1^\circ\text{C}$.

Before the test, the dense jet was first allowed to discharge into the flume for a short time until a steady state was observed. Thereafter, the towing system was initiated and the nozzle moved along the flume length at a constant speed to mimic the co-/counter-flow. Image capturing by the camera at a frequency of 50 Hz typically began between 40 to 60 s after the initiation, and the images were subsequently transferred to the computer for processing. During the image capturing, the bottom frames of the tank would disrupt the light sheet when the discharge towed past. To remove the effect of the disruption on the data

CHAPTER FIVE

analysis, the images which contained the shadow of the frames were manually eliminated. Therefore, the total time period for the data analysis (maximum being 25 seconds) was somewhat reduced by this elimination period, which increased with the towing speed. For example, the elimination period was 0.2 and 2 seconds when the towing speed was 0.15 and 0.01m/s, respectively. Nonetheless, the elimination period was still small compared to the total time period.

5.3 Results and Discussion

In the present study, a wide range of dense jet and ambient velocities were tested with two nozzle diameters ($D = 5.8$ and 8.0 mm). Fr thus varied from 7.33 to 24.3, and NFr from -3.0 to 3.3. The detailed experimental conditions are shown in Table 1. The results are summarized as follow.

5.3.1 Jet trajectory

Sample time-averaged results from the experiments in co- and counter-flows are shown in Figure 5.2. Figures 5.2(a) and 5.2(b) show that the inclined dense jet in co-flows has a typical dense-jet-like rising stage and a plume-like descending stage similar to the stagnant ambient. For counter-flows, the dense jet also has a rising stage but is deflected backward in the descending stage by the opposing current. If the counter-flow is strong, the descending stage of the plume may not even be evident, and it is instead “enveloped” by the current (shown in Figure 5.2(d)) which behavior is distinctly different from that in stagnant ambient.

CHAPTER FIVE

Table 5.1 Experimental conditions

Test No.	D [mm]	U_0 [m/s]	U_a [m/s]	U_0/U_a	g_0' [m/s ²]	Re	Fr	NFr
F14-N1.6	5.8	0.65	0.08	8.6	0.38	3730	13.8	1.61
F14-N1.7	5.8	0.64	0.07	8.6	0.34	3730	14.4	1.68
F14-N2.2	5.8	0.63	0.10	6.3	0.38	3660	13.5	2.15
F14-N2.2	5.8	0.63	0.10	6.3	0.34	3660	14.2	2.24
F14-N3.1	5.8	0.63	0.15	4.3	0.38	3670	13.5	3.12
F14-N3.3	5.8	0.63	0.14	4.4	0.34	3670	14.2	3.26
F18-N2.4	5.8	0.86	0.10	8.6	0.38	4940	18.3	2.14
F18-N2.9	5.8	0.84	0.13	6.3	0.38	4840	17.9	2.86
F19-N2.0	5.8	0.95	0.09	10.3	0.37	5510	20.4	1.98
F19-N2.2	5.8	0.85	0.10	8.5	0.34	4940	19.1	2.24
F19-N3.0	5.8	0.83	0.13	6.3	0.34	4840	18.7	2.99
F21-N0.1A	5.8	0.98	0.00	211.0	0.37	5710	21.1	0.10
F21-N0.1B	5.8	0.98	0.01	162.3	0.37	5710	21.1	0.13
F21-N0.5	5.8	0.96	0.02	40.6	0.36	5620	21.1	0.52
F21-N1.0	5.8	0.98	0.05	21.4	0.37	5710	21.2	0.99
F21-N1.0	5.8	0.96	0.05	21.0	0.36	5600	21.0	1.00
F21-N1.5	5.8	0.98	0.07	14.2	0.37	5690	21.1	1.49
F21-N2.5	5.8	0.98	0.11	8.7	0.37	5710	21.2	2.43
F22-N0.3	5.8	1.01	0.01	80.7	0.37	5870	21.8	0.27
F22-N0.5	5.8	1.00	0.02	43.2	0.37	5840	21.6	0.50
F22-N2.7	5.8	1.07	0.13	8.5	0.38	6190	22.8	2.67
F24-N1.9	5.8	1.14	0.09	13.1	0.38	6610	24.3	1.85
F24-N2.8	5.8	1.06	0.12	8.5	0.34	6200	23.9	2.80
F14-N3.3	5.8	0.63	0.14	4.4	0.34	3670	14.2	3.26
F18-N2.4	5.8	0.86	0.10	8.6	0.38	4940	18.3	2.14
F18-N2.9	5.8	0.84	0.13	6.3	0.38	4840	17.9	2.86
F19-N2.0	5.8	0.95	0.09	10.3	0.37	5510	20.4	1.98
F19-N2.2	5.8	0.85	0.10	8.5	0.34	4940	19.1	2.24
F19-N3.0	5.8	0.83	0.13	6.3	0.34	4840	18.7	2.99
F21-N0.1A	5.8	0.98	0.00	211.0	0.37	5710	21.1	0.10
F21-N0.1B	5.8	0.98	0.01	162.3	0.37	5710	21.1	0.13
F21-N0.5	5.8	0.96	0.02	40.6	0.36	5620	21.1	0.52
F21-N1.0	5.8	0.98	0.05	21.4	0.37	5710	21.2	0.99
F21-N1.0	5.8	0.96	0.05	21.0	0.36	5600	21.0	1.00
F21-N1.5	5.8	0.98	0.07	14.2	0.37	5690	21.1	1.49

CHAPTER FIVE

Table 5.1 Experimental conditions (cont'd)

Test No.	D [mm]	U_0 [m/s]	U_a [m/s]	U_0/U_a	g_0' [m/s ²]	Re	Fr	NFr
F21-N2.5	5.8	0.98	0.11	8.7	0.37	5710	21.2	2.43
F22-N0.3	5.8	1.01	0.01	80.7	0.37	5870	21.8	0.27
F22-N0.5	5.8	1.00	0.02	43.2	0.37	5840	21.6	0.50
F24-N1.9	5.8	1.14	0.09	13.1	0.38	6610	24.3	1.85
F24-N2.8	5.8	1.06	0.12	8.5	0.34	6200	23.9	2.80
F7-N0.2	8.0	0.41	0.01	31.9	0.39	3250	7.3	0.23
F7-N0.4	8.0	0.41	0.02	18.1	0.39	3320	7.4	0.41
F7-N0.6	8.0	0.42	0.04	11.7	0.40	3380	7.5	0.64
F7-N1.2	8.0	0.41	0.06	6.4	0.36	3250	7.6	1.19
F7-N1.7	8.0	0.43	0.10	4.4	0.40	3440	7.6	1.72
F8-N0.2	8.0	0.43	0.01	32.2	0.36	3440	8.0	0.25
F8-N1.0	8.0	0.44	0.05	8.2	0.36	3470	8.1	0.99
F8-N1.5	8.0	0.44	0.08	5.4	0.36	3470	8.1	1.50
F8-N2.2	8.0	0.44	0.12	3.5	0.40	3470	7.7	2.17
F8-N2.4	8.0	0.44	0.13	3.3	0.40	3470	7.7	2.35
F8-N2.6	8.0	0.42	0.14	3.0	0.36	3380	7.9	2.62
F11-N0.4	8.0	0.62	0.02	27.1	0.39	4940	11.1	0.41
F11-N0.8	8.0	0.62	0.05	13.5	0.39	4950	11.1	0.82
F11-N1.2	8.0	0.63	0.07	9.1	0.39	5040	11.3	1.24
F11-N1.5	8.0	0.62	0.08	7.6	0.36	4940	11.6	1.53
F11-N1.9	8.0	0.62	0.10	6.1	0.36	4950	11.6	1.91
F11-N2.3	8.0	0.63	0.13	5.0	0.36	5040	11.8	2.34
F15-N0.4	8.0	0.82	0.02	35.0	0.39	6530	14.7	0.42
F15-N0.8	8.0	0.84	0.05	18.1	0.39	6670	15.0	0.83
F15-N1.3	8.0	0.81	0.07	11.8	0.35	6530	15.4	1.30
F15-N1.9	8.0	0.83	0.10	8.4	0.35	6670	15.7	1.88
F17-N0.2	8.0	0.93	0.01	72.6	0.39	7440	16.7	0.23
F17-N0.5	8.0	0.96	0.03	38.2	0.39	7680	17.2	0.45
F17-N1.4	8.0	0.96	0.08	12.7	0.39	7710	17.1	1.35
F17-N1.8	8.0	0.96	0.10	9.5	0.39	7710	17.1	1.80
F17-N2.3	8.0	0.96	0.13	7.6	0.39	7710	17.1	2.25
F20-N0.2	8.0	1.08	0.01	87.4	0.36	8650	20.1	0.23
F20-N0.9	8.0	1.12	0.05	22.3	0.37	8920	20.5	0.92
F20-N1.4	8.0	1.08	0.07	14.5	0.35	8650	20.4	1.41
F21-N0.2	8.0	1.10	0.01	87.9	0.34	8950	21.1	0.24
F21-N0.4	8.0	1.15	0.03	45.7	0.36	9250	21.5	0.47

CHAPTER FIVE

Table 5.1 Experimental conditions (cont'd)

Test No.	D [mm]	U_0 [m/s]	U_a [m/s]	U_0/U_a	g_0' [m/s ²]	Re	Fr	NFr
F21-N1.8	8.0	1.12	0.10	11.2	0.36	8950	20.8	1.86
F22-N0.2	8.0	1.23	0.01	125.6	0.37	9840	22.6	0.18
F22-N0.9	8.0	1.19	0.05	23.9	0.36	9540	22.2	0.93
F22-N1.5	8.0	1.15	0.08	15.3	0.33	9250	22.4	1.46
F17-N0.25	5.8	0.75	-0.01	-57.0	0.33	4303	17.1	-0.30
F17-N0.5	5.8	0.75	-0.02	-34.2	0.33	4303	17.1	-0.50
F17-N1.0	5.8	0.75	-0.04	-17.1	0.33	4303	17.1	-1.00
F17-N1.5	5.8	0.75	-0.07	-11.4	0.33	4303	17.1	-1.50
F17-N2.0	5.8	0.75	-0.09	-8.6	0.33	4303	17.1	-2.00
F17-N3.0	5.8	0.75	-0.13	-5.7	0.33	4303	17.1	-3.00
F22-N0.25	5.8	0.95	-0.01	-72.7	0.33	5378	21.8	-0.30
F22-N0.5	5.8	0.93	-0.02	-43.4	0.32	5378	21.7	-0.50
F22-N1.0	5.8	0.93	-0.04	-21.7	0.32	5378	21.7	-1.00
F22-N1.5	5.8	0.93	-0.06	-14.5	0.32	5378	21.7	-1.50
F22-N2.0	5.8	0.93	-0.09	-10.3	0.32	5378	21.7	-2.10
F22-N3.0	5.8	0.95	-0.13	-7.2	0.33	5378	21.7	-3.00

A MATLAB program was used to identify the jet trajectory as well as the geometrical features (e.g. z_m , x_m and the concentration e^{-I} boundary). The details of the program had been described earlier in Shao and Law (2010). Figure 5.3 shows the trajectories of the dense jets in co- and counter-flows (for $Fr = 21.1$ and 17.0, respectively). It can be observed that the trajectories are affected by NFr in different cases.

CHAPTER FIVE

Figure 5.2 Time-averaged concentration contours in flows with $NFr =$ (a) 0.5, (b) 1.0, (c) -0.5, (d) -1.0 and (e) -2.0

CHAPTER FIVE

Figure 5.3 Trajectories for inclined dense jets in (a) co-flows, $Fr = 21.1$ and (b) counter-flows, $Fr = 17.0$

CHAPTER FIVE

5.3.1.1 Co-flows ($NFr > 0$)

With co-flows, the non-dimensional centerline peak height z_m/FrD is plotted against NFr in Figure 5.4 (a). Two regimes can be clearly observed from the figure. When the co-flowing current was weak ($NFr < 1.0$), the mixing behavior was dense-jet-dominated, and z_m/FrD was nearly independent of NFr with a value of approximately 1.0 which was consistent with previous studies in stagnant ambient (Cipollina et al. 2005, Kikkert et al. 2007, Ferrari and Querzoli 2010, Shao and Law 2010, Papakonstantis et al. 2011a, Lai and Lee 2012).

The transition occurred when $NFr > 1.0$, where the co-flow became dominant and z_m/FrD decreased with NFr following the power-law relationship of $z_m/FrD = 0.95NFr^{-0.39}$. The correlation was less scattered when $Fr > 16$, implying that the effect of source volume flux became less significant beyond this range (Roberts and Toms 1987). It should be mentioned that $Fr = 16$ was not used as a threshold for the effect of source volume flux. The specific Fr threshold can not be addressed in details in this study due to the limited amount of data and their uncertainties.

The relationship of non-dimensional horizontal displacement of centerline peak x_m/FrD with NFr , plotted in Figure 5.4 (b), was similar to that for z_m/FrD with the two regimes. When $NFr < 1.0$, x_m/FrD was almost independent of the co-flow with a value of approximately 2.0 which was consistent with previous studies (Cipollina et al. 2005, Kikkert et al. 2007, Shao and Law 2010, Lai and Lee 2012).

The dense-jet-dominated regime transited to the co-flow-dominated regime after $NFr > 1.0$, where x_m increased notably with NFr following the power-law relationship of $x_m/FrD = 2.09NFr^{0.31}$. From the figures, it can also be observed

CHAPTER FIVE

that both z_m and x_m were somewhat under-predicted by VISJET, with average differences of -16.8%, -12.3%, respectively.

Figure 5.4 Relationship between NFr and: (a) z_m/FrD , (b) x_m/FrD

5.3.1.2 Counter-flows ($NFr < 0$)

With counter-flows, z_m/FrD is plotted against NFr in Figure 5.5(a) (note that NFr is negative due to the negative value of U_a). Two regimes can be identified in the figure, and the transition from the dense-jet- to counter-flow-dominated regime also occurred at $|NFr| = 1.0$. In the dense-jet-dominated regime ($-1 < NFr < 0$), z_m/FrD was nearly independent of NFr with a value of approximately

CHAPTER FIVE

1.0, which was consistent with previous studies for stagnant ambient (Cipollina et al. 2005, Kikkert et al. 2007, Ferrari and Querzoli 2010, Shao and Law 2010, Papakonstantis et al. 2011b, Lai and Lee 2012).

In the counter-flow dominated regime ($NFr < -1$), however, z_m/FrD decreased when NFr further decreased. The non-dimensional centerline penetration depth x_{cp}/FrD is plotted against NFr in Figure 5.5(b).

(a)

(b)

Figure 5.5 Relationship between NFr and: (a) z_m/FrD , (b) x_{cp}/FrD

The results showed that the penetrating distance x_{cp}/FrD strongly depended on NFr with an inversely-proportional relationship of $x_{cp}/FrD = 0.97NFr^{-1.4}$. The

CHAPTER FIVE

decreasing rate for x_{cp} based on this relationship was $0.77kD$, which was much less than that for horizontal non-buoyant jets in counter-flows with $x_p = 2.8kD$ reported in the literature (Lam and Chan 1995, Yoda and Fiedler 1996). Again it can be seen that z_m was under-predicted by VISJET by 11% on average. However, x_{cp} was well predicted by VISJET, with only 5% higher.

5.3.2 Cross-sectional concentration distributions

5.3.2.1 Co-flows ($NFr > 0$)

Figure 5.6 shows the vertical cross-sectional concentration contours at three different stream-wise distances to the nozzle tip ($s = 4D$, $16D$, and x_m). From the figure, the concentration contours were elliptical, with an increasing spreading in the lower half when $NFr < 1.0$.

In stronger co-flows with $NFr > 2.0$, the spreading in the lower half became much suppressed. The dimensionless vertical and horizontal cross-sectional profiles at the centerline peak are shown in Figure 5.7 where c is the concentration at the radial distance (r) being non-dimensionalised by the maximum concentration of the cross-section (c_c).

Figure 5.7(a) shows that the upper half of the inclined dense jet can be well predicted by the Gaussian profile. However, the lower half significantly deviated from the Gaussian profile beyond $s = 9D$, and the deviation increased further downstream.

In comparison, the lateral cross-sectional profiles in Figure 5.7(b) were symmetric and Gaussian distributed. The vertical and lateral profiles at the

CHAPTER FIVE

centerline peak under different NFr are shown in Figure 5.8. The results in the figure indicated that the co-flow had only limited influence on the distribution at the centerline peak.

Figure 5.6 Vertical cross-sectional concentration distribution
($Fr = 21.1$, co-flow)

CHAPTER FIVE

(a)

(b)

Figure 5.7 Cross-sectional concentration profiles at different stream-wise distances ($Fr = 21.1$ $NFr = 1.05$) in (a) vertical and (b) lateral directions

CHAPTER FIVE

Figure 5.8 Cross-sectional concentration profiles at centerline peak ($Fr = 21.1$)
in (a) vertical and (b) lateral directions

5.3.2.2 Counter-flows ($NFr < 0$)

In order to investigate the flow structure of the dense jet in counter-flows, vertical cross-sections at different locations along the jet trajectories ($s = 1D$,

CHAPTER FIVE

$4D$ and x_{cp}) were captured as shown in Figure 5.9. From the figure, the concentration contours were laterally symmetric similar to co-flows, while the upper half of the dense jet was wider instead. The exception was at $s = x_p$ when $NFr = -1.0$ whereby the lower half was wider, which might be due to the vertical descent of the plume in the relatively weak current.

Figure 5.9 Vertical cross-sectional concentration distribution
($Fr = 17.1$, counter-flows)

CHAPTER FIVE

The vertical cross-sectional profiles in Figure 5.10(a) showed that the lower half of the inclined dense jet can be well predicted by the Gaussian profile. However, the upper half deviated substantially from the Gaussian profile beyond $s = 8D$, which can be attributed to the unstable buoyancy fluctuation induced by the counter-flow from the experimental observation. Again, the behavior was opposite to the co-flow cases. In comparison, the lateral cross-sectional profiles in Figure 5.10(b) can be represented by the Gaussian profile symmetrically.

Figure 5.10 Cross-sectional concentration profiles at different stream-wise distances ($Fr = 17.1$ $NFr = -1.0$) in (a) vertical and (b) lateral directions

CHAPTER FIVE

The vertical and lateral profiles at $s = 7D$ under different NFr are shown in Figure 5.11. As seen from the figures, the counter-flow had only limited influence on the distribution.

(a)

(b)

Figure 5.11 Cross-sectional concentration profiles at $s = 7D$ in (a) vertical and (b) horizontal directions

CHAPTER FIVE

5.3.3 Growth rate

5.3.3.1 Co-flows ($NFr > 0$)

The growth rate of the dense jet's concentration e^{-1} width, b_c , in the vertical direction in co-flows with different NFr is presented in Figure 5.12. Initially, the upper b_c grew almost linearly with $b_c = 0.117 s/D$ near the nozzle which was similar to a momentum-dominated jet in stagnant ambient (Law and Wang 2000). The lower b_c was also similar within $s < 10D$. However, it then grew at a much faster rate beyond that, from 0.114 at $s = 10D$ to 0.430 at $s = 50D$. In Figure 5.12(c), the lateral b_c/D increased symmetrically in general with a reduced rate, which was smaller than that in the vertical direction. This was expected since the lateral shear entrainment between the dense jet and current was curtailed with lower relative velocities due to their alignment. The quantitative reduction in the lateral growth rate would therefore also be dependent on the current speed.

5.3.3.2 Counter-flows ($NFr < 0$)

The growth rates of b_c in the vertical direction with different NFr in counter-flows are presented in Figures 5.13(a) and 14(b), respectively. When $NFr > -1.5$, the upper b_c grew almost linearly with $b_c = 0.191 s/D$ before $s < 15D$, but faster afterward. Similarly, in weaker currents, the lower b_c/D grew almost linearly along the jet trajectory with a growth rate of 0.542, which was much larger than that in co-flows. With a strong current at $NFr = -2.0$, however, b_c also grew linearly within this initial region, but slower afterward instead due to the deflection of the jet trajectory. The lateral b_c/D shown in Figure 5.13(c),

CHAPTER FIVE

(a)

(b)

(c)

Figure 5.12 Growth of b_c in co-flows ($Fr = 21.1$): (a) upper half, (b) lower half and (c) left and right half

CHAPTER FIVE

Figure 5.13 Growth of b_c in counter-flows ($Fr = 17.1$): (a) upper half, (b) lower half and (c) left and right half

CHAPTER FIVE

from the figure, b_c expanded with a growth rate around 0.233, which was significantly larger than that in co-flows. Again this is expected due to the strong interactions between the dense jet and counter-flow.

5.3.4 Dilution and concentration decay

5.3.4.1 Co-flows ($NFr > 0$)

The dimensionless centerline peak dilution S_m/Fr for the inclined dense jet in co-flows is plotted against NFr in Figure 5.14. From the figure, when $NFr < 0.8$, S_m/Fr was nearly independent of NFr with values of ~ 0.5 , which were slightly less than the previous studies (Zeitoun et al. 1970, Shao and Law 2010, Papakostas et al. 2011b, Lai and Lee 2012). When $NFr > 1.0$, however, S_m/Fr increased with NFr , and reached up to 0.9 with $NFr = 2.3$.

Figure 5.14 Relationship between S_m/Fr and NFr (co-flows)

The decay of c_c along the dense jet's centerline is shown in Figure 5.15(a). From the figure, c_c decayed rapidly before $s < 10D$, and NFr significantly affected the concentration along the jet trajectory. Larger NFr also typically

CHAPTER FIVE

induced a higher decay rate, which can be attributed to the forced entrainment brought by the current. When $NFr = 0.48$, the mean decay rate from $s = 10D$ to $20D$ was 0.03, and it increased to 0.04 when $NFr = 3.2$. The rate was however much lower further downstream at $s > 20D$. Figure 5.15(b) shows the concentration decay under the same NFr but different Fr . The results demonstrated that concentration decay also depended on Fr , with smaller Fr decayed slightly faster.

(a)

(b)

Figure 5.15 Concentration decay along the centerline at: (a) $Fr = 17.1$ and (b) $NFr = 1.5$

CHAPTER FIVE

Finally, the concentration decays with different Fr and NFr are plotted together on a log scale and shown in Figure 5.16. From the figure, both Fr and NFr affected the decay rate. The dimensionless decay rate beyond $s > 2D$ followed the general relationship as $c/c_0 = k_f(s/D)^{-0.8}$, where k_f is the decay coefficient related to Fr and NFr

CHAPTER FIVE

(c)

Figure 5.16 Concentration decay along the centerline at various Fr and NFr
(co-flows)

5.3.4.2 Counter-flows ($NFr < 0$)

The dimensionless centerline peak dilution S_m/Fr is plotted against NFr in Figure 5.17(a) for counter-flows. When $NFr > -1.0$, S_m/Fr was slightly decreased as NFr increased due to the reverse flow, the dimensionless dilution was consistent with the previous studies (Zeitoun et al. 1970, Shao and Law 2010, Papakonstantis et al. 2011b, Lai and Lee 2012). When $NFr < -1.0$, however, S_m/Fr increased with the decreasing of NFr , and reached up to 0.8 when $NFr = -2.0$. The relationship also revealed that S_m/Fr fluctuated with the same NFr , which indicated that S_m/Fr was also affected by the source volume flux within the test range. Figure 5.17(b) shows the relationship between the dilution at the penetration point of S_{cp}/FrD and NFr . It can be observed that S_{cp}/FrD was dependent on NFr with an inversely-proportional relationship of $S_{cp}/FrD = 0.42NFr^{-1}$. Both S_m and S_{cp} were somewhat under-predicted by VISJET, the average differences were -17.1% and -7.2%, respectively.

CHAPTER FIVE

(a)

(b)

Figure 5.17 Relationship between NFr and: (a) S_m / Fr , (b) S_{cp} / Fr

As discussed above, the inclined dense jet in counter-flows can be deflected backward by strong currents. Therefore, the near field region with strong entrainment is relatively short in this case. To standardize the comparison, the radial concentration decay was considered instead. The radial distances r_m of the maximum concentration (c_m) point from the nozzle (shown in Figure 5.18)

CHAPTER FIVE

was first determined, and c_m/c_0 was plotted against r_m/D in Figure 5.19. Both the experimental results and VISJET predictions (Figures 5.19 (a) and (b)) showed that, with $NFr > -1.5$, the dilution for counter-flow was smaller than that in co-flows within $r_m < 20D$.

Figure 5.18 Concentric circles for evaluating the radial concentration decay rate

Beyond $r_m > 20D$, the dilution in stronger counter-flows with $NFr < -1.5$ was in fact higher than in co-flows. The comparison had an implication towards mixing zone compliance, that strong counter-flows would be undesirable within $\sim 20D$ of the discharge port but can enhance the compliance consideration beyond that.

CHAPTER FIVE

Figure 5.19 Concentration decay at different radial distances from the nozzle tip ($Fr = 17.1$) from: (a) Experiments, (b) VISJET

5.4 Conclusions

In the present study, the mixing behavior of the 45 °inclined dense jets in both co- and counter-flows were investigated in the laboratory using PLIF with a wide range of discharge velocities and flowing currents velocities. The results showed that the mixing behavior can be classified into dense-jet-dominated and co-/counter-flow-dominated regimes. In the dense-jet-dominated regime ($|NFr|$

CHAPTER FIVE

< 1.0), the dimensionless parameters were almost independent of NFr , the mixing characteristics only depended on Fr similar to the stagnant ambient, while in the co-/counter-flow-dominated regimes, the dimensionless parameters depended on NFr instead. The lateral growth rates of the inclined dense jets were symmetrically distributed in all cases. The upper half of the inclined dense jet followed the Gaussian profile in co-flows, while the lower half deviated substantially due to the buoyancy induced instability. The behavior was however exactly the opposite in counter-flows. In the co-flow-dominated regime, the height of the centerline peak was suppressed while the dilution was enhanced at that location. The results also demonstrated that both Fr and NFr significantly affected the concentration decay rate. Beyond $r_m > 20D$, the dilution in stronger counter-flows with $NFr < -1.5$ was higher than that in co-flows. Finally, the predictions by VISJET were found to generally underestimate the results in the order of 10-20% over the wide range of test conditions, which might overall be deemed satisfactory for engineering assessment given the high complexities involved.

Chapter 6

Turbulence Characteristics of Inclined Dense Jets

6.1 Introduction

The mixing characteristics of the inclined dense jet are governed by its discharge momentum and buoyancy. Since the direction of the vertical momentum and buoyancy of the dense jet are opposite in the ascending stage, the characteristics are not symmetrical about the centreline, which lead to the complex behaviours of the inclined dense jet reported in the literature, including the detrainment process (Kikkert et al. 2007). As mentioned in Chapter 2, many previous studies had been conducted on inclined dense jets with different inclination angles (Zeitoun et al., 1970; Roberts et al. 1997; Shao and Law, 2010; Lai and Lee, 2012), and the mixing behaviours of dense jets under different inclinations had been presented.

Quantifying the turbulence characteristics of inclined dense jets, which drive the underlying mixing, is also important towards the design objective. Turbulence in general encompasses eddies with a wide range of time and length scales. Pope (2002) described the typical profile of temporal turbulence energy spectrum. The lower frequency range of the spectrum represents the production range whereby the shear flows generate the larger size eddies that contain bulk of the turbulent kinetic energy. Subsequently, the turbulent kinetic energy produced is

*This chapter is written based on Jiang, M., Law, A.W.K. and Lai, A.C. (2017). Turbulence Characteristics of Inclined Dense Jets. Environmental Fluid Mechanics (submitted).

CHAPTER SIX

transported by the energy cascade to smaller eddies in the inertial sub-range. According to the Kolmogorov's theory (Kolmogorov 1941, Obukhov 1941), the turbulence energy spectrum of a high Reynolds number flow exhibits a $-5/3$ slope in the inertial sub-range. Beyond that, a steep slope of -3 might be observed for two-dimensional eddies, before a very steep slope of -7 at the highest frequencies range which represents the viscous dissipation into heat (Heisenberg 1948).

Attempts to measure the energy spectra of buoyant jets had been carried out for vertical discharges. The measurement approaches included the hot-wire probes (stationary and flying), Laser-Doppler anemometers (LDA) and Particle Image Velocimetry (PIV). The turbulent intensities and the energy spectrum of vertical jet have been studied by many previous studies (Kotsovinos, 1977; Papanicolaou, 1984; Law and Wang, 2000; Wang and Law, 2002; Deshpande et al., 2009; Fellouah and Pollard, 2009). We note that for buoyant jets, the turbulent kinetic energy is directly affected by the buoyancy and discharge momentum. The spectrum should thus be different between negative and positive buoyant jets, as well as for inclined dense jets given the oblique angle between the two. It can also be expected that the profile of turbulence energy spectrum is different between the jet-like and plume-like stages.

Besides experiments, modeling studies on inclined dense jets had also been performed in recent years (e.g. Palomar et al., 2012). In particular, with the advancement of computing technology, the use of numerical simulations with various Computational Fluid Dynamics (CFD) models to predict the mixing behavior is also becoming popular for engineering designs. Vafeiadou et al.

CHAPTER SIX

(2005) used the software CFX with the Reynolds Averaged Navier-Stokes (RANS) model and $k-\varepsilon$ turbulence closure to simulate the mixing behavior of inclined dense jets. They reported some agreement of the numerical results compared to the laboratory measurements, however the terminal rise height was significantly underestimated. Oliver et al. (2008) also conducted a detailed numerical investigation of inclined dense jets using the RANS model. They concluded that the simulations provided a more accurate representation of the mixing processes for the inclined dense jet compared to the integral models. Gildeh et al. (2015) used the RANS model with different turbulence closures as well as the Reynolds Stress models (RSMs) (LRR and Launder–Gibson models) to simulate inclined dense jets. They concluded that RSMs generally yielded better results due to their ability to account for the anisotropic turbulence properties, but required more computational resources. More recently, Zhang et al. (2016) used the Large Eddy Simulations (LES) approach with both the Smagorinsky and Dynamic Smagorinsky subgrid models to investigate the mixing behavior of 45° inclined dense jets, using GCI as the grid convergence criteria targeting the dilution at the return point. They showed that the simulations were able to reproduce the first order mixing characteristics of the inclined dense jet in a satisfactory manner. However, the dilution was underestimated which implied that some aspects of the turbulence mixing are not reproduced. Overall, the discrepancy in the predictions between the simulations and experiments in these studies demonstrated a need to further improve the understanding of the turbulence characteristics of the inclined dense jet. In particular, the study of the turbulent kinetic energy spectrum of the inclined dense jet will be useful in assessing the performance of the sub-grid models in LES so that more accurate simulations can be made in the future.

CHAPTER SIX

In the present study, we performed an extensive laboratory investigation to quantify the turbulence characteristics of 45° inclined dense jets using the PIV technique. The objective was to obtain benchmark data to guide high-resolution numerical simulations for dense jets. The PIV measurements were sampled at a relatively high frequency of 50 Hz which enabled the resolution of the turbulence kinetic energy spectrum including the inertial subrange. Furthermore, we also performed numerical simulations using LES with the Dynamic Smagorinsky sub-grid model and GCI grid convergence criteria reported recently in Zhang et al. (2016, 2017), for the discharge conditions adopted in the laboratory experiments. In the following, we shall first describe the experimental setup, and then the details of the numerical simulations. Finally, a discussion of the comparison between the experimental and simulation results, with a focus on the turbulence kinetic energy spectrum, will be given.

6.2 Experimental Procedures

Experiments were performed in a towing flume with dimensions of 6.4 m (L) $\times$ 1.0 m (W) $\times$ 0.7 m (H), as shown in Figure 3.2. The density of the source solution was determined by the density meter and controlled to be 2.9% to 3.5% denser than the ambient water. The temperature of both the ambient water and source solution were kept at $27.5 \pm 1^\circ\text{C}$. Two nozzle diameters of 5.8 mm and 8.0 mm were used, and the resulting Froude number varied from 11 to 35. The detailed experimental conditions are listed in Table 6.1.

As described previously, the PIV technique was used to measure the velocity field of the inclined dense jet. A dual-cavity pulsed laser (Dantec Dynamics,

CHAPTER SIX

Class 4 Nd: Yag, DualPower 50-100 Laser, pulse repetition rate up to 50Hz) was installed below the transparent bottom for the generation of laser sheets. A high-speed Charge-Coupled Device (CCD) digital camera (Dantec Dynamics, SpeedSense 1040) was used for the image capturing. The camera was set to double frame mode synchronized with the dual-pulse laser, and was able to acquire continuously for 25 s (in full resolution). The captured images were in 8 bits grayscale with a maximum resolution of 2320×1726 pixels. With the high frame rate of the camera, the maximum laser pulsing frequency of 50Hz imposed the limiting constraint for the upper Nyquist frequency to be 25 Hz as discussed in Law and Wang (2000). The seeding particles were polyamide particles with a size of $50\mu\text{m}$.

Table 6.1 Experimental conditions

Case No.	D [mm]	U_0 [m/s]	ρ_0 [kg/m ³]	ρ_a [kg/m ³]	g_0' [m/s ²]	Re	Fr
F1	8.0	0.53	1028	998.5	0.29	4359	11.0
F2	8.0	0.58	1028	998.5	0.29	4770	12.0
F3	8.0	0.98	1028	998.5	0.29	8060	20.3
F4	8.0	1.06	1028	998.5	0.29	8717	22.0
F5	8.0	1.45	1028	998.5	0.29	11925	29.6
F6	5.8	0.67	1033	998.5	0.34	4014	15.1
F7	5.8	0.75	1033	998.5	0.34	4494	16.9
F8	5.8	0.84	1033	998.5	0.34	5033	18.9
F9	5.8	0.86	1030	997.3	0.32	5138	20.0
F10	5.8	0.89	1032	997.1	0.34	5327	20.0
F11	5.8	1.08	1030	997.3	0.32	6452	25.1
F12	5.8	1.29	1030	997.6	0.32	7706	30.0
F13	5.8	1.51	1030	997.6	0.32	9021	35.0

For PIV, possible errors needed to be minimized at various stages of the measurement. The laser sheet should accurately shine through the jet centerline

CHAPTER SIX

plane and be carefully aligned with the jet discharge direction. A deviation of 1 mm between the jet center plane and laser sheet can cause a significant decrease in the values of the measured centerline velocity near the nozzle particularly with the small nozzle diameter of 5.8 mm in the experiments. Focusing the camera accurately was also found to be critically important for the turbulence measurements. Thus, before each experiment, the images were double checked to make sure that the particles in every interrogation window were clearly visible. In double frame mode, consecutive laser pulses were generated from two different laser sources. Therefore, the light intensities from the two laser pulses were also compared and aligned to ensure that the light intensity was almost equal between two consecutive images. In the present study, in order to further improve the accuracy as well as extend the time duration (number of images) for high-quality second order turbulence statistics, the images were not recorded in full resolution but with decreased 1000×780 pixels, so that the image buffer could store continuously for a longer duration of about 100 seconds. As a result, only part of the dense jet can be captured in one image window with the actual physical size of 118×94 mm. Hence, the camera and laser were moved in a programmable manner to different locations during the experiment, until the composite images covered the entire trajectory of the inclined dense jet. For adaptive correlation analysis, the image was divided into interrogation areas (IAs). The smallest IA size was mainly determined by the requirement of having 5-15 seeding particles in each IA window (Law and Wang, 2000). In the present study, the image was divided based on 32×32 pixels IAs, with each IA having a physical size of $\sim 3.8 \times 3.8$ mm. The time between two consecutive laser pulse was also different for different parts of the dense jet due to the different velocities. For the part of the dense jet with velocities faster than 1.0 m/s, the time between pulse of 800-1200 μ s was used,

CHAPTER SIX

while for velocities less than 1.0 m/s, 1200-2500 μs was used instead. Finally, to reduce noise vectors, the algorithm of both “moving average validation” and “peak validation” were used during the adaptive-correlation analysis. Spurious vectors were removed when found, and replaced by the interpolation of three surrounding IAs. However, if the rejection percentage was high (exceeding 5%), we would repeat the measurements by varying the PIV parameters until the percentage became acceptable.

6.3 Experimental Results and Discussion

6.3.1 Overall flow characteristics and jet trajectory

Figure 6.1 shows the contours of the time average velocities of the inclined dense jet from the experimental measurements with $Fr = 15$ and 30 (Tests F6 and F12, respectively). The centerline of the dense jet is plotted in the figure as a dashed line. From the contours, the discharge momentum dominated in the region near to the nozzle, and the behavior of the dense jet was jet-like with the velocity distribution nearly symmetrical about the centerline. Further downstream, the dense jet became asymmetrical with its lower half spreading wider due to the detraining by the buoyancy induced instability (Kikkert et al. 2007). Far from the nozzle and beyond the terminal rise location, the jet behavior became plume-like. We noted that the centerline trajectory of the inclined dense jet had been quantified in a number of previous studies (Shao and Law 2010, Lai and Lee 2012). The trajectories in the present study (Tests F6, F8, F11, F12 and F13) were normalised by FrD and plotted in Figure 6.2. From the figure, the normalised jet trajectories showed a general profile

CHAPTER SIX

independent of Fr , which was in agreement with previous observation e.g. Shao and Law (2010).

Figure 6.1 Average velocity field of dense jet under:

(a) Case F6, $Fr = 15$ (b) Case F12, $Fr = 30$

Figure 6.2 Normalised jet trajectories of 45° inclined dense jet

6.3.2 Axial and cross-sectional turbulence intensity

The normalised turbulence intensity of the stream-wise velocity along the trajectory of the inclined dense jet is plotted along the axial distance from the

CHAPTER SIX

nozzle in Figure 6.3 (for Tests F6, F9, F11, F12 and F13). It can be seen that the turbulence intensity decreased from the nozzle until approximately $0.5FrD$, and then began to increase reaching an averaged intensity of 0.3, which was close to the value of 0.27 obtained by Law and Wang (2000) for non-buoyant jets. This was consistent with the observation that the jet was momentum-dominated in the rising trajectory. Figure 6.4 illustrates the turbulence intensity of the radial velocity normal to the axis was extracted from the vertical plane which contains the jet centerline of the inclined dense jet. The intensity varied from 0.12 to 0.28 correspondingly. Figure 6.5 shows the cross-sectional distribution of the turbulence intensity (from Test F9). From the figure, the peak intensity appeared at the centreline, and the magnitude increased with the distance from the nozzle. The cross-sectional profile was not axi-symmetric. The turbulence intensity at the lower half of the dense jet was relatively higher than the upper half, which can be attributed again to the buoyancy-induced instability.

Figure 6.3 Stream-wise turbulence intensity along the centerline

CHAPTER SIX

Figure 6.4 Radial turbulence intensity along the centerline

Figure 6.5 Cross-sectional distribution of stream-wise turbulence intensity
(Case F9)

6.3.3 Energy spectrum and turbulent kinetic energy (TKE)

The turbulence kinetic energy spectrum was computed by the Fourier transform of the velocity time series. A total of 8 locations along the velocity centreline

CHAPTER SIX

($x/FrD = 0.3, 0.5, 0.9, 1.2, 1.5, 1.8, 2.1$ and 2.4) were selected for the spectral analysis. Their positions are shown in Figure 6.6. From Shao and Law (2000), the terminal rise of the 45° inclined dense jet occurs around $x/FrD = 1.7$. Hence, these eight locations included both the rising and falling stages of the inclined dense jet.

Figure 6.6 Locations of analysis of turbulent energy spectrum

Figure 6.7 shows the turbulence kinetic energy spectrum at the centreline peak (Point 6) with different Fr (from Tests F6, F9, F11 and F12). Each energy spectrum was averaged from three repeated tests (100-120 seconds for each test). The inclined dense jet was driven by the upward discharge momentum to reach this location, and it was traveling primarily in the horizontal direction just before the excess buoyancy force drove it downward. From the figure, the magnitude at the lower frequency range ($f < 1$ Hz) of the spectrum increased with the discharge velocity U_o and thus Fr . This was consistent with the trend

CHAPTER SIX

for the turbulence kinetic energy (TKE) as bulk of the turbulence energy should be contained in this production range.

Figure 6.7 Experimental turbulent energy spectrum at centerline peak with different Fr

Comparatively, the influence was negligible for higher frequencies ($f > 1$ Hz). The measured spectrum exhibited the inertial subrange of $-5/3$ slope approximately from 2 Hz to 20 Hz, which was similar to the study for vertical buoyant jets by Papanicolaou (1984). There also appeared to be a correlation

CHAPTER SIX

that the subrange began at a higher frequency with a lower Fr . At even higher frequencies (beyond 20 Hz), there were substantial noises due to the uncertainties of the PIV technique which led to a flattening white noise profile that was not physically meaningful (Foucaut et al., 2004).

Figure 6.8 shows the turbulence kinetic energy spectrum at the other locations from the nozzle (for Test F11). From the figure, the spectral profile was flat at the two locations of Points 1 and 2 near to the nozzle, and the inertial subrange cannot be distinguished. This was attributed to the fact that the two points were inside the potential core of the dense jet. Thus, the production of turbulence kinetic energy by the Kelvin-Helmholtz shear-induced eddies at the jet boundaries had not penetrated there yet. Similar conclusion was also drawn by Deshpande et al. (2009), which showed the appearance of inertial subrange delayed close to the nozzle due to the influence of the jet core.

The spectra at Points 3 and 4 showed the evolution of turbulence as the dense jet moved further away from the nozzle, with the slope for the inertial subrange progressively emerged. At Points 5 and 6 (centreline peak), the inertial subrange became clearly identifiable and spanned approximately from 2 to 20 Hz, which implied that the flow had reached the fully-developed state. It can also be observed that the spectral profile at lower frequencies increased slightly with the axial distance, which implied an increase in the turbulence energy production before the dense jet reached the centreline peak (Point 6). This observation was consistent with Fellouah and Pollard (2009) who measured for a turbulent round air jet.

CHAPTER SIX

10^{-2}

Figure 6.8 Experimental turbulent energy spectrum at different locations
(Case F11)

CHAPTER SIX

In the falling stage (Points 7 and 8), the turbulence energy production began to reduce and the magnitude of the spectral profile at the lower frequencies also decreased. At all locations, the limit of the turbulence kinetic energy spectrum was constrained by the temporal PIV frequency of 50 Hz and the corresponding Nyquist frequency of 25 Hz (Law and Wang, 2000) as discussed above. Thus, the spectral profile near and beyond 25 Hz was unreliable and had a typical random noise-like behaviour.

6.4 Large Eddy Simulations

6.4.1 Previous LES modeling work on 45 ° inclined dense jet

As discussed previously, Zhang et al. (2016, 2017) simulated the mixing of 45 ° inclined dense jets by means of the LES approach, with both the Smagorinsky and Dynamic Smagorinsky sub-grid scale (SGS) models using GCI as the grid convergence criteria. Their analysis included the jet trajectory, jet spread, eddy structures and turbulence intensity. Their results showed that LES was able to predict the geometric characteristics of the inclined dense jet in a satisfactory manner. At the same time, the dilution was underestimated, which was grossly attributed to the stratification effects on the convective mixing inside the sub-grids. In the present study, the LES simulations were repeated for the specific discharge conditions as in the experiments using the Dynamic Smagorinsky sub-grid scale (SGS) model and GCI grid convergence criteria. The details of the LES simulations are briefly given in the following. More details can be found in the original references of Zhang et al. (2016, 2017).

CHAPTER SIX

6.4.2 LES simulations

6.4.2.1 Numerical Setup

In the present study, the equations were discretized using the finite volume method, and simulations were performed using the open source platform OpenFOAM (Jasak 2009). The implementation of the governing equations in OpenFOAM was carried out with the turbulence solver, twoLiquidMixingFoam. It is a standard solver for the mixture flow of two incompressible fluids, and has been used and validated in many studies (Gruber et al. 2011, Lai et al. 2014, Zhang et al. 2015).

6.4.2.2 Physical parameters

To evaluate the grid convergence, a series of mesh scheme were configured and tested for simulating the first order average characteristics first. After that, the selected grids were further tested for simulating the turbulence characteristics of the inclined dense jet. The conditions were identical to the physical parameters used in the present experimental study, which are shown in Table 6.1. The density of ambient water was 997.3 to 998.5 kg/m³. The fluid diffusivity and viscosity were 10⁻⁹ m²/s and 10⁻⁶ kg•m⁻¹s⁻¹, respectively. Two nozzle diameters of 5.8 and 8.0 mm were used.

6.4.2.3 Computational domain

Figure 6.9 shows a schematic diagram of the computational domain, where the origin of Cartesian coordinates was set to the center of the discharge nozzle. The

CHAPTER SIX

distances from the port to the surface (H), back (L_1), front (L_2), left (W_{d2}) and right sides (W_{d1}) boundaries for each case were always larger than $4DFr$, $1DFr$, $8DFr$, $4DFr$ and $4DFr$, respectively, which can ensure the full submergence of the dense jet (Jiang et al. 2014). The distance to the bottom boundary (h) was larger than $0.5DFr$, which was sufficient to avoid the Coanda effect (Shao and Law, 2010).

Figure 6.9 Computational domain

6.4.2.4 Computing conditions

The left, right, back and front boundaries of the computational domain were set to zero gradient open boundaries, while the bottom used a no-slip condition and the top surface used a free slip condition. An uniform velocity field with 5-10% turbulence intensity was applied to the nozzle outlet surface, while wall boundaries were applied to the other surface of the nozzle. Other corresponding computational conditions were specified in Table 6.2. The divergence term and

CHAPTER SIX

the Laplacian term were computed using upwind scheme, while the discretization of the temporal term was carried out by a second order implicit backward scheme. In order to ensure the stability of the computation, the automatic time step was selected and the convergence criterion for the velocities simulation was set to 10^{-6} .

6.4.2.5 Computing hardware

The simulations were performed with parallel computing at the High-Performance Computing Centre at the Nanyang Technological University. The calculations of each case were decomposed using the technique of domain decomposition and computed with parallel executions using 16 or 96 CPU cores. The time of simulation duration, t_s , from the beginning of the simulated discharge was from 60s to 130s to ensure the flow was fully-developed and had reached steady state. The real-time computing duration for most of the LES simulations ranged from 8-18 days as shown in Table 6.2.

6.4.2.6 Grid scheme

The computational domain was discretized with a structured mesh. The spacing of the grid gradually increased from the center of the nozzle to the boundaries. In addition, for the region which contained the potential core of the dense jet, a double refinement was carried out. In the present study, the size of the nozzle was much smaller than the flume. Therefore, in order to connect the grids between the nozzle and the flume smoothly, a tool of OpenFOAM, namely snappyHexMesh was used to generate the grids attached to the discharge tube.

CHAPTER SIX

In theory, if the grid spacing for LES is sufficiently small into the inertial subrange, the sub-grid model would then be able to represent the turbulence within the cell in a near exact manner. In the present conditions, however, the Kolmogorov length scale was estimated to be about 2.4×10^{-5} m. This requirement was too demanding when considering the computing resources available to this study. Thus, similar to Zhang et al. (2015), the method of Grid Convergence Index (GCI) (Celik et al. 2008) was used instead for the gross grid convergence. The first order key parameters selected for GCI evaluation were the centreline peak velocity and centreline peak height of the inclined dense jet. In addition, the effect of grid size for the simulation of the turbulence spectrum beyond GCI was also examined through different mesh schemes. Three different meshes with the minimum grid spacing of 3.0×10^{-3} , 2.2×10^{-3} and 1.1×10^{-3} m were used. The corresponding grid numbers were 8, 10 and 16 million, respectively (shown in Table 6.2).

Table 6.2 Numerical conditions

Test No.	D [mm]	U_0 [m/s]	ρ_0 [kg/m ³]	ρ_a [kg/m ³]	g_0' [m/s ²]	Re	Fr	Number of computing CPU core	Number of grids points (million)	Run time (days) for 120s
N1A	8.0	0.53	1028	998.5	0.30	4240	11.0	96	8	8
N1B	8.0	0.53	1028	998.5	0.30	4240	11.0	96	10	12
N6A	5.8	0.66	1030	997.6	0.32	3842	15.1	96	16	18
N9A	5.8	0.86	1030	997.3	0.32	5046	20.0	16	8	12
N9B	5.8	0.86	1030	997.3	0.32	5046	20.0	96	10	12
N9C	5.8	0.86	1030	997.3	0.32	5046	20.0	96	16	17
N11A	5.8	1.08	1030	997.3	0.32	6235	25.0	16	10	10
N11B	5.8	1.08	1030	997.3	0.32	6235	25.0	96	16	17
N12A	5.8	1.51	1030	997.6	0.32	8737	30.0	96	10	12
N12B	5.8	1.51	1030	997.6	0.32	8737	30.0	96	16	18

CHAPTER SIX

The numerical conditions were as follow. Cases N1A and N1B simulated Experimental Test F1 ($Fr = 11$, $D = 8\text{mm}$) by using two different grid spacing with grid numbers of 8 and 10 million, respectively. Case N6A simulated the Test F6 ($Fr = 15$, $D = 5.8\text{mm}$) with grid number of 16 million. Cases N9A, N9B and N9C simulated Test F9 ($Fr = 20$, $D = 5.8\text{mm}$) with 8, 10 and 16 million, respectively, and Cases N11A and N11B simulated Test F11 ($Fr = 25$, $D = 5.8\text{mm}$) with 10 and 16 million, respectively. Finally, Case N12A simulated Test F12 ($Fr = 30$, $D = 5.8\text{mm}$) with the grid number of 16 million.

6.4.3 Overall flow characteristics and jet trajectory

Figure 6.10 shows the mean velocity contours from experimental Test F6 and numerical Case N6A. The centerlines are plotted as black dashed lines in the figure. The simulated behavior was in general agreement with the experiment as mentioned before, with the jet-like stage in the region near to the nozzle. The flow field was symmetrical about the centerline in the region near to the nozzle, and became asymmetrical further downstream due to the buoyancy induced instability. The simulated velocity magnitudes in Figure 6.10 (b) were also close to the experimental results.

Figure 6.11 shows the normalised jet trajectories for both the experiments (Tests F6, F9, F11, F12 and F13) and simulations (Cases N1B, N9B, N11B, N12A). From the figure, the trajectories showed a general profile independent of Fr , which was consistent with previous observation e.g. Shao and Law (2010). Upstream of the centerline peak, the simulated trajectories by LES agreed well with the experimental results. Beyond that, the simulated rise

CHAPTER SIX

height was slightly larger, but was still within the range of experimental data observed previously.

Figure 6.10 Experimental and numerical results for horizontal velocity field
(For experimental case F6 and numerical Test N6A)

Figure 6.11 Normalised jet trajectories of 45° inclined dense jet

6.4.4 Velocity decay

The velocity decay along the centerline was determined from both the experimental and numerical results. Previously, Chen and Rodi (1980)

CHAPTER SIX

suggested a power law relationship for vertical buoyant jets between the non-dimensional centerline dilution and distance from the nozzle as follow:

$$Fr.C_m/C_0=a(z/D/Fr)^b \quad (6.1)$$

where a and b are constants dependent on whether the flow is in the jet-like, transition, or plume-like regime. Shao and Law (2010) observed a similar relationship for the velocity decay between FrU_m/U_0 and $s/D/Fr$ for the inclined dense jet, where s is the axial distance along the centerline.

The variations of the normalised maximum centerline velocity and normalised downstream distance are presented in Figure 6.12, where the axes are in a logarithmic scale. s was calculated in a discretized manner both for the experiments (Tests F1, F6, F7, F9 and F11) and numerical simulations (Cases N1B, N9C). As seen from the figure, the numerical results followed the experimental data reasonably well. The transition from jet-like to plume-like occurred within approximately $1.0 < s/D/Fr < 8.0$. Moving away from the nozzle, i.e. $s/D/Fr > 1.0$, the data points collapsed on a curve, which was consistent with the observation reported by Shao and Law (2010). Nevertheless, it should be noted that the larger exponent on the right-hand side beyond 1.0 indicated the early effect of buoyancy on the jet-like range.

Figure 6.12 Comparison of velocity decay along the centerline

6.4.5 Velocity fluctuations

Figure 6.13 shows the fluctuations of the horizontal velocity at the centerline peak (Point 6) for the experimental Test F1 and numerical Cases N1A and N1B. The time average velocity was close to 0.11 m/s for both. However, N1A had a relatively coarse grid with a total grid number of 6 million, and the magnitude of velocity fluctuations was much smaller than what was measured in the experiments as shown in the figure. Thus, although both N1A and N1B satisfied the GCI criteria in terms of convergence for the first order parameters, the turbulence intensities for N1A were grossly underestimated. Comparatively, the magnitude of the velocity fluctuations in N1B using a finer grid scheme was

CHAPTER SIX

much closer to the experimental results. Therefore, simulation results from N1A and N9A which had the coarse grid were not presented in the following discussion. This demonstrated that further examination of turbulence details is necessary beyond the GCI compliance in order to achieve satisfactory predictions on turbulence mixing characteristics.

Figure 6.13 Experimental and numerical instantaneous velocities fluctuations at
Point 6

6.4.6 Cross-sectional velocity profile

The cross-sectional distributions of the normalised average stream-wise velocity (U/U_m) are plotted in Figure 6.14 at four different locations ($s/FrD = 0.4, 0.8, 1.2$ and 1.6 respectively) along the centerline (for Test F11 and Case

CHAPTER SIX

N11B, $Fr = 25$). In the figure, the upper and lower halves of the inclined dense jet are represented by negative and positive values of r/D , respectively.

Again, it can be observed that near to the nozzle (e.g. $s/FrD = 0.4$), the velocity profiles were symmetrical and followed the Gaussian distribution. Further downstream, the spread of the lower half became wider. The asymmetry increased with s/D , and the profile deviated from the Gaussian curve progressively. The behavior was again repeated in Figure 6.15 (Tests F1, F6, F9, F11 and Cases N1B, N6A, N9C, N11B) whereby the normalised stream-wise velocity is plotted with different normalised values of s/D . Overall, the simulated results can be seen to be in good agreement with the experimental data.

The normalised velocity $1/e$ widths b_e (defined as where the velocity decreases to e^{-1} of the centerline maximum value in the cross-section) from the experiments (Tests F1, F6, F7, F9, F11 and F12) and simulations (Cases N9C, N11B and N12A) are shown in Figures 6.16 and 6.17. Generally, the spread width increased linearly with the stream-wise distance as had been commonly reported in previous studies. However, in Figure 6.17, the lower half of the dense jet can be observed to grow markedly faster than the upper half in the plume-like regime (~ 0.14 for the upper half and 0.36 for the lower half). The numerical results were close to the experimental results for the upper half, but much lower for the lower half where the jet behavior was affected by the buoyancy induced instability. In other words, the simulations were not able to fully capture the convective mixing generated by the instability.

CHAPTER SIX

Figure 6.14 Cross-section distribution of stream-wise velocity along the trajectory (Test F11 and Case N11B)

Figure 6.15 Cross-section distribution of radial velocity at different $s/D/Fr$ values

CHAPTER SIX

Figure 6.16 Variation of upper spread width along the centreline

Figure 6.17 Variation of lower spread width along the centerline

CHAPTER SIX

6.4.7 Axial and cross-sectional turbulence intensity

The simulated (Cases N9C, N11B and N12A) stream-wise turbulence intensity along the centerline trajectory is plotted in Figure 6.18. The stream-wise intensity increased until $s = 1.8FrD$ and fluctuated began to decrease after that, which was slightly lower than the experimental results (Tests F6, F9, F11, F12 and F13). Figure 6.19 illustrates the simulated radial intensity along the trajectory in the same spatial range. The radial intensity varied from 0.12-0.20 with an average of 0.15, which was close to the experimental results. It can also be observed that both intensities decreased slightly as Fr increased.

In Figure 6.20, the turbulence intensity profile at the centerline peak is compared between Experimental Test F9 and Numerical Case N9C. At this location, the simulated turbulence intensity was lower in the upper and particularly the lower half where the buoyancy-induced instability was present.

Both the experimental and numerical results showed again that the cross-sectional distribution of turbulence was not axis-symmetric. The intensity in the lower half was obviously larger than the upper half when $s > 1.5FrD$. Closer to the nozzle when $s = 0.5FrD$ and $1.0FrD$, double peaking of turbulence intensity can be clearly observed from the simulated profile. On the contrary, the distribution was uniform in the central region of the inclined dense jet from the experimental measurements. This direct comparison implied that the magnitude of turbulence inside the dense jet was higher in the experiment which led to stronger lateral mixing that diminished the distribution peaks.

CHAPTER SIX

Figure 6.18 Variation of stream-wise turbulence intensity along the centreline

Figure 6.19 Variation of radial turbulence intensity along the centerline

CHAPTER SIX

Figure 6.20 Cross-sectional distribution of stream-wise turbulence intensity

6.4.8 Turbulent energy spectrum and turbulent kinetic energy (TKE)

Figure 6.21 shows the comparison of spectra at the centreline peak for Experiment Test F12 and Numerical Cases N12A and N12B. The difference between the simulated energy spectra for Cases N12A and N12B was small, yet it can be clearly observed that N12B with the finer grids yielded higher turbulence energy production before the inertial sub-range. The numerical and experimental spectra had similar magnitude at the lower frequencies representing the main production range approximately up to ~ 1 Hz. Thus, the results implied that the present LES simulations can efficiently resolve bulk of the turbulence kinetic energy for the inclined dense jet. However, the simulated spectral profiles dropped off much faster compared to the experiments towards the higher frequencies, with the inertial subrange showing up much earlier in the lower frequencies for both N12A and N12B. Thus, the additional turbulence energy production in this transitional range which was obviously present in the

CHAPTER SIX

physical tests, was not fully reproduced in the LES simulations.

Figure 6.21 Numerical and experimental turbulent energy spectrum at centerline peak

The stream-wise turbulence kinetic energy spectrum at the different locations are shown in Figure 6.22 for Experimental Test F9 and Numerical Case N9C ($Fr = 20$), and also Figure 6.23 for Test F12 and Case N12B ($Fr = 30$). Earlier, we had discussed that the experimental spectral profiles at Points 1 and 2 were relatively flat which can be attributed to the presence of the potential core. This can also be seen in the numerically simulated spectra up to about ~ 1 Hz (i.e. below the sub-grid modeling frequency), but not for higher frequencies. The likely reason was that the LES simulation had assumed sub-grid turbulence

CHAPTER SIX

characteristics following the Dynamic Smargorinsky model, which was not strictly applicable for this potential core region. From Points 1 to 8, the simulated spectrum decreased with the log slope which was approximate $-5/3$ between the frequency of 2 to 20Hz. Subsequently, the predicted spectrum decreased much faster at higher frequencies. The magnitude of the turbulence energy density simulated by LES at low frequencies (less than 1Hz) was actually close to the experimental results. However, the simulated turbulence energy density failed to capture the energy production between ~ 1 to 3 Hz before the start of the inertial subrange. We believe that the main source of this transitional energy production was due to stratified effects within the sub-grid, particularly the convective overturning due to the buoyancy induced instability at the lower half of the inclined dense jet.

Comparing Figures 6.22 and 6.23, the agreement between experimental and LES results improved, which was consistent with the expectation that the transitional turbulence production due to buoyancy induced instability played a lesser role in Test F12 with higher U_o and thus Fr which would be more jet-like. Further refining the grid spacing and increasing the grid number beyond 16 million was not possible in this study due to the constraint in computational resources and budget. We note that our constraint is already at the higher end of what would be typically available to engineering companies to validate their final design at the moment.

CHAPTER SIX

Figure 6.22 Experimental and numerical turbulent energy spectrum at different locations (— LES N9C - - - Experiment F9 — Slope $-5/3$)

CHAPTER SIX

Figure 6.23 Experimental and numerical turbulent energy spectrum at different locations (— LES N12B - - - Experiment F12 — Slope $-5/3$)

6.5 Conclusions

An experimental investigation was performed to quantify the turbulence characteristics of 45 °inclined dense jets using the PIV technique. The objective was to provide benchmark data to guide high-resolution turbulence simulations of dense jets in the future. The PIV measurements were taken at a high sampling frequency so as to resolve the turbulence kinetic energy spectrum at different locations along the jet trajectory (which was identified using the time-averaged velocity field). The average velocity of the inclined dense jet generally decayed with the stream-wise distance of s following the relationship of $FrU_m/U_0=4.8(s/D/Fr)^{-1.1}$ after $s/Fr/D > 1.0$. The experimental turbulence kinetic energy spectrum decreased with the log slope of $-5/3$ at the frequency from ~ 2 to 20Hz near and beyond the centreline peak. LES simulations with different mesh schemes were also conducted. The simulated turbulence kinetic energy spectrum was close to experimental results for lower frequencies (from 0.01-1.0Hz), however the transitional energy production beyond ~ 1 Hz and before the inertial subrange was not reproduced satisfactorily in the simulations due to the minimum grid spacing adopted. In summary, the present results demonstrated that the evolution of the turbulence characteristics for 45 degrees inclined dense jet along the trajectory is complex, and thus the numerical modeling of the mixing behaviour is challenging. The LES simulations performed in this study was able to reproduce the first order dense jet mixing characteristics and also a large part of the turbulence spectrum at the production range when proper sub-grid model and grid size were selected. However, the results also show that further improvement in terms of sub-grid models that can incorporate the stratification effects is necessary for engineering simulations in the future.

Chapter 7

Mixing of Swirling Inclined Dense Jets – a Numerical Study

7.1 Introduction

In the design considerations for the outfall, the terminal rise height and return point dilution are the two key parameters which are typically analysed for the near field mixing. The ideal scenario calls for the terminal rise height to be lower than the water surface i.e. a full submergence of the inclined dense jet, while the return point dilution satisfies the requirements for the mixing zone compliance (Jiang and Law, 2014).

As discussed previously in Jiang and Law (2014) and Jiang et al. (2014), large scale desalination plants now have to cope with a wide range of brine discharge flowrate due to different operation modes (e.g. full operation, standby, etc), and the corresponding wide range of Fr is a challenge to the outfall design. In addition, the consideration of full submergence implies that the outfall needs to be located in deeper waters to avoid the surface interactions. The construction cost would thus increase correspondingly, which would also translate to a higher unit water cost for the desalination with the typical financial arrangement of cost recovery upon operation. A possible enhancement to the brine outfall is to impart a swirl to the effluent discharge. This can be accomplished in the form

*This chapter is written based on Jiang, M. and Law, A.W.K. (2018). Mixing of Swirling Inclined Dense Jets – a Numerical Study. Journal of Hydro-Environment Research (submitted).

CHAPTER SEVEN

of a swirl valve installed at the outlet as proposed in Jiang and Law (2013). As mentioned in Chapter 3, previous experimental studies and theoretical analysis had shown that the addition of swirls can affect the mixing behavior significantly.

Detailed velocity measurements can directly illustrate the distribution inside the swirling jet and the mixing process involved. However, such measurements involve the use of high-resolution three-dimensional velocimetry techniques, which are typically complex. Moreover, further information on characteristic eddy length scales and temporal dynamics of coherent structures require the spatial correlation of the velocity measurements which is very difficult to achieve at this point. Thus, Computational Fluid Dynamics (CFD) simulations had also been explored in the literature for the analysis of swirling turbulent non-buoyant jets (Leschziner and Rodi, 1984; Kollmann et al., 2001; Ruith et al., 2003; McIlwain and Pollard, 2002; García-Villalba et al., 2007; Fröhlich et al., 2008; Stoellinger et al., 2017). Hu et al. (2001) conducted a Direct Numerical Simulation (DNS) of a round swirling jet. Their numerical results showed that the stream-wise vortical layer developed in the initial stage broke down rapidly into small eddies under the joint stretch of the combined axial and tangential shears, which can significantly enhance mixing.

In summary, previous studies had shown that the addition of swirl can significantly influence the mixing characteristics of non-buoyant jets. However, similar studies on the effect of swirl on dense jets are rare in the literature. Only Jiang and Law (2013) and Jiang (2014) had reported limited experimental results using the Stereoscopic Particle Image Velocimetry (SPIV) and Planar Laser Induced Fluorescence (PLIF) techniques. In the present study, the mixing

CHAPTER SEVEN

characteristics of swirling inclined dense jets were further investigated using numerical simulations. Two approaches of LES with the Dynamic Smarginsky SGS model and RANS with the standard $k-\varepsilon$ closure were applied to examine a wide range of Swirl Number, beyond what was tested experimentally. In the following, we shall first summarise briefly the experimental results of Jiang and Law (2013) and Jiang (2014) before discussing the simulations.

7.2 Experimental Results by Jiang and Law (2013) and Jiang (2014)

The experimental setup consisted of a 45 degree inclined dense jet discharging into a stagnant ambient in a glass test flume. A swirl valve similar to Ortega-Casanove et al. (2011) was installed at the nozzle outlet, with an array of guide vanes to generate different initial swirl intensity. A laser imaging system comprised of a pulsed laser with two synchronized charge-coupled device (CCD) cameras were installed for data acquisition. The two cameras were positioned to view a specific image window, and the angle between them was set to 60 degrees. Based on the SPIV technique, the velocity field near the nozzle outlet was quantified including the initial swirl intensity of the swirling inclined dense jet. In addition, the PLIF technique was applied to obtain the spatial concentration distribution and evaluate the dilution at the centreline peak and return point. The experimental conditions covered the range of Swirl Number, G , from 0 to 0.33. The detailed experimental procedures and results can be found in Jiang and Law (2013) and Jiang (2014). Overall, the results showed that the addition of swirls generally led to the shortening of the potential core as well as increased the mixing efficiency of the inclined dense

CHAPTER SEVEN

jet. Particularly, when G exceeded ~ 0.2 , the terminal rise height was found to be much lower due to the enhanced mixing which would potentially translate to a shorter outfall length as a result.

7.3 Numerical Simulations

The numerical conditions (shown in Table 7.1) were identical to the physical parameters in the experiments. The density of ambient water was 998.0 kg/m^3 . The fluid diffusivity and viscosity were set to be $10^{-9} \text{ m}^2/\text{s}$, $10^{-6} \text{ kg}\cdot\text{m}^{-1}\text{s}^{-1}$, respectively. The nozzle diameter was 8.0 mm .

Table 7.1 Numerical conditions

CFD model	Case No.	D [mm]	U_0 [m/s]	G	ρ_0 [kg/m ³]	ρ_a [kg/m ³]	g_0 [m/s ²]	Fr
LES	L1	8.0	0.55	0	1028.0	998.0	0.29	11.3
	L2	8.0	0.55	0.15	1028.0	998.0	0.29	11.3
	L3	8.0	0.55	0.22	1028.0	998.0	0.29	11.3
	L4	8.0	0.55	0.33	1028.0	998.0	0.29	11.3
	L5	8.0	0.55	0.44	1028.0	998.0	0.29	11.3
	L6	8.0	0.55	0.55	1028.0	998.0	0.29	11.3
	L7	8.0	0.55	0.66	1028.0	998.0	0.29	11.3
RANS	K1	8.0	0.55	0	1028.0	998.0	0.29	11.3
	K2	8.0	0.55	0.11	1028.0	998.0	0.29	11.3
	K3	8.0	0.55	0.22	1028.0	998.0	0.29	11.3
	K4	8.0	0.55	0.33	1028.0	998.0	0.29	11.3
	K5	8.0	0.55	0.44	1028.0	998.0	0.29	11.3
	K6	8.0	0.55	0.55	1028.0	998.0	0.29	11.3
	K7	8.0	0.55	0.66	1028.0	998.0	0.29	11.3

The computational domain is shown in Figure 7.1. The origin of Cartesian coordinates was set to the center of the discharge nozzle. The distances from the nozzle tip to the back (L_1), front (L_2), left (W_{d2}) and right sides (W_{d1}), and surface

(H) boundaries were always larger than $1D_{Fr}$, $8D_{Fr}$, $4D_{Fr}$, $4D_{Fr}$ and $4D_{Fr}$, respectively, to make sure the full submergence of the dense jet (Jiang et al 2014). The distance from the nozzle tip to the bottom boundary (h) was larger than $0.5D_{Fr}$, which was sufficient to avoid the Coanda effect (Shao and Law, 2010). For both LES and RANS, the discretization of the temporal term was computed by a second order implicit backward scheme. The divergence and Laplacian terms, were computed by an upwind and a linear scheme, respectively. The time step was set to adjust automatically to make sure that the Courant number was less than 1.0.

The computational domain was discretized with a structured mesh. The spacing of the grid increased from the center of the nozzle to the boundaries and refined using snappyHexMesh. The grid convergence was examined using the GCI method as mentioned before, with the criterion of 10^{-6} set for both the velocities and concentrations. After the convergence tests, a mesh with 16 million grids

CHAPTER SEVEN

was used for the LES simulations, and another with 3 million grids for the RANS simulations.

Figure 7.2 shows the comparison for both the axial velocity U and tangential velocity W at the cross section 2mm away from the nozzle outlet between the

(a)

(b)

Figure 7.2 Distribution of tangential and axial velocity at the nozzle exit

CHAPTER SEVEN

experimental and numerical results, where the radial distance was normalised by D . From the figure, the axial velocity distribution of all cases was close to a top-hat profile. The W component was also symmetrically distributed about the nozzle axis, and the peak magnitude of W increased with the swirling intensity as expected. More importantly, the simulated magnitude of U and W agreed well with the experimental results. This implied that the velocity boundary conditions in the numerical simulations were set correctly matching those in the experiments.

7.4. Results and Discussion

For analysis, the inclined dense jets were classified into non-swirling ($G = 0$), weak swirling ($G \leq 0.2$), moderate swirling ($0.2 < G \leq 0.3$) and strong swirling ($G > 0.3$). The simulated spatial distributions of the normalised time-average concentration (c/c_0 , where c_0 is the source concentration) of the non-swirling inclined dense jet with $Fr = 11.3$ are shown in Figure 7.3. From the figure, the trajectory from the RANS simulation was lower than the experimental results which was consistent with what had been reported previously by Zhang et al. (2016a). At the same time, the LES simulations reproduced the trajectory well, again verifying the previous results by Zhang et al. (2016b, 2017).

The series of simulated vortex rings from LES along the trajectory also matched the larger eddies observed in the experiments. Finally, the length of potential core region predicted by LES agreed well with the experiments, while the predictions by RANS were shorter which was attributed to the stronger isotropic turbulence assumed by RANS at the discharge outlet leading to the faster spreading.

CHAPTER SEVEN

Figure 7.4 shows the concentration contours of the swirling inclined dense jet with the strong Swirl Number $G = 0.33$. The comparison reversed from those for the non-swirling cases. From the figure, it can be clearly observed that the presence of strong swirl led to the shortening of the potential core region and a bulge spreading in the initial rising stage. The terminal rise height was also clearly lower.

Figure 7.3 Concentration contours for non-swirling inclined dense jets

CHAPTER SEVEN

Figure 7.4 Concentration contours for swirling inclined dense jets

RANS predictions obviously matched well to the experimental results compared to LES. The predicted stronger mixing by RANS in the presence of the strong swirl led to higher entrainment and lower rise height, in agreement with the experimental observations. The contrasting trend with better

CHAPTER SEVEN

performance by LES for non-swirling and RANS for strong swirling cases is illustrated again by means of the centreline trajectory, defined as the locus of maximum concentration in Figures 7.5 and 7.6. The contrasting performance was clearly shown in the figure by the comparison with the experimental results.

The variation of the normalised concentration e-width (b_c/D) is shown in Figures 7.7 (upper half) and 7.8 (lower half). From the figures, the experimental results increased almost linearly with s , and the spreading rate increased with G . The simulated upper b_c from RANS was close to the experimental results with strong swirl, while the LES predictions underestimated significantly. From Figure 7.8 (a), the experimental b_c increased linearly with s before $s/Fr/D < 1.0$, but became much faster beyond that due to the buoyancy-induced instability.

Both LES and RANS were unable to reproduce the additional entrainment of the lower half of the inclined dense jet fully, but the RANS results were again closer to the experiments. Most importantly, the experimental results showed that the convective mixing by the buoyancy induced instability was significantly reduced by the strong swirls, and RANS was able to simulate this trend much better than LES based on the results obtained. The normalised cross-sectional distributions of c/c_m at various stream-wise distances from the nozzle are extracted and plotted against r/b_c in Figures 7.9 and 7.10. Axisymmetry was achieved in the presence of strong swirls and associated turbulence, and RANS was able to predict the trend better.

CHAPTER SEVEN

Figure 7.5 Trajectory for non-swirling inclined dense jets

Figure 7.6 Trajectory for swirling inclined dense jets

CHAPTER SEVEN

(a)

(b)

Figure 7.7 Growth rate of upper half

CHAPTER SEVEN

(a)

(b)

Figure 7.8 Growth rate of lower half

CHAPTER SEVEN

Figure 7.9 Normalised concentration distribution at various stream-wise distance from the nozzle

To investigate the possible breakup of the inclined dense jet by swirling, simulations were carried out with G increased beyond the value of 0.33 which was the highest attempted in the experiments, and up to the extremely strong swirl of 0.66. The results are also presented in the previous figures. However, no significant changes can be observed, and the dense jet presented its overall

CHAPTER SEVEN

behavior beyond 0.33. In particular, the Gaussian spreading achieved by the strong swirl of $G = 0.33$ remained.

(a)

(b)

Figure 7.10 Normalised concentration distribution at centerline peak with different G

CHAPTER SEVEN

Figure 7.11 shows the decay of the centerline concentration (c_m) along the jet trajectory. From the figure, both experimental and numerical results indicated that the centerline concentration of the dense jet began to decay earlier with swirls. The rate of decay was also faster for the swirling dense jet, and depended on the Swirl Number G . Besides, it can be observed directly that the swirl enhanced the mixing efficiently near the nozzle outlet due to the faster rate of entrainment. However, the decay rate became independent of the swirl at the downstream sections, which implied that the swirl effect became insignificant away from the outlet. Comparing Figure 7.11 (a) and (b), the concentration decay rate from RANS was faster than LES, which was consistent with the observation that RANS predicted a wider jet spread.

The variations of normalised centerline peak height (z_m/FrD) under different discharge conditions are shown in Figure 7.12. Experimental data from previous studies on non-swirling jets are also added in the figure. It can be observed from the experimental and numerical results that with weak swirling $G < 0.2$, the rise height was not significantly affected by the presence of rotating swirl. However, when G increased, an obvious reduction occurred due to the enhanced mixing. Therefore, both the experimental and numerical results confirmed that a minimum initial swirl of $G = 0.2$ is necessary for the 45° inclined dense jet, such that the swirl can effectively reduce the terminal rise height. Figure 7.13 illustrates the variations of the dilution at the return point normalised by the initial Froude number Fr against G . It can be observed from the figure that when the swirling intensity was strong, the swirl can shorten the jet trajectory as well as enhance the mixing of the dense jet. It should be mentioned that more experiments in the range of $G > 0.3$ would help to determine the optimal G for the brine disposal. However, only moderate

CHAPTER SEVEN

swirling intensities were tested due to the fact that the 3-dimensional tests in the present study are very time-consuming comparing to the normal 2-dimensional measurements. Both LES and RANS underpredicted the dilution at the return point significantly with weak and moderate swirls. At the strong swirl $G = 0.33$, the dilution prediction became much closer to the experimental observations. Thus, it is believed that the dilution predicted by numerical simulations would be more accurate with strong swirls beyond $G = 0.33$

(a)

CHAPTER SEVEN

Figure 7.11 Concentration decay along the centerline

Figure 7.12 Relationship between centerline peak height and G

CHAPTER SEVEN

Figure 7.13 Relationship between dilution at return point and G

Finally, the turbulence kinetic energy spectrum was computed by the Fourier transform of the velocity time series along the dense jet trajectory based on the LES results. A total of 8 locations ($x/x_m = 0.2, 0.3, 0.5, 0.7, 0.9, 1.0, 1.2$ and 1.4) were selected for the spectral analysis. As shown in Figure 7.14 ($G = 0$, $x_m = 1.8FrD$). From Shao and Law (2000), the terminal rise of the 45° inclined dense jet occurs around $x/FrD = 1.7$. Hence, these eight locations included both the rising and falling stages of the inclined dense jet.

CHAPTER SEVEN

Figure 7.14 Locations of points for analysis of turbulence kinetic energy spectrum

The spectra at the different locations for inclined dense jets with $G = 0, 0.33$ and 0.66 are shown in Figure 7.15. For non-swirling dense jets (shown in Figure 7.15 (a)), the spectral profiles at Points 1 and 2 were relatively flat, which can be attributed to the presence of the potential core. We noted however that the LES simulations had assumed sub-grid turbulence characteristics following the Dynamic Smagorinsky model, which might not be strictly applicable for this potential core region (Zang et al., 1993).

With the strong swirl $G = 0.33$ (shown in Figure 7.15(b)), the simulated spectrum at the different locations decreased with the log slope for the inertial sub-range of approximately $-5/3$ between the frequency of 3 to 20Hz. However, compared to the spectrum of the non-swirling jet, an increase in the turbulence energy density can be observed between ~ 1 to 3 Hz before the start of the

CHAPTER SEVEN

inertial sub-range, which may indicate the energy production due to eddy break up in the vortical layer caused by the swirl.

Figure 7.15(c) shows the turbulence kinetic energy spectrum at different locations with $G = 0.66$. Comparing to $G = 0.33$, the turbulence kinetic energy increased in an overall manner. In particular, the turbulence energy of the lower frequency production range (between ~ 0.01 to 1) increased more obviously than the higher frequency range, implying the formation of additional larger scale eddies by the extremely strong swirl. As discussed above, the LES simulations were less satisfactory compared to RANS with strong swirling cases. Nevertheless, these LES results demonstrated that the effects of swirl on the inclined dense jet can be different depending on the swirl magnitude, which had been qualitatively described in earlier studies on non-buoyant jets.

7.5. Conclusions

We investigated the effect of the swirl on the mixing characteristics of 45 degree inclined dense jets numerically in the present study, and evaluated the performance of the numerical models in the simulations by comparing with the experimental results from Jiang and Law (2013) and Jiang (2014).

CHAPTER SEVEN

(a)

CHAPTER SEVEN

(b)

CHAPTER SEVEN

Figure 7.15 Turbulence kinetic energy spectrum at different locations along the trajectory based on LES results: $G =$ (a) 0, (b) 0.33 and (c) 0.66

CHAPTER SEVEN

Two numerical approaches were adopted, namely LES with the Dynamic Smagorinsky Sub-grid Model which is more advanced in the modelling of turbulence but computationally intensive, and RANS with the standard $k-\epsilon$ turbulence closure which is computationally efficient but involves simplifying assumptions including isotropic turbulence behavior. The comparison showed that LES simulated the trajectory better for non-swirling and weakly swirling dense jets, which was consistent with what had previously been reported (e.g. Zhang et al., 2016, 2017). The difference was attributed to the fact that the turbulence characteristics of the inclined dense jet were highly anisotropic without significant swirling, and LES was able to account for the anisotropy in a more accurate manner compared to RANS. Both approaches however underestimated the additional spreading in the lower half of the inclined dense jet due to the convective mixing by the buoyancy induced instability, and thus the dilution overall. With strong swirls, the role of buoyancy induced instability reduced and the distributions became more axisymmetric, and RANS predictions were much closer to the experimental results than LES. The breakup of dense jet did not occur with the extremely strong swirl of $G = 0.66$. Finally, the turbulence kinetic energy spectrum of the swirling inclined dense jet was analysed along the trajectory based on the LES results. They showed that at $G = 0.33$, the disintegration of the vortical layer into smaller eddies increased the turbulence energy production in the frequency range just before the inertial range. With extremely strong swirl of $G = 0.66$, the formation of additional large scale eddies added to the lower frequency range of the energy production. Overall, the numerical study confirmed the experimental finding that a swirl magnitude of at least $G \sim 0.2$ is necessary to reduce the terminal rise height and increase the entrainment significantly. Additional swirl beyond $G = 0.3$

CHAPTER SEVEN

however did not lead to further changes to the dense jet behaviour. These findings can assist in the potential design of swirling brine outfalls in the future.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

The mixing behavior of non-swirling and swirling inclined dense jets were investigated in the present study. The spatial development of the turbulence spectrum was also quantified. In addition, the performance of different CFD turbulence models was evaluated for the simulations of the inclined dense jet. The key results are summarized in the following:

8.1.1 Mixing behaviors of 45 °inclined dense jets in currents

- The nominal number NFr was proposed to quantify the influence of the ambient currents. Two different regimes, namely dense-jet-dominated and co-/counter-flow-dominated regimes, were identified for the mixing of 45 ° inclined dense jets in co-/counter-flowing currents based on NFr .
- In the dense-jet-dominated regime ($|NFr| < 1.0$), the geometric features only depended mainly on Fr similar to the stagnant ambient, while in the co-/counter-flow-dominated regimes, the dependence was on NFr instead.
- In co-flows, the upper half of the inclined dense jet followed the Gaussian profile, while the lower half deviated substantially due to the buoyancy

CHAPTER EIGHT

induced instability. The behavior was however exactly the opposite in counter-flows.

- In the co-flow-dominated regime, the centerline peak height was suppressed while the dilution was enhanced at that location. Within $r_m < 20D$ (r_m is the radial distance from the nozzle tip), the inclined dense jet in co-flows decayed faster than in counter-flows, but the trend reversed beyond that. The observation had a strong implication towards mixing zone compliance.
- The predictions by VISJET were found to generally underestimate the results in the order of 10-20% over the wide range of test conditions, which was consistent with the study conducted by Lai and Lee (2012). The prediction might overall be deemed satisfactory for engineering assessment considering the high complexities of the process.

8.1.2 Turbulence characteristics of inclined dense jets

- The turbulence kinetic energy was related to the mixing behavior along the jet trajectory. The full developed turbulence enhanced the mixing of the jet.
- The high sampling frequency of PIV measurements can resolve the turbulence kinetic energy spectrum of the dense jets in the inertia sub-range. The experimental turbulence kinetic energy spectrum demonstrated an inertial sub-range with the log slope of $-5/3$ at the frequency from ~ 2 to 20Hz near and beyond the centreline peak. The energy spectrum was relatively flat in the low frequency range.

CHAPTER EIGHT

- The LES simulations were able to reproduce the first order dense jet mixing characteristics, and resolve the turbulence kinetic energy spectrum well for lower frequencies (from 0.01-1.0Hz) when proper sub-grid model and grid size were selected.
- The transitional energy production beyond ~ 1 Hz and before the inertial sub-range was not reproduced satisfactorily in the LES simulations due to the current grid size adopted, which indicate that further improvement in sub-grid models that can incorporate the stratification effects is necessary for engineering simulations.

8.1.3 Mixing of swirling inclined dense jets

- Swirl can shorten the potential core length and increase the jet spread as well as the turbulence energy of the inclined dense jet.
- LES performed better for non-swirling and weakly swirling cases, while RANS predictions were much closer to the experimental results for strong swirling cases. The difference also implied that the convective mixing by the buoyancy induced instability was significantly reduced by the strong swirls.
- The turbulence spectral profile showed that the strong swirl and its associated disintegration of the vortical layer did increase the turbulence energy production in the frequency range just before the inertial range, which eventually led to the increase of dilution of the inclined dense jet.

CHAPTER EIGHT

- Additional swirl beyond $G = 0.3$ did not lead to further changes to the dense jet behaviour. However, additional large scale eddies will still break up when swirl number further increased, which added to the lower frequency range of the energy production.
- Both the numerical and experimental study showed that there was an optimum Swirl number G , which can bring relatively lower rise height as well as highest return point dilution. The results showed that the optimum G exists between 0.22 to 0.45.

8.2 Recommendations and Future Works

The present study was limited to the 45 °inclination angle for the inclined dense jet. Therefore, experimental investigations with more inclination angles should be conducted in the future. Additional measurements of velocity fields, especially the cross-sectional velocity and concentration distributions are also necessary to demonstrate the flow structures. Besides, the turbulence characteristics of dense jet under different ambient flow conditions can also be further investigated.

In the numerical simulations, LES simulations were able to simulate the velocity fields, geometric characteristics of the inclined dense jet as well as the turbulence spectrum at the low frequency range. However, it is still limited in simulating the dilution at the lower half of the inclined dense jet. Similarly, the energy spectrum at the higher frequency range can not be resolved with the

CHAPTER EIGHT

current grid scheme because the Dynamic Smargorinsky model may not be applicable to the unstable stratified flow. Therefore, further improvement in terms of sub-grid models that can incorporate the stratification effects is necessary for engineering simulations.

For swirling dense jets, the results from the numerical simulations were compared with the experimental results. However, further information on characteristic eddy length scales and temporal dynamics of coherent structures require the spatial correlation of the velocity measurements which is very difficult to achieve at this stage. Therefore, experiments with spatial velocity measurements and higher Swirl Number G are recommended in the future. The detailed measurements will also benefit the developing of SGS model for LES simulations.

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Author' s Publications

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Journal Papers

Jiang, M. and Law, A.W.K. (2018) "Mixing of Swirling Inclined Dense Jets – a Numerical Study." Journal of Hydro-Environment Research (Accepted for publication).

Jiang, M., Law, A.W.K. and Lai, A.C. (2017). "Turbulence Characteristics of Inclined Dense Jets." Environmental Fluid Mechanics, 1-128.

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APPENDIX A

Appendix A.

MATLAB Program for Data Processing

The appendix lists some selected MATLAB codes which were used in the data processing for the experiments as well as numerical simulations. The functions of the codes were to determine (1) the jet trajectory; (2) cross-sections which were vertical to the jet trajectory; (3) boundary of concentration e-width; (4) concentration decay along the trajectory and (5) dimensionless concentration cross-sectional profiles which were plotted with r/b_e and c/c_m at different downstream distance from the nozzle.

A.1 Jet_trajectory.m

```
%%-----JET_TRAJECTORY ---- MINGTAO, Dec 2016-----%%
%%-----Find out the trajectory by scanning and correction iterating -----%%

%%----- Path and parameters -----%%

h = **;    % Number of grids in horizontal direction
v = **;    % Number of grids in vertical direction
N = **;    % Number concentration maps (if the map is time averaged, set Nt=1)

%% ----- Import PLIF data into Matlab environment.-----%%

froot1 = ['D: / Extendedpiv/', num2str(i), '/' ...];
```

APPENDIX A

```
cd(froot1);

filename=dir('*.*txt');

nam=filename(1).name;

name=nam(1:11);

froot2 = [name; ...];

froot = [froot1(1,:), froot2(1,:)];

fout = ['Concentration_map.mat'; ...];

    for tn = 1:N;

        fnum = num2str(1000000+tn-1);    %% to start from a time stamp.

        fname = [froot, fnum(2:7), '.*txt'];

        [ttt9] = textread(fname, '%*d %*d %*f %*f %*f %*f %*f %*f %*f %*f %*f %*d',

            'headerlines',9);

        C(:, :, tn) = reshape(ttt9, h, v);

    end

    save(fout(ien,:), 'C', 'h', 'v', 'N');

end

end

%% ----- Tracking the jet concentration centreline-----%%
%% ----- Setting the Parameters for Tracking-----%%

origin_data=mean(C,3);

%% input section

% case relevant input

% input constant parameters

deta_L = ***;

inclination =***;

iteration_number = ***;

rib_length = ***;
```

APPENDIX A

```
%% read raw data from specific case

%load(' Concentration_map.mat ')

concen_map = origin_data;

[map_x,map_z] = meshgrid(0:0.00025:0.336,0:0.00025:0.128);

theta = inclination;

L = ***; % Starting point of the tracking

x = ***;

z = ***;

combin_data = zeros(iteration_number,5); % define the recording file%

    for n = 1:iteration_number

        deta_x = deta_L * cosd(theta); % set the steps for tracking

        deta_y = deta_L * sind(theta);

        x = x + deta_x;

        z = z+ deta_y;

%% ----- Create area for scanning-----%%

        rib_x_min = x - rib_length * sind(theta);

        rib_x_max = x + rib_length * sind(theta);

        rib_x = [rib_x_min : (rib_x_max - rib_x_min)/30 : rib_x_max];

        rib_z = z + cotd(theta) * (x - rib_x);

%% -----Find max concentration value and its location-----%%

        concen_interp = interp2(map_x, map_z, concen_map, rib_x, rib_z);

        max_concen = max(concen_interp); % search max value of concentration
```

APPENDIX A

```
max_xz_number = find(concen_interp == max_concen); %location
max_x = rib_x(max_xz_number);
max_z = rib_z(max_xz_number);

%% -----Correct again-----%%

rib_x_min = max_x - rib_length * sin(theta); % create corrected rib values
rib_x_max = max_x + rib_length * sin(theta);
rib_x = [rib_x_min : (rib_x_max - rib_x_min)/30 : rib_x_max];
rib_z = z + cotd(theta) * (x - rib_x);

%% -----Find corrected max concentration and its location -----%%

concen_interp = interp2(map_x, map_z, concen_map, rib_x, rib_z);
max_concen = max(concen_interp);
max_xz_number = find(concen_interp == max_concen);
max_x = rib_x(max_xz_number);
max_z = rib_z(max_xz_number);

%% ----- Adjust the value of theta & deta_x, deta_z, deta_L -----%%

correct_deta_x = max_x - x + deta_x;
correct_deta_z = max_z - z + deta_y;
correct_theta = acotd(correct_deta_x / correct_deta_z);
correct_deta_L = sqrt(correct_deta_x.^2 + correct_deta_z.^2);

%% ----- Adjust all data for the next loop, save data
-----%%

%% -----Re-calculate theta, x, z, L based on corrected results -----%%

theta = correct_theta;

L = L + correct_deta_L; % accumulate length of the streamline
```

APPENDIX A

```
x = max_x;

z = max_z;

combin_data(n,:) = [n, L, max_x, max_z, max_concen]; save all the data

end

%% -----Smoothing (Optional) -----%%

smooth_z = smooth(combin_data(:,4));%combin_data(:,4)%

tx=combin_data(:,3);

ty=smooth_z;

%% -----Output the trajectory together with the map for double checking-----%%

contourf(map_x,map_z,concen_map);

axis equal;axis([** ** ** **]);hold on

plot(combin_data(:,3),smooth_z,'ro');

tx1=combin_data(:,3);

ty1=smooth_z;

%save tpoints.mat xxx yyy;

%% -----Optional function for calculating the concentration decay -----%%

Fr=**; %Set the Froude number

D=**; %Set the Nozzle diameter

for dec=1:**;

u=concen_map(floor(yyy(dec)/0.0005),floor(xxx(dec)/0.0005));

decay(dec,1)=(deta_L*dec)/D;

decay(dec,2)=(concen_map(floor(yyy(dec)/0.0005),floor(xxx(dec)/0.0005)));

end;

save decay.mat decay
```

APPENDIX A

A.2 Concentration_e-width.m

```
%%-----E-width, MINGTAO, Dec 2016-----%%
%% -----Set the basic parameters for the cross-sections-----%%

Fr = **;

D = **;

crosssectionL=**; %set the distance interval between correction points
crosssectionpoints=**; %number of points for each cross-section

k1=1;

ss=1; %the number of cross-section, will be refered at the end

load('trajectory.mat');
load('crosssection.mat');
load('Concentration_map.mat ')

%% -----Determine the inclination of the cross-sections-----%%

mmm=size(tx);

for k=1:mmm(:,1)-1;

    sta=(ty(k+1)-ty(k))/(tx(k+1)-tx(k));

    vsta=atan(-1/sta); % corners of the trajectory

    deltax=crosssectionL*cos(vsta); % center of the cross-section

    deltay=crosssectionL*sin(vsta);

%% -----Draw the cross-sections which vertical to the trajectory -----%%

for kk=1:2*crosssectionpoints+1;

    cx=tx(k)+(kk-crosssectionpoints-1)*deltax;
```


APPENDIX A

```
        cy=ty(k)+(kk-crosssectionpoints-1)*deltay;

        location(k1,1)=cx;

        location(k1,2)=cy;

        location(k1,3)=crosssectionL*(kk-crosssectionpoints-1);

        k1=k1+1;

    end;

end;

cox=location(:,1);
coy=location(:,2);
plot(location(:,1),location(:,2),'ro');hold on
plot(tx,ty,'b');
axis equal;axis([** ** ** **]);
save crossection.mat cox coy crosssectionpoints crosssectionL

%% -----Then, determine the boundary of 1/e concentration -----%%

k1=1;

%% -----Convert the cross-section points into actual coordinates-----%%

sizec=size(cox);
mx=max(max(map_x));
mz=max(max(map_z));
for i=1:sizec(1)/(2*crosssectionpoints+1);

    k=1;

    for j=((2*crosssectionpoints+1)*(i-1)+1):((2*crosssectionpoints+1)*i);

        if cox(j)<=0||cox(j)>mx||coy(j)<=0||coy(j)>mz;

            CONC(k,i)=0;

            k=k+1;

        end;

    end;

end;
```

APPENDIX A

```
        else
            CONC(k,i)=interp2(map_x, map_z, C, cox(j), coy(j));
            k=k+1;
        end
    end
end;

end;

%% ----find out the point with maximum concentration in each cross-section-----%%
%% -----find out the upper and lower concentration 1/e points-----%%

ccm=1

for mm=1:size(c1)/(2*crosssectionpoints+1);
    si=size(CONC(:,mm))
    ee=max(CONC(:,mm))/2.718281828459
    FFF=find(CONC(:,mm)==max(CONC(:,mm)));
    MF=max(FFF);
    if MF==(2*crosssectionpoints+1);
        RRR=CONC(MF,mm);
    else
        if MF==1;
            LLL=CONC(MF,mm);
        else
            RRR=CONC(MF+1:si(1),mm);
            Q1=abs(RRR-ee);
            Q2= find(Q1==min(Q1));
            LOWB=max(Q2)+MF-1;
            ccolx(ccm,1)=cox(((mm-1)*(2*crosssectionpoints+1))+LOWB);
            ccoly(ccm,1)=coy(((mm-1)*(2*crosssectionpoints+1))+LOWB);
        end
    end
end
```

APPENDIX A

```

LLL=CONC(1:MF-1,mm);

Q3=abs(LLL-ee);

Q4= find(Q3==min(Q3));

UPB=min(Q4);

ccorx(ccm,1)=cox(((mm-1)*(2*crosssectionpoints+1))+UPB);

ccory(ccm,1)=coy(((mm-1)*(2*crosssectionpoints+1))+UPB);

ccm=ccm+1;

end;

%% -----Generate dimessionless concentration profile-----%%
%% -----Determine the dimensionless radial distance r/be -----%%

for ih=(MF+1):si(1);

    hx(ih)=crosssectionL*(ih-MF);

end;

hx(MF)=0;

for ih=1:MF-1;

    hx(ih)=crosssectionL*((ih)-MF);

end;

for ihx=(MF+1):si(1);

    hxx(ihx)=hx(ihx)/hx(LOWB);

end;

for ihx=1:MF;

    hxx(ihx)=hx(ihx)/-hx(UPB);

end

%% -----Determine the dimensionless concentration -----%%

```

APPENDIX A

```
CONCX=CONC(:,mm)/(max(CONC(:,mm)));

%% -----Put the r/be and c/cm together for plotting-----%%

    crossection(:,ss)=hxx';
    ss=ss+1;
    crossection(:,ss)=CONCX;
    ss=ss+1;
end;

end;

%% ----plot the upper and lower boundaries together with the map for checking----%%

contourf(map_x,map_z,C,40);
axis equal;axis([** ** ** **]); hold on
plot(tx,ty,'o');
plot(ccolx,ccoly,'ro');
plot(ccorx,ccory,'ro');
```