Hydraulic characteristics of co-planar jets

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**HYDRAULIC CHARACTERISTICS OF CO-
PLANAR JETS**

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2013

HYDRAULIC CHARACTERISTICS OF CO- PLANAR JETS

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Abstract

The mixing of turbulent jets can be applied in a wide variety of fields. For the sake of effective mixture, the jets configuration needs to be properly addressed. From an environmental aspect, it is vital to design a jets configuration so that the efflux flows can mix rapidly and effectively with the ambient fluid. Previous studies have suggested that jets interactions with inclination configuration to be an optimal scheme in terms of improving mixture. However, most previous studies only concern the side jets as zero mass flux compared to the central jet, i.e., 1~5%, which might not be suitable for most engineering applications.

In this study, the writer investigated the behaviour of three submerged round jets injecting convergingly to stationary recipient water in the laboratory. The three jets are set in the same vertical plane and have intersectant axes. Four parameters were investigated in this investigation: the inclined (converging) angle of the side jets with respect to the central jet, the momentum coefficient (velocity ratio) of the side jets, the Reynolds number of the central jet and the jet spacing ratio. Two incline angles (30° and 45°), four momentum coefficients ($1/16$, $1/9$, $1/4$ and $1/1$), three Reynolds numbers (4240, 6400 and 8000) and three jet spacing ratios (2, 3 and 4) were applied. The complex interactions had been investigated by employing the advanced laser diagnostic techniques of particle image velocimetry (PIV). With the PIV system, both ensemble-averaged and instantaneous characteristics of the complex flow fields were acquired. Geometric features and gross mixing characteristics were addressed by the ensemble-averaged (long time average) results, e.g., the location of the merging point, combining point and necking point. The mixing behaviour of the converging jets was also investigated through the analysis of the longitudinal and cross-sectional velocity distributions. The cross sectional distribution of the mean streamwise and lateral velocity on both the X-Y and X-Z planes, respectively, were found to attain self-similarity after the flow was fully developed and the merging processes were complete. The jet boundary was elucidated by the jet half-width based on the cross-sectional velocity distribution. The converging jets were observed to grow linearly on the X-Y plane and shaped like a parabola curve with open rim on the X-Z plane. The growth rate of the jet half width for converging jets was marginally enhanced than that of a single pipe jet on the X-Y plane but significantly enlarged on the X-Z plane. Based on the experimental

results, the cross-sectional profiles of the streamwise velocities were found to show strong resemblance on both the central planes and the parallel offset planes. The mean streamwise velocity for converging jets might be prescribed by the corresponding values on the two central planes (X-Y and X-Z). It was also demonstrated by the velocity measurements that the entrainment (mixture) from ambient fluid to the jets were enhanced when suitable parameters had been chosen based on jets spreading and the lateral velocity gradient near the jets edges.

The dynamic processes in the interactions among the three converging jets are revealed by time series of instantaneous flow fields. Galilean decomposition of the velocity vectors and calculation of λ_2 (complex eigenvalues) in conjunction with the vorticity fields are used to discriminate the swirling and the shearing in the evolution of the flow. The free outer shear layers of the side jets depict the standard K-H roll-ups similar with that of a single pipe jet flow in the merging region. These K-H structures become unstable gradually and the instability is characterized by “sinuous” flow motions. The two shear layers interact with each other, forming large-scale discrete vortices. The periodic nature of the interactions between the negative and positive Karman-like vortices enhances mixing among three converging jets. The translational velocity of these discrete vortices is estimated to be about 60~80% of the average efflux velocity U_0 .

Based on the experimental results in the present study, it has been found that the large-scale mixing of jets would be maximised when the jets momentum flux is matched (1:1:1). The geometrical features of the flow field are altered at different jet spacing ratios and inclination angles. The merging and combining of the coplanar jets take place earlier with smaller jet spacing ratios or bigger inclination angles. In these situations, the 45° jets at jet spacing ratios of 3 are found to be more receptive to the influence from the side jets because the side jets penetrate the central jet at a location close enough to the nozzle where the central jets’ instabilities have not yet developed, but not so close as in those cases with smaller jet spacing where there are still sufficient room of the evolution of the mixing layer for the jets.

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List of Symbols

C_u	Momentum Coefficient
D	Nozzle Diameter
d_{pixel}	Pixel Pitch
$E(f)$	Spectral Energy at a Particular Frequency
f	Jets Flapping Frequency
K	Centreline Velocity Decay Coefficient for Conventional Jets
K_u	Centreline Velocity Decay Coefficient for Pipe Jets
K_y	Jet half Width Coefficient in the Y or Lateral Direction
K_z	Jet half Width Coefficient in the Z or Lateral Direction
N_{int}	Size of the Interrogation Window in Pixels
Re	$= U_0 D / \nu$, Reynolds Number Based on the Central jet
S	Jet Spacing
SF	Object-to-Image Scale Factor
St	$= fD/U_0$, Strouhal Number Based on the Jets Flapping Frequency
t	Time
U_l	Local Mean Velocity Component in the X or Streamwise Direction
U_0	Average Efflux Velocity
U_c	Centreline Velocity Component in the X or Streamwise Direction
U_{lc}	Local Centreline Velocity Component in the X or Streamwise Direction
U_e	Centreline Axial Velocity Component at the Jet Nozzle Exit
U_{max}	Maximum Velocity Estimated in the Flow Field
u	Local Instantaneous Velocity Component in the X or Streamwise Direction
u_i, v_i, w_i	Local Instantaneous Velocity for the $i - th$ Sample
u'	Local Turbulent Fluctuation of the Velocity Component in the X or streamwise Direction
$\overline{u'v'}$	$= \frac{1}{N} \sum_{i=1}^{i=N} [(u_i - U)(v_i - V)]$, Reynolds Shear Stress on the X-Y plane
$\overline{u'w'}$	$= \frac{1}{N} \sum_{i=1}^{i=N} [(u_i - U)(w_i - W)]$, Reynolds Shear Stress on the X-Y plane
$\widehat{u'^2}$	Integral Turbulent Stress Component in the X or Streamwise Direction
V_l	Local Mean Velocity Component in the Y or Lateral Direction

V_i	Instantaneous Velocity Vector
v	Local Instantaneous Velocity Component in the Y or Lateral Direction
v'	Local Turbulent Fluctuation of the Velocity Component in the Y or Lateral Direction
$\widetilde{v'^2}$	Integral Turbulent Stress Component in the Y or Lateral Direction
W	Local Mean Velocity Component in the Z or Transverse Direction
w	Local Instantaneous Velocity Component in the Z or Transverse Direction
w'	Local Turbulent Fluctuation of the Velocity Component in the Z or Transverse Direction
$\widetilde{w'^2}$	Integral Turbulent Stress Component in the Z or Transverse Direction
X	Cartesian Coordinates in the Streamwise Direction
X_{0y}	Virtual Origin of Converging Jets on the X-Y Central Plane
X_{0z}	Virtual Origin of Converging Jets on the X-Z Central Plane
Y	Cartesian Coordinates in the Lateral Direction
$Y_{l1/2}$	Local jet half width in the Y or lateral Direction, based on $U_l = 1/2 U_{lc}$
$Y_{1/2l}$	Jet half Width in the Y or Lateral Direction, based on $U_l = 1/2 U_c$
Z	Cartesian Coordinates in the Transverse Direction
$Z_{l1/2}$	Local jet half width in the Y or transverse Direction, based on $U_l = 1/2 U_{lc}$
$Z_{1/2l}$	Jet half Width in the Z or transverse Direction, based on $U_l = 1/2 U_c$
θ	Incline Angle of the Side Jets with respect to the Central Jet
$\alpha_1, \alpha_2, \alpha_3$	Empirical Coefficient of a Double-Peak Distribution from Superposition of Two Gaussian Profiles.
β	Empirical Coefficient of a Gaussian Distribution for a Single Jet
C_μ	Momentum Coefficient
l	Subscript, Denote the Local Value and is dropped in the X-Y and X-Z Planes
λ_2	$= (\partial u / \partial X + \partial w / \partial Z)^2 - 4(\partial u / \partial X \cdot \partial w / \partial Z - \partial u / \partial Z \cdot \partial w / \partial X)$ Second Discriminant for Complex Eigenvalues
Δt	Time Interval between Two Consecutive laser Pulses
ν	Fluid Viscosity
∇u	Velocity Gradient Tensor
$\hat{S}$	Symmetric Parts of the Velocity Gradient Tensor ∇u

$\hat{\Omega}$	Anti-Symmetric Parts of the Velocity Gradient Tensor ∇u
$\overline{\Omega_y}$	Mean Cross-Stream Vorticity
$\overline{\Omega_z}$	Mean Spanwise Vorticity
Ω_y	Instantaneous Cross-Stream Vorticity
Ω_z	Instantaneous Spanwise Vorticity

Chapter 1. Introduction

1.1 General Introduction

Jet or plume like flow tends to entrain the surrounding fluid water into the core stream, and hence generate growing bulk by mixing with the emitted fluid and the recipient body. Over the years, such flow has been of great interest because of the many practical applications in industry and environmental engineering. The mechanisms of a single jet affecting mixing and entrainment have been investigated for many years. Recently, multiple jets and their mutual interactions become more prevalent in many applications, i.e., combustors and flow control in industry, jet engines in aerospace engineering, boiler or injection and carburetor system in various aspects, and waste water disposal or diffuser in environmental engineering.

When large number of jets are involved in the interactions (particular in large multiport diffusers), most early studies are directed to adapting the solution of a single round jet or slot jet (Abraham 1963, Koh and Fan 1970, Liseth 1970, and Jirka and Harleman 1973). The “transition criteria”, according to which an abrupt transition occurs from 3-dimensional to 2-dimensional, is used to analyse the characteristics of multiple jets as a line source. Mean axial concentration profiles and maximum dilutions along the flow trajectories are most concerned in these fields. However, jet or plume flows formed by such installations can be very complicated due to the interactions between jet with either the adjacent jets or the ambient flow field. Therefore, environmental protection claims profound knowledge of the mechanic of the interacting jets flow to help the design of arrangements of multiport diffusers (Yannopoulos 2010). Unfortunately, because of the inherent complexity of the flow structures within the multiple interacting jets (particular, a large number of jets), comprehensive understanding of the dynamical processes of merging and mixing, especially in the initial region, are limited.

The interactions between dual parallel plane jets have been investigated extensively (Tanka 1970; Elbana *et al.* 1983; Wang *et al.* 1993; Soong *et al.* 1998; Anderson and Spall 2001; Wang and Tan 2007). Tanaka (1970) described the basic flow patterns and entrainment mechanisms of parallel jets, and divided the flow field into three relative regions in the streamwise direction: the converging region, the merging region and the combining region. Great efforts have been made on the measurements of time-averaged characteristics, such as

mean velocity distributions, streamwise, transverse velocity fluctuations and Reynolds stresses by various methods (windmill anemometer, hot wire anemometer and burst mode Laser-Doppler anemometer). Modern development in visualization and measurement technology makes it possible to capture instantaneous velocity profile in the field of view explicitly. Experimental studies on the interacting jets using X-film and schlieren-film (Anderson and Spall 2001, Bunderson and Smith 2005) reveal an instability characterized by sinuous “flapping” of the jets and would enhance mixture of the jets with the ambient fluid. The frequency and amplitude of such instability is found to be associated with the jet spacing ratio and momentum flux ratio of the interacting jets. Such oscillations are found to enhance the large-scale mixing of the two jets. The mixing is maximised when the two jets momentum flux are matched (1:1) but minimised (the flow becomes almost steady) when two jets is mismatched by as much as a factor of three. At the matched momentum flux, the amplitude of jets flapping reaches a minimum near a spacing of 2 jets width but gets appreciable for spacing of 7 jets width.

Compared to parallel dual jets, very little investigation is available regarding the mixing and development of inclined dual jets. However, the jets interactions with inclination configuration can be frequently applied in flow control to improve mixing, noise suppression, thrust vectoring, and control of the transition from a laminar to a turbulent flow. By using one or two side jets toward the central or main jet, the overall flow field may be altered greatly. Quantitative experimental results have obtained (New and Tay 2006, Tamburello and Amitay 2006, 2008) to explore the effects of the incline angle of the side jets (with respect to the central jet), the momentum ratio and the main jet’s Reynolds number. By choosing pertinent parameters (incline angle, momentum ratio and Reynolds number of the central jet), either a stabilizing or enhanced mixing and destabilizing effect can be achieved. However, most related studies only concern the side jets as zero mass flux compared to the central jet, i.e., 1~5%. Hence, investigation on the interaction among jets (with comparable mass flux) with non-parallel axis is really limited.

1.2 Objectives and Scopes

Considered the limitation in the literature regarding the interaction among jets with non-parallel axis and enlighten (motivated) by their applications in flow control, the writer believes that the investigation on the complex velocity fields generated by interacting jets at would yield significant insight in the hydrodynamics of the flow, entrainment and mixing of the plume with the recipient water. The flow data obtained in well-controlled multiple jets experiments would

be able to elucidate the physics and dynamics of the multiple converging jets. In addition, these data will also form valuable data sets to calibrate and validate future numerical modelling works.

In this study, the interactions among three converging jets are investigated in the laboratory. The three jets are set in the same vertical plane and have intersectant axes. Four parameters are mainly concerned in the investigation: the inclined (converging) angles of the side jets with respect to the central jet, the momentum coefficients (velocity ratio) of the side jets, the Reynolds numbers of the central jet and the jet spacing ratio. Two incline angles (30° and 45°), four momentum coefficients ($1/16$, $1/9$, $1/4$ and $1/1$), three Reynolds numbers (4240, 6400 and 8000) and three jet spacing ratios (2, 3 and 4) are applied. The complex interactions have been investigated by employing the advanced laser diagnostic techniques of particle image velocimetry (PIV). With the PIV system, both ensemble-averaged and instantaneous characteristics of the complex flow fields can be acquired. For a turbulent flow, the mean flow may be an artificial construct, but it remains useful as an analytical tool as a base flow over which is superimposed the motion of vortex structures (Lyn *et al.* 1995). Geometric features and gross mixing characteristics have been revisited by the ensemble-averaged (long time average) results. The dynamic processes in the interactions among the three converging jets are revealed by time series of instantaneous flow fields.

Based on the experiments results, the merging and combining phenomenon and hydrodynamic characteristics of the interactions among converging jets are studied. The writer also notes that in most cases of outfall applications, dilutions rely mainly on the theoretical length of jets and plumes trajectory. In practice there always exists certain limitation whereby the outfall design may not be able to achieve their fully established state, and hence the full potential of design dilution. Here lies the desire and motivation to find different geometries of jets configurations that can provide the desirable extent of mixing in a “faster” manner (achieve fully established state).

In summary, the first objective of the present study is to identify the overall characteristics of the complex flows generated from the interactions among converging jets. And the second is to investigate the effect of the initial conditions or arrangements of the converging jets. The third objective of this study is to establish whether the converging-nozzle jets, could generate a flow field that would facilitate better entrainment and mixing right after the jets have merged.

1.3 Outline

This report is organized into five chapters. Chapter 1 is an overall introduction of the present study. The objective and scope of the study are described in this chapter as well. Chapter 2 presents the literature review. After highlighting the basis of fluid kinematics and dynamics, the methodology, accomplishments and knowledge gaps of relevant reported studies are briefly summarised from the perspective of general environmental impact, near-field and far-field studies, and compared with the objective of the present study. Chapter 3 presents a systematic development of the experimental system including the experimental setup and procedures as well as relevant fundamentals of the key experimental techniques employed in the present study. A validation test is also included in this chapter. In Chapter 4, a novel configuration of jets arrangement is presented. Effects of different incline angles, momentum coefficients, Reynolds number of the central jets and jet spacing ratio are discussed in sequence. The final chapter, Chapter 5 summarizes the findings during the course of this study together with some recommendation for possible future studies.

Chapter 2. Literature Review

2.1 Introduction

Chapter 2 briefly summarizes the published studies on multiport diffusers (Section 2.2), phenomenon of the jets “flapping” during jets interactions of parallel jets (Section 2.3), manipulation of inclined control jets (Section 2.4), and the oblique impingement of circular water jets on plane boundaries (Section 2.5). This review focuses on the methodologies, contributions as well as the deficiency in the reported works.

2.2 Jets from linear distributed configuration

As the discharged flow rates are usually large, it may be impossible to adopt a single jet for each and every outfall application. As such, diffusers and multi-port design has been developed to cater for large flow applications. In this case, jets and plumes interactions in the flow fields and the mixing characteristics of such flow play an important role in the design of an outfall (see Figure 2.1).

Figure 2.1: Typical linear distributed jets in multiport diffuser in Ohio River

2.2.1 Laboratory and field experiments

Payne and Schetz (1974) conducted a pioneer study on identifying the efficiency of multiple port diffusers. An experimental comparison had been made of the behaviour of thermal effluents released through a single jet and that through a multiple port diffuser. The former was simpler but showed slower dispersion and dilution. The submerged multiple port diffuser, which was designed to enhance mixing of the discharge with the receiving water, was shown to exhibit small temperature gradients in the receiving stream while a single jet located at the water surface was observed to exhibit large temperature gradients, although this latter

arrangement showed better heat dissipation to the ambient environment. The idea that multiple port diffusers would provide better dilution was also reported in a number of experimental studies (Pincince and List 1973; Roberts *et al.* 1989; Roberts and Snyder 1993).

Isaacson *et al.* (1983) studied the linear multiport diffuser to investigate the near field plume dilutions from ocean outfall. The outfall design comprised line diffusers consisting of evenly spaced risers with clusters of two to eight ports per riser. A series of two-dimensional sectional hydraulic model tests were conducted under both idealized and measured ocean current and stratification conditions. The laboratory results showed that, for the cases studied, the initial dilution was at most a weak function of whether the discharge ports were clustered or evenly distributed along the diffuser, and that the minimum dilution increased with decreasing port size (limited, ultimately, to that of a line source). Therefore, the most cost effective design for ocean wastewater diffusers with risers might be one with small port diameters, and clustering many ports per risers to decrease the number of risers needed.

Other than the initial discharge condition, the recipient water body was also of interests. Roberts *et al.* (1989) conducted experiments to study the dilution and formation of waste-field resulting from discharge into a linearly distributed density-stratified steady current of arbitrary speed and direction, using a model multiport diffuser for a range of parameters typical of ocean wastewater outfalls. Experiments were conducted for Froude numbers F of 0, 0.1, 1, 10 and 100 with diffusers perpendicular, at 45° , and parallel to the current. Dilution was shown not affected by the current for $F < 0.1$, but thereafter increases with current speed. For $F > 0.1$ a diffuser perpendicular to the current was shown to exhibit a higher dilution than that where the current was parallel to the diffuser, although dilutions for parallel flowing currents were always higher than that with zero current speed. The same observations were made by Roberts (1979) for diffusers discharging into unstratified receiving water. Roberts (1979) attributed this observation to the fact that in the case of unstratified flow, the waste-fields always reach the surface, regardless of current direction. Whereas in the case of stratified flow, the rise height was dependent on current direction, with perpendicular currents result in lower rise heights than that for parallel flow. The experimental results were compared to the numerical model of Roberts (1979) which was based on an extrapolation of his unstratified experimental results to that of the stratified case. Although the measured data do follow the power laws and these trends are clearly shown, direct applications of this model results in underestimate of the measured dilutions.

By using the dimensional analysis technique, a number of equations regarding the gross jet properties such as (a) the initial dilution, (b) rise height, and (c) thickness of the established waste-fields at the end of the initial mixing have been derived. It is noted that the effects of port spacing and jet momentum flux have been found to be not significant if not negligible. Hence one may argue that dilution might be independent of port spacing and source momentum flux over the range tested, and was dependent on the buoyancy flux per unit length. This finding is a strong confirmation of the value of the "line plume" approximation for ocean outfalls first used by Brooks and Koh (1965).

Roberts (1979) and others considered the length of the initial mixing region for strong perpendicular currents and the rate of lateral gravitational spreading of the waste-fields for parallel and perpendicular currents and speculated that the end of the initial mixing region should be redefined as the location where the discharge induced turbulence ceased (turbulence collapse). These arguments were in good agreement with measurements of the distance required for the limiting value of dilution to be reached, and consistent with observations of turbulence collapse inferred from the shadowgraphs. For parallel currents the waste-field spread linearly with distance up to and beyond the end of the diffuser. The rate of lateral spreading in parallel currents was analysed by applying a Galilean transformation to the results of previous observations of the spreading of a continuous release of homogeneous fluid from a slot source into a linearly stratified fluid at its level of neutral buoyancy. The expression for the rate of spreading in stratified currents was of the same form as that previously reported for unstratified currents, except that the effect of stratification was considerable reduction of the speed with which the waste-field spread. The waste-field was observed to collapse vertically and spread horizontally for perpendicular currents beyond the initial mixing region. One may argue that this process was analogous to the collapse of submarine wakes or mixed regions and the spreading rate was analysed by applying a Galilean transformation to the results of previously published studies of this problem. The results were applied to predict the properties of the waste-field resulting from the West Point outfall of Metropolitan Seattle. This observation implied that, because of gravitational spreading, a line ocean outfall diffuser would result in a waste-field width of the order of the diffuser length for most typical oceanic conditions. Roberts (1979) further argued that currents flowing parallel to the diffuser were observed not to cause impaired dilution. It followed that Y shaped or similarly complex diffuser configurations might not be necessary to produce a widely dispersed waste-field. The

primary effects of increasing port spacing and momentum flux were on the waste-field rise height and thickness.

Méndez-Díaz and Jirka (1996) conducted an experimental study of the central portion of a unidirectional multiport diffuser discharging in the direction of a uniform ambient current in deep non-turbulent water by using a towed model in a laboratory tank. They reported that the trajectories of the two-dimensional plane plumes that resulted after merging of the individual jets could be divided into weakly deflected plumes, with upstream spreading upon reaching the surface; and strongly deflected plumes, with an intermediate range that contains an upstream blocked wedge. The multiport diffuser in their work was designed to evenly distribute the incoming flow into 24 ports. Three different ports spacing were used ($8d$, $16d$, $24d$, d is the diameter of the port). Méndez-Díaz and Jirka (1996) employed a “leakiness parameter” to determine whether the plume attached to the bottom or rises more or less quickly and finally mixed over the full water column.

Besides buoyancy-driven flow, Moawad and Rajaratnam (1998) presented a laboratory study on the mixing of circular non-buoyant multiple jets discharged into relatively deep river-like cross-flow. Experiments were performed for two different velocity ratios. Three and five ports were used and the spacing between the ports was varied from $8d$ to $16d$, where d is the diameter of port. The concentration measurements were carried out for a maximum relative distance of $160d$. The concentration profiles in the vertical as well as the lateral directions in the planes of maximum concentration were found to be similar. It was found that the minimum dilution decreased with increasing velocity ratio and the number of ports. Increase of the spacing between the ports resulted in considerable enhancement of the dilution. The trajectory of the multiple jets was identified based on the maximum concentration location. Trajectory data indicated that multiple jets rose more slowly than a single jet. A number of equations were developed to describe the growth of the width and thickness of the jets.

Others had attempted to measure the mixing characteristics in close proximity to the diffusers. Kim and Seo (2000) conducted laboratory experiments to investigate mixing characteristics of the co-flowing multiport diffusers, particularly the temperature field on the water surface near the diffuser. The results of his work on heated water mixing was analysed using the 3d grid-based numerical model in which discharge momentum flux was addressed using the concept of a numerical slot diffuser and multi-jet theory. The proposed model gave good prediction for the shapes of thermal plume and also simulated the velocity induced by a co-flowing diffuser in proximity to a shoreline boundary, as was confirmed by Lee and Jirka

(1980). The dimensionless excess temperature along the centreline of the diffuser at the water surface showed that dilution of the co-flowing diffuser increased with increasing momentum ratio because the thermal plume was swept away rapidly from the near field due to strong ambient current. The transverse distributions of experimental dimensionless excess temperature resembled Gaussian curve and the results of the numerical model were generally in good agreement with the measured values.

Moaward *et al.* (2001) conducted a laboratory investigation of chemical mixing in an open channel with multiple circular turbulent jets. The experiments were carried out for cross-flow velocity ratio (varied from 8 to 16), with a combination of co-flowing and cross-flowing jets and only cross-flowing jets. The number of ports for the jets was varied from 20 to 36 and the spacing between the ports was varied from 12d to 24d where d is the diameter of the port. Concentration measurements covered a distance of 2000d downstream. Near the diffuser, Moaward *et al.* (2001) found that the distance from the nozzles at which the jets merged was dependent on the velocity ratio. As the ratio increased, merging between the jets was observed at shorter distance from the nozzles. The results of this study showed that the turbulent jets could be a viable alternative to mechanical methods for achieving chemical mixing.

With the development of laser technology, it becomes possible for one to capture the instantaneous variation of concentration and velocity profiles. Wang and Davidson (2003) proposed an experimental investigation into the merging of horizontal jets in a quiescent ambient fluid. Fifteen equally spaced pipes with two different sets of internal diameters were used in the experiments. A laser-induced fluorescence (LIF) system was used to record the behaviour of the merging jets. The images of the merging jets were converted to quantitative concentration data through the image processing system. A more detailed explanation of the processes involved was reported in Wang (2000). The fluctuation statistics such as the root-mean square and intermittency of the concentration fluctuation were analysed by using the complete sets of images provided in the premeasured system. The tracer and velocity profiles were Gaussian and self-similar throughout the merging process in the X-Z plane (perpendicular to the jets plane). These profiles changed from being Gaussian as merging commenced and became uniform as the merging process was complete in the jets plane (X-Y). The author also reported that all the experimental data obtained in the same observation plane, with different port spacing ratios, collapsed into a single curve. The concentration spreading rate in the X-Z plane increased during the jet merging process, and the increase was about 30% from the axisymmetric to the two-dimensional limit. In contrast, the concentration spreading rate in the

X-Y plane decreased by a similar amount from the axisymmetric to the two-dimensional limit. These results indicated that the growth of individual jets is no longer axisymmetric once the interference from neighbouring jets was sufficiently strong. The change in growth rates during jet merging was also evident in the velocity data obtained by Knystautas (1964). According to Knystautas (1964) the tracer profiles became uniform in advance of the velocity profiles and this was consistent with the difference in their respective rates of spread. The increased growth rate in the vertical plane indicated that the interactions between jets during the merging process increased the rate of jet entrainment in the free entrainment plane. This observation was also consistent with reported experimental results indicating that the spreading rate of a two-dimensional jet was significantly larger than that of an axisymmetric jet. The merging process reduced the mean shear in the jets plane and limited the scale of the large eddies in this plane. These eddies were largely responsible for initiating the entrainment and energy dissipation processes. While on the other hand, more energy would be dissipated by the large eddy motions in the X-Z plane, which in turn enhanced entrainment and spread in that plane.

In contrast to single jets, very little is known about the flow and turbulence structure in multiple jet configurations where the additional factor is the interactions between neighbouring jets. Depending on their mutual distance, a multi-jet diffuser could have a significant effect on heat transfer intensity, especially on heat distribution over the impingement surface. Few results are available on the measurements of the turbulence characteristics. Among the handful of reported studies, Barata (1996) conducted laser-Doppler anemometry (LDA) measurements and numerical simulations in an arrangement of three jets and studied the effect of cross flow on the jets below a V/STOL (vertical/short take-off and landing) aircraft in ground proximity. Findlay (1999) also investigated jets in a cross-flow with configuration consisted of a row of square nozzles. Matsumoto *et al.* (1999) examined qualitatively the flow patterns and heat transfer from an array of circular impinging jets. Other studies on impinging jet and impingement heat transfer have been reported by Geers *et al.* (2004) who performed measurements of velocity field in multiple impinging jets using PIV and heat transfer measurements on the impingement surface using liquid crystal thermo-graph (LCT) to gain a better understanding of the interaction of the flow and turbulence structure with the heat transfer in impinging jet arrays.

2.2.2 Theoretical model and numerical modelling

Jirka and Akar (1991) proposed a scheme of hydrodynamic classification of submerged multiport-diffusers discharges, in which a rigorous flow classification for the expected discharge behaviour from discharges in different ambient conditions and with various discharge geometries was presented. Through dimensional analysis of the basic flux quantities, together with the ambient parameters, Jirka and Akar (1991) proposed six length scale definitions: discharge (geometric) length scale; slot jet/cross-flow length scale; slot jet/stratification length scale; slot plume/stratification length scale; and cross-flow/stratification length scale. Based on these length scales, Jirka and Akar (1991) determined the individual flow class within three major flow categories which include: (a) flow affected by linear stratification leading to internal trapping; (b) buoyant flows in a uniform ambient layer; and (c) negative buoyant flows in a uniform ambient layer;

Lee and Jirka (1980) discussed the method of treating multiport diffuser as a line source of momentum in shallow water. In his work, a model for the velocity and temperature field induced by the line momentum source of multiport diffusers (MPD) was developed. Two important features of the diffuser plume from MPDs were demonstrated both analytically and experimentally. First the initial plume characteristics were controlled by the contracting high-velocity slipstream downstream from the momentum line source. Second, momentum of the plume was dissipated exponentially through turbulent bottom friction which led to ultimate plume stagnation and put an upper limit on the total lateral entrainment flow and a lower limit on the temperature rise.

The dilution of such two-dimensional discharges has been studied, for example, Kotsovinos (1975, 1976); finite line discharges (Roberts 1979) and closely spaced radically discharged flows (Roberts and Snyder 1993)

Less common are studies that focus on the interactions and merging of closely spaced discharges. Knystautas *et al.* (1964) studied the merging of a long line of identical jets in a quiescent ambient fluid. In this situation, fluids released from the central ports were not influenced by edge effects and had two limits to their behaviour. Initially where there was no interaction between neighbouring discharges, the flow develops as a single axis-symmetric jet. As they mixed with the ambient fluid the jets grew and began interacting with each other. Eventually the jets merge fully and their behaviours resembled that of a two-dimensional jet. Knystautas *et al.* (1964) also developed a merging still jet model, based on an axis-symmetric jet model utilizing Reinhardt's hypothesis. The merging of a line of jets was modelled by

adding the momentum from each of the merging jets at a given location. With an appropriate definition of the spread function, the model correctly predicted the bulk behaviour of the merging jets.

Hodgson *et al.* (1999) extended Knystautas' model to provide prediction of tracer dilution. The spreading rate and ratio of the concentration to the velocity length scales were assumed not to change during the merging process.

Wang and Davidson 2003 showed that jet interaction in a still ambient fluid exhibited a changeable spreading rate that occurred when jets merged and moved from axis-symmetric to that of a two-dimensional jet. These differences in spreading rates were evident in reported experimental studies of axisymmetric and two-dimensional jets (Fischer *et al.* 1979). The studies suggested a 10 to 20% increase in the spreading rate during the merging process.

Yannopoulos and Noutsopoulos, (2006) performed experiments using two, three or five interacting identical round vertical turbulent buoyant jets, using tap water as the jet liquid and salt water as the ambient liquid. Yannopoulos and Noutsopoulos, (2006) also conducted theoretical analysis based on both "entrainment restriction" approach (ERA) and "superposition" method and found that the analysis could be carried out by simplifying the partial differential equations of continuity, momentum and tracer of flows. For the ERA, the integration was made on a reduced cross-sectional area, which was the available spreading area for one of two buoyant jets or for a middle jet in a row of an infinite number of buoyant jets. This spreading area extended up to the symmetry planes between the nearby jets and, consequently, was smaller compared to that of a single buoyant jet. In this way, the effects of interactions between buoyant jets were taken into account. In his work, the asymptotic values of the normalized centreline velocities and concentrations for two interacting buoyant jets were found to be $(2^{1/2}, 2^{1/2})$ for jets and $(2^{1/3}, 2^{2/3})$ for plumes, respectively. However, the corresponding asymptotic values for an infinite row of buoyant jets tended to infinity. A second model was proposed to complement the first model, and was used to predict the behaviour of a row of interacting buoyant jets and. This superposition method was based on the concept that the flow and concentration fields of a row of interacting jets might be established by the superposition of suitable quantities of the corresponding single fields of all jets contained in the row.

Later Yannopoulos (2010) proposed an integral model that combined all advantages of "superposition method", "Entrainment Restriction Approach" and "second order approach" to predict the mean axial velocity and concentration fields of a group of N interacting vertical

round turbulent buoyant jets. Two different arrangements of jets were considered: linear diffusers and rosette-type risers.

In summary, a very significant problem encountered when one derives a simulation model for complex flow interactions is that the velocity-concentration correlation is complicated and generally. There is as yet no reported attempted at modelling multiple jets and ensuing flow interactions with multiple jets as a starting point. Instead, most of the models today are based on the modification from that of a single jet.

2.3 Pair of plane jets

2.3.1 Pairs of parallel plane jets

With the development of advanced measurement and computer technology, it becomes possible for one to conduct extensive experimental and numerical studies on the interaction of pairs of parallel plane jets. The earliest studies were those of Tanaka (1970), in which the geometric effects were investigated by varying the spacing between the two jets. The basic flow patterns and entrainment mechanisms were reported in terms of mean velocity, turbulence intensity, momentum, and mean pressure. In addition, three relevant regions of the flow field were identified in the streamwise direction, which is illustrated in Figure 2.2. The first was the converging region, i.e. the interval between the nozzle and the merge point (where the inside shears layers of the jets merge). The velocity on the symmetry plane was equal to zero at that point. The merging of the jets due to the asymmetric nature of the entrainment rates resulted in a region of sub-atmospheric pressure between the jets (Anderson and Spall 2001). The second region was the intermediate, or merge region that existing between the merge point and the combined point. The combined point was the location where the jet velocity reached its maximum on the plane of symmetry. Finally, the combined region was that downstream of the combined point and where the two jets began to resemble a self-similar single jet. Experimental investigation on mixing between two parallel jets by Elbanna *et al.* (1983) showed that the mean velocity profile of the parallel jets attained self-similar and agreed well with the single jet in the region downstream of the combined point. The mean velocity in this region decayed like a single jet although the magnitude of the velocity was higher for the parallel jets. In addition Elbanna *et al.* (1983) report a linear jet spreading of the parallel jets with slightly smaller rate than that of a single jet. Compared to the self-similarity for the mean flow after the combined point the turbulent velocity fluctuation attained self-similar only after 120 diameters.

Soong *et al.* (1998) conducted numerical investigation on unventilated parallel plane jet flow with confinements of wall boundaries at low Reynolds number. Periodic oscillation was observed at certain critical Reynolds number for certain jets proximity. Soong *et al.* (1998) used Strouhal number to make comparisons of the behaviour of dual-parallel jets with that of flows behind bluff bodies. A resemblance in oscillatory state was observed. Soong also stated that the vortex shedding phenomenon in confined jet flows were not sustained downstream due to the different dissipation mechanisms and suppression of the side walls. Other reported work on the oscillation patterns similar to Soong could also be found in the study of a single confined jet by Lawson and Davidson (1999, 2001) and Arruda and Lawson (2004).

Figure 2.2: Schematic diagram of two parallel plane jets proposed by Tanaka (1970)

Anderson *et al.* (2003) reported a distinct instability for small jets spacing to jet width ratio based on the peaks in the velocity spectra. The periodic behaviour appeared to be independent of the Reynolds number when the jets spacing ratio were in the range of 0.5 to 1.7. The “jets flapping” phenomenon was firstly described by Anderson and Spall (2001), in his CFD investigation on the interactions of parallel plane jets. Spall’s results showed that parallel jets with matched momentum flux would become unstable and such instability was characterized by “flapping” of the jet columns. The flapping demonstrated a vortex shedding behaviour which was very close to that observed in the wake behind a bluff body (Anderson. *et al* 2001, 2003). The flapping or oscillation frequency was further investigated experimentally by Bunderson and Smith (2005). The flow motion was found to be “sinuous” with both jets moving in the same direction at the same time. According to Bunderson and Smith (2005), the Strouhal number based on the non-dimension flapping frequency f , $St = f D / U_0$ (f was also

the vortex shedding frequency) was about 0.1~0.33. It was noteworthy that although the interactions between parallel jets was mainly driven by the deflection of jets toward to the centreline due to the pressure gradient, the Strouhal number could still be expected to be of the same order of magnitudes. Hence the frequency f was estimated to be in the order of tens' Hz. which was of the same order as the PIV recording frequency in the present study (15Hz).

2.3.2 Pairs of inclined plane jets

Compared to that of dual parallel plane jets the study regarding the structures and development of dual inclined plane jets is very limited in the literature. The one available reference was the work by Wang *et al.* (1993) and included a series of investigation on the mean and fluctuations of velocity for inclined pairs of plane jets. Three incline angles of 9° , 18° and 27° were involved. Wang *et al.* (1993) divided the flow field into three regions that are analogous to that in parallel jets but with some modifications: (1) converging region A, (2) merging region B and (3) combining region C as depicted in Figure 2.3. The mean velocity was found to be self-similar in both the converging and combining region while the turbulent quantities approach self-similar in the combining region only. The merging and combining points were located at more upstream with larger angle of inclination. The entrainment and spread was similar to that of a single plane jet flow. The square of the decay of the maximum velocity was reported to be linear and the decay rate was less than that of a single plane jet Wang *et al.* (1993).

Figure 2.3: Schematic diagram of two inclined plane jets proposed by Wang *et al.* (1993)

2.4 Inclined round jets

It's interesting to note that although various investigations have been carried out, the jets configurations used were of linear arrangements, with very few that were based on for converging and diverging group of jets. There was reported work on converging and diverging group of jets that dated back to 1960s. Several theoretical and experimental studies (Loitsyanskii 1953; Abramovich *et al.* 1960; Abramovich and Smirnova 1970) had been reported in which the fundamental characteristics of fan jets (flow away from an axis of symmetry) were established. Following the usual treatment using turbulent jet theory (conservation of momentum condition, universal velocity profiles in cross-sections, usual form of the dependence of the jet width on the excess velocity at the jet axis, etc.) one could obtain satisfactory agreement between the calculated parameters of the diverging fan jet and the experimental data, if the empirical constant was assigned a value about 25% smaller than that of the usual straight turbulent jet (0.16 rather than 0.22). This author is not aware of any experimental data for converging fan jets.

Park and Reitz (2009) provided a gas jet superposition model for CFD modelling of group-hole nozzle sprays, in which multiple sprays jets interact with one another. An equation to estimate the merged jet velocity from each of the individual jets was derived based on momentum conservation for equivalent gas jets. The superposition model was validated against experimental results for parallel, diverging and converging group-hole nozzles as a function of the angle between the two holes at various injection and ambient pressures.

2.4.1 Flow stabilization

Although studies about the interactions of converging jets issuing from multiple port diffusers were limited, application of synthetic jets in flow control has been widely investigated. The latter studies may provide supplementary information and insights into the mechanisms associated with the interaction of jets. Tamburello and Amitay (2006) manipulated an axisymmetric jet system comprising a main jet and the control jets. The control jets were located on the opposite sides of the main jet. The characteristics of mixing; spreading and direction of spread were examined experimentally. Several parameters affecting the efficiency of the control were investigated: the effects of the momentum coefficient of the control jets on the instantaneous and time-averaged velocity fields of the main jets were examined using PIV in two orthogonal planes, i.e. along and across the control jets' axis. When the two control jets are activated, the normalized velocity distribution's width in the x - y plane is reduced, where

the main jet becomes wider in the x - z plane (Figure 2.4, x - y is the jet plane and x - z is the normal plane). The penetration of the control jets into the core of the main jet is visible in the double peak distribution of the velocity in the x - z plane. It was found that when low momentum coefficients were applied, a stabilizing effect on the main jet flow field due to the stretching of the main jet was observed. An increase of the momentum coefficient resulted in an opposite effect where the control jets penetrated the main jet core, disturbed its natural growth, and initiated the transition to a turbulent jet. The angle of the control jets, with respect to the main jet flow, also influenced the effectiveness of the control. The control jets with $\alpha = 60^\circ$ (the acute angle between the longitudinal axes of the main jet and control jets) had a greater effect on the main jet flow than those with $\alpha = 45^\circ$. Tamburello and Amitay (2006) attributed this to the fact that the $\alpha = 60^\circ$ jets penetrated the main jet flow closer to the orifice (than that for the $\alpha = 45^\circ$ jets) where the main jet instabilities had not developed, making the main jet flow more receptive to the influence of the control jets. However, because the 45° control jets did not penetrate the main jet flow to the same extent, they were more effective at stabilizing the main jet flow at the lower momentum coefficient.

Figure 2.4: Mean velocity fields of a single round jet with two side injection at 45 degree by Tamburello and Amitay (2006)

Tamburello and Amitay (2006) also investigated the instantaneous flow fields. Their results showed that the vorticity along the shear layer began to break up into smaller structures near the central jet exit due to the interaction of the control jets with the shear layer of the main jet, and further downstream these structures broke up, forming smaller structures that advected downstream with decreasing strength. However, the interaction between the two sides of the

shear layer is somewhat smaller, suggesting that the jet is less unstable than the single jet (without side injections).

2.4.2 Vortex generation and flow control

Inclined air jets have been a common tool to generate vortex for flow separation control. This application was first studied systemically by Johnston and Nishi (1990). They employed vortex-generator-jet method which consisted of spanwise arrays of skewed and pitched jets that can generate longitudinal vortices in the boundary layer and hence increased the cross-stream mixing of streamwise momentum and suppressed flow separation. Compton and Johnston (1992) conducted experimental investigation on the streamwise vortices resulted from the interactions of pairs of skew jets that were pitched up at 45 degree to a turbulent boundary layer. According to their work, the vortices production was strongly dependent on the skew angle and the ratio of the initial velocity of the jets to the surrounding free-stream. It was stated that if the two jets were set at a higher pitched angle, say about 75 degree, then no strong vortex could be generated. However, the physical mechanism was not yet understood until Zhang (1999) investigated the counter-rotating vortices generated by arrays of inclined jets. Zhang (1999) suggested that once a skew angle was introduced, a single dominant streamwise vortex would be formed and if arrays of inclined jets were applied then counter-rotating vortices would be generated. Johnston and Nishi (1990) found that these vortices could cause significant spanwise skin-friction variation and provided good performance in separation control in stall regions. A judicious choice of skew angles could produce effective flow control. Selby *et al.* (1992) identified an optimal skew angle that ranged from 60 degree to 90 degree while Compton and Johnston (1992) gave a smaller value of between 45 degree to 60 degree and Zhang (1999) suggested a value in range of 30 degree to 60 degree.

2.5 Impinging wall jets

Naib (1974) conducted an experimental study on oblique impingement of submerged air jets set at different incident angles (15° , 30° , 45°). The spreading of the deflected jet and the velocity field up to $35d$ (d is the diameter of the jet) were investigated. The velocity distribution was found to be similar with wall-jet like flow and the spreading rate in the lateral direction was about five times than that in the perpendicular direction. Beltaos (1976) provided the measurement of pressure field as well as the boundary stress on the plate. Araujo *et al.* (1981) measured some turbulent stresses, for oblique angle of 0° , 10° , 15° and 20° .

Kate *et al.* (2007) investigated the hydraulic jumps due to oblique impingement of circular liquid jets on a flat horizontal surface. Jumps corresponding to the range ($25^\circ < inclination \leq 90^\circ$) were observed and found to be bounded by smooth curves. The oblique impingement of circular water jets on a plane boundary were further studied by Jalil and Rajaratnam (2006). A wide range of oblique angles ($15^\circ, 30^\circ, 45^\circ, 60^\circ$ and 60°) were reported. The deflected jet was mostly in the forward direction and with little backward flow when the angle was smaller than 45° . The thickness profiles of the deflected jets in both the central plane and transverse plane were found to be similar for certain cases in their work, and with appropriate scales.

The subject of three-dimensional wall jets had received a great deal of attention in the past few decades. A scan of the literature revealed that the mean velocity profiles in both the streamwise and spanwise direction were similar in the zone of established flow. Rajaratnam and Pani (1974) showed that, in the established flow region, the half-width of both streamwise and spanwise plane varied linearly in the flow direction with lateral growth at a rate 4 to 5 times faster than vertical growth.

Similar anisotropy of the two expansion rates were also observed by Newman *et al.* (1972), Padmanabham and Gowda (1991). Launder and Rodi (1983) suggested that the augmented lateral spread was mainly caused by a secondary vortex motion, which was later confirmed by Abrahamsson *et al.* (1997) with LDA measurements.

Law and Herlina (2002) conducted a laboratory investigation on the characteristics of a circular three-dimensional turbulent wall jet. Velocity profiles in their work exhibited similarity in both the streamwise and spanwise directions after $20d$ and $25d$, respectively, where d is the diameter of jet exits.

2.6 Summary

Published studies on the conventional arrangements of diffusers with linear jets configuration including laboratory and theoretical research were reviewed; and the resultant near-field and far-field processes in the recipient water body are summarised in this chapter. The review revealed a huge growing need for better understanding and knowledge about the design of outfall diffusers, hence the strong motivation for this present study.

It is noted that great effort have been expended on the interactions between jets from several types of outfall arrangements, especially for linear diffusers and rosette-type diffusers. By treating the jet axis as parallel straight lines in the development of the flow, the integration

method and superposition method have been applied to develop theoretical analysis for such complex flow. It remains doubtful whether these methods can be applied to jets flux from multiport diffusers with interlaced axis. In the literature, pairs of inclined jets were manipulated to stabilize the flow and avoid separation. Although the developments of vortex generated by inclined jet pairs have been studied by many researchers, detailed characteristics of the whole flow field are surprisingly sketchy and scarce. Only a handful of studies reported work on 30° and 45° inclined dense jets. There is a general consensus on the inadequacy of the limited data set to support the development of predictive models (Jirka, 2008; Bleninger and Jirka, 2008), not to mention the disparity among certain reported gross flow characteristics. It is also noted that the effects of bed proximity has not been examined until Shao (2010) who first considered the so-called Coanda effect on the behaviour of the inclined and offset horizontal dense jets. The impingement between a jet-like flow and a plate boundary was also of interest to research works on impinging wall jets.

Chapter 3. Experimental Methodologies

3.1 Introduction

As noted in the introduction, the advanced laser-based measurement tools - particle image velocimetry (PIV) is employed in the present experimental investigations to measure the velocity fields of the flows. In this chapter, the author first reviews the major previous studies using PIV as the experimental techniques, through which the author has gained a general idea of how the technique has been evolved to its current state (Section 3.2). Then the author describes in details the specific setup used in the present study. The key components and accessories, their configuration and work mechanism are elaborated (Section 3.3). Then the general experimental procedures are introduced and discussed (Section 3.4). The experiments were conducted in the laboratory of the School of Civil and Environmental Engineering, Nanyang Technological University. The relevant experimental uncertainties are identified and analysed (Section 3.5).

3.2 PIV technique

In the past decades, traditional intrusive techniques such as Pitot tubes or hotwire anemometry (HWA), and non-intrusive laser Doppler velocimetry (LDV) or acoustic Doppler velocimetry (ADV) have been widely used to measure velocity in various fluid flows. Single-point measurements have the advantage of relatively high temporal resolution, or sampling frequency. However, they do not provide such information of the whole flow field at any one time. To reconstruct the spatial velocity distribution of a steady flow, one can repeat point measurement at different locations. The procedure is tedious and time-consuming. If the flow is unsteady, such an attempt becomes very difficult or even impossible. With the technological advancement of lasers, optics, modern cameras, and computer hardware/software, new whole field velocimetry techniques have emerged. Different from the point-based techniques, the state-of-the-art planar velocimetry such as particle image velocimetry (PIV) and particle tracking velocimetry (PTV) are now available and these techniques are capable of resolving the spatial variation of the turbulent flows. In recent years, PIV and PTV have been used extensively to measure complex spatially varying turbulent flows. The fundamental working principle of PIV is straightforward. The general setup of 2D PIV system is depicted in Figure

3.1. The flow is seeded with tiny, neutrally buoyant particles that were illuminated twice by the light sheet formed by passing a double pulsed laser beam through an optical arrangement including cylindrical lenses. Instantaneous marker locations are then optically frozen and recorded on a sensor medium such as a video array detector. The recorded images are then correlated to obtain the instantaneous velocity, V_i from the basic kinematic relation: $V_i = \Delta s / \Delta t$, where Δs is the marker displacement within two consecutive laser pulses and Δt is the time interval in between. A comprehensive in-depth account of the PIV technique can be found in Willert and Gharib (1991).

Figure 3.1: General setup of a 2D PIV system

3.3 Experimental setup

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

3.3.1 Facilities

A schematic diagram of the overall experimental set-up for the experiments of jets from multiport diffusers is shown in Figure 3.2. The experiment was set up in a Perspex tank with dimensions of 600 mm (Length) by 500 mm (width) by 600 mm (High). The transparent wall allowed the laser beam to shine into the tank from various directions. The test tank was designed to include a test domain and an overflow basin. A perspex mounting platform was installed at the bottom of the tank to simulate the sea bed, as well as to allow the nozzles to protrude from it. The effluent (in this study, the effluent was the same fluid as the recipient fluid) was injected from three bronze nozzles (inner diameter of 8mm). The centre of the

nozzle tips were protruded to a certain depth to ensure negligible disturbance from the bed. The nozzles were sufficiently long to generate fully developed turbulent flow at the exit. The mounting platform was changeable so that different inclined angles could be applied as discussed in detail in sections 4 and 5. The nozzle spacing S was defined as the distance between the centres of the tip of two adjacent nozzles.

Figure 3.2: Schematic diagram of experimental set up (not to scale)

3.3.2 Accessories

Flow meter

A calibrated flow meter (Model: L101SA-2, capacity: 0.1/1.0 GPM or 0.4/4.0 LPM, accuracy 1%, connection: ½ inch F/NPT) was installed between the submerged and the nozzle exit to measure the flow rate in the pipe hose. Installation of the flow meter is shown in Figure 3.4 (a).

Submerged water pump

Three submerged water pumps (EASY PUMP®, EP400040- SUB 200 model, V240-Hz50, and Watts 200, is shown in Figure 3.4(b)) were used to pump water to the bronze nozzle through the flexible hose during the experiments. The maximum delivery capacity was 6000L/Hours and the maximum head was 6m. The flow rate provided by the submersible pump was fully controllable using the flow regulating valves.

3.3.3 PIV system

The velocity fields in the vertical plane of the various experiments were measured using the PIV technique. The advantage of PIV technique over the point-based techniques and its basic principle was discussed briefly in Section 3.2. In the following section, the individual component of the PIV system employed in the present study is reviewed. Figure 3.3 shows the schematic diagram of the PIV system.

Figure 3.3: Schematic diagram of the PIV system

Figure 3.4: Experimental apparatus: (a) flow-meter, (b) seeding particle, (c) submerged pump and (d) nano laser emersion

Seeding particles: In the PIV measurement, it is actually not the velocity of the flow that was being measured, but those of the particles suspended in the flow were measured. It was required that the seeding particles had to be as small as possible to follow the flow faithfully and passively, i.e., to follow the motion of the fluid without significant lag and yet not to alter the flow dynamics. However, at the same time, particles must be large enough to scatter sufficient light so that distinct particle images could be captured clearly, which in turn enhanced the accuracy of the image analysis that followed. A narrow particle diameter distribution would also be desirable. The particles should also be neutrally buoyant in the fluid. Typically, the diameters of the seeding particles used for PIV measurement range from 0.1 to 50 μm . In this study, Spherical[®] 110P8 hollow glass spheres, which were neutrally buoyant with a mean diameter of 15 μm were selected as tracer particles.

Nano Nd: Yag laser A double cavity Nd: YAG laser (Litron model) was placed below the test tank to illuminate the flow. This arrangement greatly reduced the penetration length of the laser in water, and thus reduced the potential attenuation of light intensity. The laser had an energy output of 135 MJ per pulse and emitted green light with a wavelength of 532nm. By using the Quantel-switch, the pulse duration could be as short as 5 ns, which produced a stroboscopic effect and optically froze the movement of the particles during the illumination.

Charge-coupled device (CCD) camera: The particle images were recorded using a 12-bit charge-coupled device (CCD) camera, which had a resolution of 1600×1200 pixels and a frame rate of 15Hz. Considerable care was taken to ensure the high quality of the images.

For PIV measurements, the displacement of particles in the time between the laser pulses is recorded as either a single image exposed twice or as a pair of two single exposure images. Depending on the flow velocity and the factor of magnification of the camera lens the

delay of the two pulses have to be chosen such that adequate displacements of the particle images on the CCD are obtained.

There are two possibilities to evaluate the particle images that depend on the way these images have been recorded by the used camera. One is to record the scattered light of both illuminations in one frame what is called “single frame/ double exposure”. These pictures can be evaluated by auto-correlation. The other possibility is record the scattered light from the first illumination in one frame and the scattered light from the second illumination in another frame. This is called “double frame/ double exposure”, in which the double frame images are evaluated by cross-correlation. However, the auto-correlation function cannot detect the sign of the displacement since one does not know which particle is illuminated by the first and the second laser pulse. In consequence, the information from the auto-correlation is ambiguous and not conclusive. Therefore, the “double frame/ double exposure” with cross-correlation are used in the present study. One thing important during the “double frame/ exposure” procedures is, as the second frame cannot be shuttered the two images would have different background intensity. To safeguard the image quality suitable filter is installed in front of the cameras lens. The filter is a 532 nm band-pass filter that only allows a narrow band of 1 nm wave length around 532 nm that is scattered by the seeding particles to pass through. In addition, the author used dark room and switched off the room light during the measurement to keep the ambient light intensity as minimum.

Flow Master DaVis 7.2 Software: The Flow Master DaVis 7.2 was a CCD image acquisition and processing software package developed by LaVision and constituted the core of the PIV system. The software system included a modular processor consisting of correlators units, input buffers and a synchronization board.

Vector field computation: The computation and analysis of the raw images are documented in detail in LaVision Flow Master PIV Product-Manual (2007). A general procedure of the correlation analysis method is described as follows.

For the evaluation of images via correlation the complete is divided in so-called Interrogation Windows. The velocities of PIV are measured based on interrogation windows (IW) rather than randomly distributed individual particles. The correlation function operates on the intensities inside each IW and passes through the complete PIV recording with a specified window shift, yielding one velocity vector for each IW.

In the present study, the particle displacement based on the instantaneous PIV image was calculated using the cross-correlation algorithm with the standard Gaussian sub-pixel fit

structured as an iterative multi-pass method. Evolved from the standard cross correlation, the multi pass method is used to calculate the vector field by an arbitrary number of iteration N_x with a decreasing IW size. The calculation starts in the first pass with the initial IW size and evaluates a reference vector field. In the next pass the IW size is half the size of the previous pass and the vector calculated in the first passes is used as a best-choice window shift. In this manner the window shift is adaptively improved to compute the vectors in the following steps more accurately and more reliably. This method allows the author to use much smaller final IW size and finally improves the spatial resolution of the vector field and produces less erroneous vectors. For the present study, the final IW size is configured as 32×32 pixels and the number of multi-pass (decreasing window size) N_x is 1, thus, the initial IW size is 64×64 pixels. The final grid size of the vector field in the PIV measurement is determined by the IW size and the window overlap. The overlap defines the overlap among neighbouring IWs. In the present study, a 50% overlap is used to enlarge the spatial resolution. A schematic illustration of the overlap is shown in Fig 3.4.

Figure 3.5: Schematic diagram of 50% interrogation window overlap

3.4 Experimental Procedures

In this section, the general experimental procedures adopted for all experimental tests are presented. The procedure consists of four main stages: (a) preparation, (b) laser alignment, camera focusing and image re-sampling, (c) calibration and data acquisition, and (d) data analysis.

3.4.1 Preparation

Before starting the experiment, the test tank was drained, and refilled to a certain depth to ensure that the jet exits and pertinent plume domain would be kept well below the free surface.

A small amount of seeding particles was injected into the ambient water around the measurement area to enhance the velocity measurements in the vicinity of the plume flow. The tank was filled and left to be stationary for 2 hours prior to the experiments to establish a desirable stagnant ambient water condition.

Figure 3.6: Laser alignment and camera operation

3.4.2 Laser alignment, camera operation and capture of images

The Nd: Yag laser head used in this study was mounted on the top of a lead screw base (Figure 3.6) and could be moved to any desired location during the experiment. The emitted laser light (marked by dot line in Figure 3.6) was aligned to coincide with the vertical central plane of the nozzle to illuminate the target area by adjusting the leveling feet at the base of the laser support.

The PIV system included two CCD cameras. Only one camera was used most of the time. The CCD camera was placed normal to the tank and when the needs arose, the camera could be rotated by 90° so that the image captured for the jets flow would be horizontal on the screen instead of being vertical in the real version, which ensured a better observed space in the longitudinal direction. When the camera was moved to the desired location, a reference object, a steel ruler or self-constructed grid, was lowered into the tank and aligned with the central plane of the nozzle, both to act as the target focusing the camera(s) and to ensure that the camera(s) captured exactly the same target area. By placing the reference object in the measurement plane, the writer obtained a relationship between the pixels on the CCD chips and the physical distance in that plane, i.e., the object-to-image scale factor of the captured images.

After this step, a small amount of seeding particles was then scattered inside the tank near the target location, and the setting of “adaptive correlation” was selected in the operating system to initiate capturing the images.

3.4.3 PIV measurements parameters

The time interval between laser pulses, Δt , was a significant experimental parameter in the PIV measurement since it determined the maximum and minimum velocities that could be measured (Shao 2010). Shao (2010) also gave a preliminary upper-bound limit of the time interval based on the maximum particle displacement during such period, expressed as the following formula:

$$\Delta t \leq \frac{0.25N_{int}SFd_{pixel}}{U_{max}} \quad (3.1)$$

in which U_{max} is the maximum velocity estimated in the flow field, N_{int} was the size of the IW in pixels (which is 32 in the present study), SF is the object-to-image scale factor and d_{pixel} is the pixel pitch (e.g., $6.05 \mu m$ for the Nikon D60 camera used in the presented study).

Meanwhile, the Flow Master DaVis 7.2 utilized in the presented was equipped with a function that computed the time interval Δt . An estimation of the maximum velocity was also required. By reviewing the reported study in PIV measurements (Wang and Tan 2007; Shao 2010), the IW was finally chosen to be 32×32 pixels and the time interval between pulses was set in the range of $400 - 1000 \mu s$ in the present study.

3.4.4 Data acquisition

At the beginning of the experiment, the regulating gate valves were opened gradually until the target flow rate was obtained. After the flow rate had been stabilized (typically took about 90 seconds), the laser system was then switched on. Since the interacting jets were three-dimensional flow, 2 central planes were selected. They were the restricted plane (containing the jets) and free entraining plane (the normal plane), which has been shown in Figure 3.2. Thus, each group of experiment has two tests for the two target planes. Once initiated, the laser would set to be activated and images captured until 1050 images were recorded. This number of images would ensure that one could perform time-averaged parameter analysis reliably. Different flow rates were investigated for each test/nozzles configuration. After each test, the mounting platform was rotated 90 degree horizontally and the experimental procedures repeated. In this way, the flow fields in two orthogonal vertical planes were captured.

3.4.5 Data analysis

The instantaneous PIV images were analysed using the cross correlation algorithm with the standard Gaussian sub-pixel fit structured as an iterative multi-pass method. As mentioned before (Section 3.3.3), the final size of Interrogation Window (IW) in the present study was 32×32 pixels. Therefore using an interrogation window (IW) size of 32×32 pixels and an overlap of 50% for the image of 1600×1200 pixels (according to the resolution of the CCD Camera) gave 100×75 IWs and 7500 vectors. Then the grid size of the vector field was 16 pixels corresponding to a spatial resolution of $2.5 \text{ mm} \times 2.5 \text{ mm}$ (according to the size of measurements domain $270 \text{ mm} \times 200 \text{ mm}$, see Figure 3.2). As noted earlier, the overlapping is necessary due to errors inherently present close to the edges of the IWs. Raw vectors from the adaptive correlation included both valid and invalid vectors. The invalid vectors due to the noise peaks in the correlation function were typically unavoidable, and were eliminated or substituted by using validation algorithms (in this study, both Range and Moving-Average validations were performed together, sequentially). The 1050 instantaneous moving-averaged velocity maps were then time-averaged to obtain the mean velocity field. In the mean velocity map, only valid vectors were retained to obtain a better representation of the velocity field.

3.5 Image sampling

The physical measuring process and the methods of evaluation of the collected data including the recording frequency and the sampling size are discussed in this section.

3.5.1 Image recording frequency

In the past, the experiments using PIV were always constrained by the limitation of the recording duration and frequency. The adequacy requirement for determining turbulence properties with a specific averaging time and recording (sampling) frequency had been addressed by Law and Wang (2000) for turbulent buoyant jets. Theoretically, turbulence fluctuation of the velocity was directly related to the turbulent energy content in whole system according to Tennekes and Lumley (1983) as: $\overline{u'^2} = 2 \int_0^\infty E(f) df$, where $E(f)$ was the spectral energy density at a particular frequency f . However, the integration on the entire energy spectrum was not possible and also might not be really essential in practice. Therefore to determine the magnitude of the velocity fluctuation for turbulent jets, an appropriate measurement could be obtained only if most of the energy content in the associated spectrum was taken into account in the range of the measuring frequencies, i.e., $\overline{u'^2} \cong 2 \int_{f_l}^{f_u} E(f) df$,

where f_u and f_l were the upper and lower limits in the measuring frequencies (also see in Shao 2010). Papanicolaou and List (1988) suggested an optimum recording frequency of 20 Hz for buoyant jet in highly turbulent region. Whereas, in the present system, the CCD camera used was capable of maximum frame frequency of 15 Hz that was marginally slower than that suggested by Papanicolaou and List (1988). The writer believed that this limitation was not critical and results based on 15 Hz might still be reasonable considering the fact that the Reynolds numbers in the present study were smaller, which meant that the upper limit of the turbulence energy spectrum that the system was capable to resolve would be the Nyquist frequency of 7.5 Hz. This frequency would be sufficiently high for the determination of the turbulence velocity fluctuation in those mixing processes with bulk of the energy production occurring at a much lower frequency suggested in Shao (2010) and experiments by Papanicolaou (1984) of a vertical pure jet into stagnant ambient fluid. For the streamwise velocity, the energy production occurred primarily in the range of 0.1 to 1 Hz with a decay magnitude of 3 orders from 0.1 to 3Hz. For the radial velocity, the turbulent energy spectrum decayed less rapidly with a decrease of about 2 orders of magnitude in the same range. According to Papanicolaou and List (1988), vertical jets issuing into stagnant ambient were estimated to have large-scale times of 0.8 second, see Law and Wang (2002) who adopted a recording duration of 60s and a frequency of 5 Hz. Their measurements were shown to be adequate for statistical turbulence analysis in terms of conservation of total mass and total momentum (including turbulence contributions). Therefore, the writer concluded that the measurement frequencies utilized the present set-up would still be sufficient to determine the turbulence properties.

3.5.2 Image sampling size

To conduct a reliable measurement, an assessment of the minimum data sampling size that is able to achieve the statistical significance was performed by a trial run. The trial run is concerned with a single pipe jet flow. The experimental conditions are given in Table 3.1. Four time-independent sets of sample data were measured for the same region with 210, 630, 1050 and 1470 images respectively. The same procedure was used to process these four data sets, i.e., multi-pass from 64×64 pixels to 32×32 pixels IWs with 50% overlap and the same correlation and validation schemes. The raw map of the mean velocity (U, V) and associated velocity fluctuations for the horizontal component $\sqrt{u'^2}$ for S1 are shown in Figure 3.7 and Figure 3.8.

Table 3-1: Experimental conditions of the trial run

Jet configuration	Incline angle	Nozzle diameter (mm)	Average discharge velocity (m/s)	Reynolds number Re
Single jet (S1)	0	8	0.53	4240
Single jet (S2)	0	8	0.80	6400
Single jet (S3)	0	8	1.00	8000

From the comparison of the results associated with the different sample sizes, it is clearly evident that although the difference in the mean velocity is little (Figure 3.7), the fluctuations of the velocity derived from 210 and 630 samples contrast greatly with that derived from data sets with larger sample sizes (Figure 3.8). Whereas the results from data set with 1050 and 1470 samples are generally consistent with each other (little or no difference). Considering the recording duration and the time consumption of data processing, sampling size of 1050 images were chosen for all the experimental run in the present study.

Figure 3.7: Raw map of mean velocity vector for data sets of S1 with (a) 210 (b) 630 (c) 1050 (d) 1470 samples

Figure 3.8: Raw map of velocity fluctuation for data sets of S1 with (a) 210 (b) 630 (c) 1050 (d) 1470 samples

3.6 Validation test run

The target experiments were jet and group of jets. The first thing the author did was to ascertain that the experiments began with a test series of single jets. There were several reasons for this and they include the followings:

1. Results of single jet flow experiments had been published;
2. Empirical and semi-empirical relationships describing the jet flow and evolution of the plume with certain flow parameters; and
3. Comprehensive characterization of the development of a single jet had been reported.

Therefore, the writer first conducted experiments with a single jet and characterized the jet flow and compared the results obtained with published findings. In this way, the writer confirmed that the experimental methodology and data analysis for a single jet were valid. As it was difficult to verify the results of converging jets and experimental results were scarce, the writer's approach of starting with experiments of single jets was a logical first step to establish the validity of the experimental methods and data measurements. The following describes the results obtained and data analysis for the writer's experiments with a single jet.

In the data analysis, a range validation and calibration together with a moving filter were used to exclude singular or erroneous vectors. For each experiment, a set of 1050 frames of the instantaneous flow field were acquired at a frequency of 15Hz (i.e. 70s of recordings). The time interval between subsequent laser pulses was 400-700 μ s which satisfied the criteria proposed

by Boillot and Prasad (1996) and Shao (2010). The velocity of the flow at the nozzle exit was such that one obtained a displacement of 6.5 pixels near the jet exit. Other parameters such as the particle image size (3-4 pixels) and seeding densities (about 30 particles/mm²) were established based on the experience gained by peer researchers working on the same system, see Wang and Tan (2007), Gao *et al.* (2011). The maximum uncertainty in the particle displacements was estimated to be 0.1 pixels, yielding a relative uncertainty error of 1.5% (0.1 pixels normalized by 6.5 pixels) for instantaneous velocities measurement. Therefore the uncertainty of the instantaneous vorticity ($\Omega_k = u_{i,j} - u_{j,i}$) was four times of 1.5% or 6%. The statistical characteristics of the flow in the present study were obtained by ensemble-averaged value of 1050 instantaneous fields. The uncertainty estimation and analysis of PIV technology followed the same approach recommended by Scarano and Riethmuller (1999), Forliti *et al.* (2000).

The geometric conditions of the validation test are the same as that is given in Table 3.1. Three averaged-exit velocities (U_0) of 0.53 m/s, 0.8 m/s and 1.0 m/s were applied during the validation experiments. The Reynolds numbers $Re = U_0 D / \nu$ were 4240, 6400 and 8000 respectively, where the kinematic viscosity of water at 20 °C $\nu = 10^{-6}$ m²/s. The jet flow utilized in the present was corresponded to a typical pipe jet that depicted different initial velocity profiles with that of contraction jet or orifice jet.

Distributions of the mean streamwise velocity normalized by the centreline value and jet half width at $X/D = 2, 5, 8$ are shown in Figure 3.9(a) for S1 (almost identical to that of S2 and S3). The two end tails of the initial pipe velocity profile are gradually affected by the shear layer at the edges of the jet. The distribution follows a Gaussian form as suggested by Vouros and Panidis (2013). Ferdam *et al.* (2000) found that the evolution of the pipe jet with an axisymmetric fully developed inlet profile would evolve toward a self-preserving state more rapidly than that of a jet with a uniform (top-hat) initial velocity distribution. Distributions of the mean streamwise velocity normalized by the centreline velocity at $X/D = 12, 17, 22$ and 27 from the jet exit are presented in Figure 3.9(b). Also included in Figure 3.11 are the results measured of Hussein *et al.* (1994), represented by a solid line, for $X/D = 70$ from the jet exit of a jet with significantly higher Reynolds number $O(10^5)$; and the results of Vouros and Panidis (2013) by dashed line, from $X/D = 15$ to 60 for a single pipe jet at the same order of magnitude Reynolds number (5500). Note that the results of Hussein *et al.* (1994) and Vouros and Panidis (2013) shown in Figure 3.9(b) have been reformatted to suit the current coordinate

system. Downstream of $X/D = 12$, the profile of the mean streamwise velocity in the X-Y plane shows almost perfect Gaussian form. The observed small deviations of the profiles from a Gaussian distribution at successive locations are within the estimated maximum errors, indicating that the mean velocity has reached self-similarity at this point.

In the present study, the self-similarity of Gaussian profile is attained downstream of $X/D = 12$ as shown in Figure 3.9(b), which is very close to those of $X/D > 15$ presented by Hussein *et al.* (1994) and Vouros and Panidis (2013). The centreline velocity U_c and jet half width $Y_{1/2}$ remains constant from the jet exit till $X/D = 6$. Further downstream the centerline velocity U_c and jet half width would decay and grow linearly, respectively. The longitudinal profile of U_e/U_c and $Y_{1/2}/D$ are illustrated in Fig 3.7 and 3.8. Similar linear growth for both U_e/U_c and b_u/D could be observed at $X/D > 5$ and the linear correlation could be described by the expression of: $U_e/U_c = (X - X_0)/K_u D$, $Y_{1/2}/D = (X - X_{0b})/K_b D$, where K_u is the decay coefficient and X_0 was the virtual origin of the jet. The subscript u and b denote the parameter associated with the mean velocity and jet half-width, respectively. Here, U_e/U_c was utilized to be the dimensionless velocity scale for the convenience of making comparison with those from reported studies. The parameters described here are summarised in Table 1 along with the values reported by others. Good agreements can be observed for the velocity decay coefficient and the spreading rate while the virtual origin of the present experiment is found to be located further more upstream than most reported studies especially that of (Vouros and Panidis 2013).

A pertinent test of validity of any experimental data is whether it satisfies the governing equations (George 1990 and Hussein *et al.* 1994). For a single axisymmetric jet in a free infinite environment, the most commonly accepted criterion of validity is whether the velocity moment profiles satisfy the momentum integral equation: $2\pi \int_0^\infty [U^2 + \overline{u^2} - \frac{1}{2}(\overline{v^2} + \overline{w^2})] r dr = M_0$. A first order analysis of the integrated momentum balance has been proposed by Hussein 1994 who used the mean velocity profiles as fitted Gaussian profile (see Figure 3.9b). The momentum balance is then a function of only the centreline velocity decay constant and the jet half width constant K and $K_r: \frac{M}{M_0} = 2\pi \int_0^\infty \left[\frac{U}{U_c} \right]^2 (\eta) \eta d\eta = 2.27(K_r K)^2$. Noting that the velocity decay constant K is that for the conventional (contraction) round jet, a conversion has been made for a single pipe jets as $\frac{M}{M_0} = 2.89(K_r K_u)^2$. Using the values of K_u and K_r establish in the current investigation (see Table. 3.1), the first order contribution to the

momentum integral is 86% of the source momentum. This is higher than the value of 69% obtained from data of Wygnanski and Fiedler (1969) and comparable to that of 85% from the LDA/FHW experiments by Hussein *et al.* (1994) but much lower than their SHW value of 106%.

Figure 3.9: Radial distribution of the mean axial velocity for a single jet a) near the exit b) after 12D

Figure 3.10: streamwise variation of the centreline velocity decay for a single pipe jet

Figure 3.11: streamwise variation of the jet half width for a single pipe jet

Table 3-2 : Summary of jet's development properties

Authors	Re	K	X_0/D	K_b	Diagnostic
Boguslawski and Popiel 1979	$0.5 \sim 1.25 \times 10^5$	5.9	-0.5	0.08	HWA
Xu and Antonia 2002	8.6×10^4	6.5	2.6	0.086	HWA
Malmström <i>et al.</i> 1997 ^a	1.3×10^4	5.94	-2.0		HWA
Voursos and Panidis 2013	5.5×10^3	5.7	2.65	0.078	LDA
Hussein <i>et al.</i> 1994 ^a	9.5×10^4	5.9	2.7	0.102	LDA
Kwon and Seo 2005 ^a	$3 \sim 5 \times 10^3$	5.5		0.113	PIV
Tamburello and Amitay 2006	6600	9.74	-3.3	0.13	
	26500	9.74	-5.6	0.11	PIV
Present study	$5 \sim 8 \times 10^3$	6.4	-0.2	0.085	PIV

^a studies on orifice or contraction jets

3.7 Concluding remarks

Based on the findings of the experiments with singles jets and comparison of the results obtained with published data, the writer was satisfied and confirmed that, the current experiment setup was robust and captured the flow characteristics of a single jets satisfactorily. This observation render confidence for the writer to use the same setup and measurement methodology to conduct the experiments with converging jets as presented in the following chapters.

Chapter 4. Interactions among Converging Jets

4.1 Abstract

Mixing phenomena of jets have an essential role in a variety of engineering applications. To enhance mixing, one may consider interacting jets as the arrangement could generate additional lateral instability that may enhance entrainment of ambient fluid into the jet plume. The extent of mixing may be controlled by selecting the pertinent flow rate, jet spacing and the incline angle of jets. There are substantial amount of reported works dealing with the zero-degree inclined (parallel) pair of plane jets (see the review in Chapter 2). The parallel pair of plane jets was found to provide greater entrainment and spreading rate in the combined region by some, example Lin and Sheu (1990) and smaller by others, for example Elbanna *et al.* (1983). When the jets are inclined, larger spreading rate was found in the converging region (Wang *et al.* 1993) than that of a single plane jet. Wang *et al.* (1993) did not conclude the effect of different incline angle while implied by their results the three different angle of 9° , 18° and 27° had the almost equivalent spreading rate throughout the measurement fields.

Considered the limitation in the literature regarding the interaction among jets with non-parallel axis and enlighten by their relative applications in flow control, the writer believes that a thorough investigation including more parameters (momentum coefficients, jets spacing, inclination angle and Reynolds number) on the complex flow fields generated by one central jet and two side injections would provide significant insight hydraulic characteristics of the mixing and entrainment of the jets with the recipient water. In this chapter the writer presents the findings of a laboratory investigation on the interactions among three identical (with the same diameter) converging jets (set at an inclination angle in the same vertical plane, namely the X-Y plane) into stationary water. The objective of the study is to elucidate the fluid-dynamic features produced by converging circular pipe jets. Various Reynolds numbers and nozzle spacing diameters ratios were selected to quantify the mixing behaviour of the converging jets. Advanced laser diagnostic techniques of PIV system described in Chapter 3 were used as the measurement approaches in the experiments (Wang and Tan 2007). Based on the experimental results, the geometrical characteristics of the converging jets, including the impingement or combining point as well as the location where the compound flow became fully established,

were recorded and described. Other features, such as the velocity spreading widths and centreline velocity decay along the jets axis as well as the quantitative measurement of turbulence were also analysed based on the ensemble-averaged flow field. Instantaneous flow fields were also presented to illustrate the dynamic interactions among three converging jets in terms of the vortical structures generated. Based on the findings of the investigation, the writer found the complex flow generated by the three converging jets in the vertical plane that contained the jets (X-Y) was characterized by rows of large-scale Karman-like vortex that interact with each other periodically, instead of the standard Kelvin-Helmholtz (K-H) roll-up located in the shear layer for a single pipe jet. However, in the plane normal to the jets (X-Z), the flow structures are found to be complex. The K-H structures in the mixing layers are significantly expanded at the very beginning of the merging and break into smaller structures when the two mixing layers start to flap sinusously and interact with each other. These interactions are noteworthy in the central portion on this plane indicated by pairs of counter-rotating vortices.”

4.2 Experimental setup and procedures

A schematic sketch of the overall experimental set-up is shown in Figure 4.1. The experiments were conducted in a tank of 0.5 m (L) by 0.5 m (W) by 0.65 m (H). All the side walls and the base of the tank were made of smooth perspex to allow optical access from various directions. A perspex rig was installed at the base of the tank for mounting the bronze nozzles each of which was 8 mm in inner diameter and 80mm in length. The centres of the three nozzle tips were set to protrude to 45 mm from the base to ensure negligible disturbance from the bed. The bronze nozzles of 80 mm length were sufficiently long to produce fully developed turbulent jet flow conditions at the nozzle exit. Various nozzle spacings $S = 16, 24$ and 32 mm was selected. Here the nozzle spacing was defined as the distance between the centres of tips of two adjacent nozzles. Hence the nozzle spacing-diameter ratios were 2, 3, and 4, respectively. The water depth was kept constant at 0.65 m from the base and was of sufficient depth to ensure negligible influence of counter flow from the free surface. To check for the free surface effects, 2 series of tests had been carried out, and they were (i) brass tube mounted vertically at the bed and issued the jet flow vertically upward into a water body with free surface, and (ii) brass tube mounted vertically at the bed and issued the jet flow vertically upward into a water body with the surface covered using a perspex sheet. The measurements of these 2 series of experiments, in terms of the development of the velocity profile with

longitudinal distance, were shown to be almost identical. Therefore the authors were of the opinion that the free surface effects were negligible. The boundary effect of the tank wall has also been concerned as the inclined jets in the present experiments would meet at the longitudinal axis of the central jet that essentially results in a vertical combined jet. The writer had conducted elaborate visual inspections and dye trace and had confirmed that the lateral boundaries were of sufficient distance away to affect the flow field significantly. The flow rate in present study was accurately calibrated (accuracy of 0.005 L/m) prior to the experiments. Data measurements and acquisitions were accomplished through a PIV system supported by LaVision. A double cavity Nd: YAG laser was placed below the test tank to illuminate the flow. This arrangement greatly reduced the penetration length of the laser in water, and thus reduced the potential attenuation of light intensity. The laser had an energy output of 135 MJ per pulse and emitted green light with a wavelength of 532nm. By using the Quanta-switch, the pulse duration could be shortened to 5 ns, which produced a stroboscopic effect and optically froze the movement of the particles during the illumination. The particle images were recorded by using a 12-bit CCD camera at a resolution of 1600×1200 pixels and maximum frame frequency of 15 Hz. The flow was seeded with co-polyamide particles (diameter of 15 μ m) produced by Lavision GmbH, Anna-Vandenhoeck-Ring 19, 37081 göttingen / Germany. The density of the particle is 1.03(g/cm³) which is almost identical to that of the water in the present study. Therefore the falling velocity of the particle could be treated as zero as the particle would float in the stationary water body voluntarily. Therefore it could be assumed that the tracers followed the flow faithfully and passively, i.e., followed the motion of the fluid without significant lag and yet did not alter the flow dynamics. To capture high quality images and to improve the measurement accuracy, several consideration were made: (a) the bottom-to-top configuration of the laser greatly reduced the penetration length of the laser in water, and thus reduced the potential attenuation of light intensity; (b) using dark sheet to cover the unlighted walls of the tank to reduce reflection of light; and (c) light sheet of 1 mm in thickness was produced to reduce the background noise.

Figure 4.1: Schematic diagram of (a) experimental setup, (b) nozzle configuration

The cross correlation algorithm with standard Gaussian sub-pixel fit structured (Adrian 1991, Willert and Gharib 1991) was utilized in the form of an iterative multi-grid (Scarano and Riethmuller 1999) to calculate the particle displacement. The image processing algorithm included two passes, starting with a grid size of 64×64 pixels, stepping down to 32×32 pixels and overlapping by 50% to minimize the velocity discrepancy across the integration window. The final velocity vector grid was 16×16 pixels, therefore the spatial resolution in measured velocity for the present set-up is about $2.5\text{mm} \times 2.5\text{mm}$ which was larger than the Kolmogorov length scale ranging from 0.1 to 1.0 mm in the studied area. A range validation and calibration along with a moving filter were used to exclude singular or erroneous vectors. For each experiment, a set of 1050 frames of the instantaneous flow fields were acquired at a frequency of 15Hz (i.e. 70s recordings). This frequency is suggested to be sufficiently high for statistical turbulence analysis in terms of conservation of total mass and total momentum (including turbulence contributions) by Wang and Law (2002). The particle images were evaluated by “double frame/ double exposure”, during which the CCD camera recorded the

scattered light from the first illumination in one frame and the scattered light from the second illumination in another frame. The time interval between subsequent laser pulses was 400-1000 μs which satisfied the criteria proposed by Boillot and Prasad (1995), obtaining a displacement of 6.5 pixels near the jet exit. Other parameters such as the particle image size (3-4 pixels) and seeding densities (about 30 particles/ mm^2) could be referred to Wang and Tan (2007), and Gao *et al.* (2011).

The coordinates, X, Y and Z denoted the streamwise, transverse and spanwise directions, respectively, and the origin O was set at the centre point of the exit of the central jet. And to make clearer specification the individual jet is numbered in sequence from the Y- to Y+ with Jet 1, Jet 2 and Jet3 as shown in Figure 4.1. Throughout the experiments, the side jets were always oriented along X-Y plane, where the orientation of the camera and the dual-pulse laser varied for measurement along (X-Y plane) or across (X-Z plane) the jets plane (see Figure 4.2).

C series

For C series, the two side effluents were identical to the central jet. As was mentioned before, the interaction of such jets were performed by two side injections issuing into the central jet. Intuitively, the compound jet would be characterized by strong three-dimensional flow. Hence to better understand the complex flow, a different approach was made on C1, C2 and C3 for which data were acquired at multiple planes including two central planes and additional six and seven offset planes paralleled to the X-Y and X-Z plane, respectively. The gird configuration is shown in Figure 4.2. The main reason for using this method on only two cases instead of on all the cases is that the multiple planes measurements required huge computing space and time and the results of C1, C2 and C3 provided substantial comments (will be discussed later) that the flow field on the central plane revealed most of the dynamic process on the jets interaction. The interval of sequent offset plane is 5.318 mm which reduced the typical spatial resolution on the Y-Z plane half to that on the X-Y and X-Z plane. Such data reduction technique (similar to the technique developed by Schabacker and Böds 1996 and Sakakibara *et al.* 2001) was used to create three-dimensional flow renderings.

Figure 4.2: Grid used in the multi-plane measurements

D series

For D series, the two side effluents were applied at different flow rate with respect to the central one at ratios of $1/4$, $1/3$ and $1/2$. Given the jet diameter is constant in the present study the initial jet momentum flux $\frac{1}{4}\pi D^2 U_0^2$ can be decided by the jet efflux velocity U_0 . Therefore the momentum coefficient C_μ that denotes the ratio of the momentum flux between the side and central jet can be determined by $U_{0_{side}}^2 / U_{0_{central}}^2$ (i.e., $1/4^2$, $1/3^2$ and $1/2^2$). The flow rate was carefully calibrated before the experiments. Through the calibration, it was found that the maximum flow rate of 1 L/min (16.667 ml/s) can be set with a high accuracy of ± 0.005 L/min (0.05%).

T series

For T series, the incline angle of the two side jets with respect to the central jet was set at 30 degree. The incline angle was carefully calibrated to ensure the experimental accuracy.

S series

For S series, single pipe jets with different efflux velocities are investigated to provide as the benchmark condition.

A total of 33 tests (9 for C series, 15 for D series, 3 for T series and 3 for S series) were conducted. The experimental conditions are tabulated in Table 4.1.

Table 4-1: Experimental condition

Exp. No.	Inclined Angle θ	Nozzle Diameter $D(mm)$	Nozzle Spacing $S(mm)$	Discharged Flow rate $Q(L/min)$ (jet1;jet2;jet3)	Momentum Coefficient C_μ	Averaged Discharged Velocity $U_0(m/s)^a$	Reynolds Number Re_a
C1	45°	8.00	32.00	1.60 : 1.60 : 1.60	1	0.53	4240
C2	45°	8.00	32.00	2.40 : 2.40 : 2.40	1	0.80	6400
C3	45°	8.00	32.00	3.00 : 3.00 : 3.00	1	1.00	8000
C4	45°	8.00	24.00	1.60 : 1.60 : 1.60	1	0.53	4240
C5	45°	8.00	24.00	2.40 : 2.40 : 2.40	1	0.80	6400
C6	45°	8.00	24.00	3.00 : 3.00 : 3.00	1	1.00	8000
C7	45°	8.00	16.00	1.60 : 1.60 : 1.60	1	0.53	4240
C8	45°	8.00	16.00	2.40 : 2.40 : 2.40	1	0.80	6400
C9	45°	8.00	16.00	3.00 : 3.00 : 3.00	1	1.00	8000
D1	45°	8.00	32.00	0.60 : 2.40 : 0.60	1/16	0.80	6400
D2	45°	8.00	32.00	0.80 : 2.40 : 0.80	1/9	0.80	6400
D3	45°	8.00	32.00	1.20 : 2.40 : 1.20	1/4	0.80	6400
D4	45°	8.00	32.00	0.75 : 3.00 : 0.75	1/16	1.00	8000
D5	45°	8.00	32.00	1.00 : 3.00 : 1.00	1/9	1.00	8000
D6	45°	8.00	32.00	1.50 : 3.00 : 1.50	1/4	1.00	8000
D7	45°	8.00	24.00	0.60 : 2.40 : 0.60	1/16	0.80	6400
D8	45°	8.00	24.00	0.80 : 2.40 : 0.80	1/9	0.80	6400
D9	45°	8.00	24.00	1.20 : 2.40 : 1.20	1/4	0.80	6400
D10	45°	8.00	16.00	0.60 : 2.40 : 0.60	1/16	0.80	6400
D11	45°	8.00	16.00	0.80 : 2.40 : 0.80	1/9	0.80	6400
D12	45°	8.00	16.00	1.20 : 2.40 : 1.20	1/4	0.80	6400
D13	45°	8.00	16.00	0.75 : 3.00 : 0.75	1/16	1.00	8000
D14	45°	8.00	16.00	1.00 : 3.00 : 1.00	1/9	1.00	8000
D15	45°	8.00	16.00	1.50 : 3.00 : 1.50	1/4	1.00	8000
T1	30°	8.00	24.00	1.60 : 1.60 : 1.60	1	0.53	4240
T2	30°	8.00	24.00	2.40 : 2.40 : 2.40	1	0.80	6400
T3	30°	8.00	24.00	3.00 : 3.00 : 3.00	1	1.00	8000
S1	0	8.00	0.00	0.00 : 1.60 : 0.00	Na	0.53	4240
S2	0	8.00	0.00	0.00 : 2.40 : 0.00	Na	0.80	6400
S3	0	8.00	0.00	0.00 : 3.00 : 0.00	Na	1.00	8000

^a The averaged discharged velocity and Reynolds number is based on main discharge value.

4.3 Ensemble-averaged Flow Characteristics

In this section, typical ensemble-averaged and instantaneous flow characteristics of the compound jets generated by three converging jet are illustrated using test series C1, C2 and C3 and the flow field measurements based on multi-planes measurement. Interactions among pipe jets with different flow rates, spacing and configurations are elaborated further and focused on jet axis trajectory, gross geometrical and mixing features, centreline peak, and cross-sectional velocity profile, jet spreading width and turbulence quantities.

4.3.1 General flow characteristics and jet trajectory

Figure 4.3: Schematic diagram of the flow regime: (a) X-Y plane, (b) X-Z plane

Similar to that of the interactions among parallel jets, the flow field could be divided into three regions but with certain differences. The first is the converging region which extends from the exits of the nozzles to the merging points. In the literature, the merging point (M.P) is defined as the location where the recirculating flow vortices between adjacent jets appeared to have vanished. Since there are three jets in the present study, then there are two merging points located symmetrically about the central jet axis, as seen in Figure 4.3. In fact, one can view the location as the merging plane, and the merging point is the point of intersection of the plane

and the central jets axis. The second region is the merging region located between the merging point (M.P) and the combining point (C.P). This definition is analogous to that of interacting plane jets (see in Wang *et al.* 1993) where the mean streamwise velocity in the centreline attains a local maximum value. However, there are three additional characteristics in this region and they are: (1) at C.P section, the three jets combine and show a single peak distribution of mean velocity on the X-Y plane; (2) the contribution of the lateral velocity component from the two side jets appear negligible compared to the magnitude of the streamwise value near the centreline; and (3) necking of the combined jets is observed immediately downstream of the C.P section. Further downstream, the combining region could be divided into three subzones and are analogous to those of a single round jet. In the first subzone, the necking process is completed and the velocity distribution shows to a Gaussian-like profile gradually and with almost constant jet half-width. This zone is analogous to the “preserving” core for a single pipe jet and the end of this subzone is denoted as N.P. The second subzone is a transition zone from the first subzone to the third subzone, the distribution of mean velocity attained self-similarity indicating the establishment of the compound flow and the starting point of this subzone is denoted as E.P. The established point (E.P) can be obtained when the maximum difference of mean streamwise velocity between two successive cross-sections (at each corresponding lateral and transverses locations) is lower than 0.5% of the centreline value.

Figure 4.4 and Figure 4.5 show typical ensemble-averaged full-field velocity vector maps of Series C (C3) along the (X-Y) and across the (X-Z) jets plane, respectively. A reference vector with the magnitude of the efflux velocity is also included in the maps. To make a better illustration, the magnitude-length ratio of the vector is set at 1.5, 2 and 3 for Figure 4.5 (a)-(d), (e)-(f) and (g)-(h), respectively. The jets in the present study are typical pipe jet flows which show clearly symmetrical velocity distribution as can be seen in the trial run of single pipe jets in Section 3.4 (Figure 3.9). When the two side jets inject toward the central jet, they approach the outer layer of the central jet after $X/D \approx 1.5$ (location M.P) where the reverse flow downstream of the two side jets ceased in the X-Y plane as can be seen in Figure 4.4 (a) (Plot of the cross-sectional distribution of mean streamwise velocity in the converging and combining region are included in the Appendix). Further downstream, the individual characteristics of the three jets attenuate and finally merge into a compound distribution at $X/D \approx 4.5$ (location C.P). After this location the width of the merged flow is maintained constant value until $X/D \approx 7.5$ (location N.P), and could be treated the preserving “core” of the newly formed combining jet. From then on, linear flow structures are clearly evident. The

width of the combined jet is larger than that of a single jet. With reference to the flow field in the offset planes parallel to the jets (X-Y) plane, see in Figure 4.4 (b)-(f), the initial regions do not exhibit individual jet characteristics. Instead, the flow vectors are essentially zero in magnitude. Further away from the central axis ($Z/D \geq 0.65 \sim 3.25$), the near-zero flow regions spread further downstream. Therefore, one can deduce that the impingement and combining jets form a distinct jet core with little evidence of mixing and entrainment from the ambient fluid into the core at the initial zone.

 Figure 4.4: Mean velocity field at $Z/D = 0$ to 3.25 (run C3)

With reference to the X-Z plane and the parallel offset planes, one can observe distinctive and similar flow features on these planes as seen in Figure 4.5. Compared to that of the jets (X-Y) and parallel planes, the jets' velocity profiles in the X-Z and parallel planes are significantly (almost two times) wider since the two side jets penetrate into the central one and expand laterally in the Z-direction. The velocity profiles include the distinctive double peak velocity distributions on the X-Z planes, a tell-tale sign of the result of the converging jets. It is also noted that the velocity vectors are zero in magnitude in the initial region, see Figure 4.5 (h).

Figure 4.5: Mean velocity field at $Y/D = 0$ to 4.55 (run C3)

The jet longitudinal centreline, typically characterizes the development of the ensemble jet trajectory (Shao 2010). For a single jet, the jet longitudinal axis need not be a straight line and is conventionally established by following the locus of the locations of the maximum velocity at various downstream cross-sections. One could adopt the same strategy for converging jets. Figure 4.6 shows the jet centreline trajectory based on the contours of velocity. Since the jet is neutrally buoyant (same fluid as the recipient body) the three jets depict their own jet axis, see Figure 4.6 (a). The intersection of these three individual jet axes would be the location where the three jets are merged and combined into one. A distinct “core” of velocity contour is also observed at this point on both the X-Y and X-Z plane as shown in Figure 4.6 (a) and (b). Further downstream, the combined jet depicts a common axis as expected since the jets configuration is arranged symmetrically.

Figure 4.6: Jet centreline trajectory superimposed on the velocity contours (run C3)

4.3.2 Centreline velocity decay

Once the centreline trajectory is established, the velocity attenuates along the jet axis and the rate of attenuation can be estimated. The various normalized centreline velocity U_c/U_e profiles are presented in Figure 4.7. The result of a single pipe jet reported by Vouros and Pandis 2013 and jet controlled by using radial injection reported by New and Tay 2006, as well as the dual-jet reported by Wang and Tan 2007, are included in Figure 4.7 for comparison.

Figure 4.7: Comparison of centreline velocity decay in different jets configuration

It can be seen that at $X/D < 1.5$, the variation of the centerline velocity U_c/U_e of C3 is almost similar to that of a single pipe jet (Vouros and Panidis 2013). This is to be expected since the individual converging jets are not yet merged. Upon merging of the three jets, a sudden amplification of U_c/U_e is observed at $X/D \approx 4 \sim 5$ for C3 as expected, since the volume of the cross section of the combined jet is not tripled and the magnitude of the resulting jet velocity has to be larger than unity. The peak amplification of U_c/U_e is observed to be up to 1.24 (related empirical parameters in other series will be summarised in Section 4.9). After the peak, the centreline velocity U_c/U_e depicts a rapid decrease from $X/D = 4.5$ to 7.5. Compared to Wang and Tan (2007), and New and Tay (2006), the decay rate of C3 in present study is marginally larger in this streamwise range (X/D), (see Figure 4.7). The centreline velocity U_c/U_e is almost of the same magnitude as that of a single pipe jet (Vorous and Panidis 2013) at $X/D = 20$ but decay at a slightly slower rate that after. In the literature, the inverse of centreline velocity U_e/U_c increases linearly against streamwise distance for a single pipe jet. When the two side jets are active, the inverse of centreline velocity U_e/U_c is seen to increase linearly in the whole combining region and may be expressed as:

$$U_e/U_c = \frac{1}{K_u}(X/D) + b \quad (4.1)$$

For C3, $K_u = 6.13$ and $b = 0.545$. It is noted that the average efflux velocity U_0 is utilized in most reported studies on non-pipe jets (orifice or contraction jets, in which U_0 was equivalent with U_e). For the convenience of making comparison with the results of these non-pipe jets, the writer would use the notation of U_e/U_c instead of U_0/U_c . Wang *et al.* (1993) gave a value of $K_u = 7.63$ for the square of the velocity decay $(U_e/U_c)^2$ (noting that the power of 2

is due to the difference between plane and round jets) for two plane jets at an incline angle of 27° . Tamburello and Amitay (2006) gave values of K_u between 5 to 6 for a single round jet with two controlling side jets set at angle 45° with different momentum ratio (only data with $X/D < 8$ was given in their work). It can be seen that the interaction of jets do not alter the decay pattern of the centreline velocity ($\sim X^{1/2}$ for plane jets and $\sim X^1$ for round jets) but the decay coefficients are dependent on the jets configuration.

4.3.3 Cross sectional axial velocity profile

In turbulent jet studies, one often makes the assumption that the axial velocity profile follows the Gaussian distribution after the flow is established (ZEF). The profiles plotted using the normalized velocity against normalized lateral coordinates collapse onto the single curve. The common velocity scale is the centreline velocity U_c and there are two length scales that are commonly used to normalize the radial coordinates, and they are: Y_u and $Y_{1/2}$ (which is the velocity spreading width using e^{-1} and $1/2$ notation, respectively). For the convenience of comparison with the peer studies, the half spreading width is chosen to be the characteristic length scale in the presentation of Figure 4.9. In Figure 4.9 non-dimensional cross-sectional distributions of the axial velocities U/U_{lc} (U_{lc} is the local centerline velocity) on the jets (X-Y) plane ($Z/D = 0$) and other parallel offset planes ($Z/D = 0.65 - 3.25$) are plotted against $Y/Y_{l1/2}$ ($Y_{l1/2}$ is the local spreading half width, where the local velocity $U_l = 1/2 U_{lc}$) and compared with the standard Gaussian profiles. The definition sketch of the velocity and length scale notation is shown in Figure 4.8.

Figure 4.8 Definition sketch of the velocity and length scale notation

Figure 4.9: Normalized streamwise velocity component distribution at various downstream locations for $Z/D = 0$ to 3.25 (Run C3)

Five downstream cross-sections are shown for each plane in Figure 4.9 (a)-(e). It can be seen that the difference between profiles at successive locations is marginal, indicating that the mean velocity had reached self-similarity at $X/D = 17$. The distributions of the mean streamwise velocity agree with the Gaussian profile, similar to those presented by Hussein *et al.* (1994) and Vouros and Panidis (2013).

Figure 4.10 shows the self-similar profiles of the axial velocity for both the central plane (X-Y) and parallel offset planes ($Z/D = 0 - 3.25$) at $X/D = 30$. One can observe that

all the profiles are consistent with the same Gaussian curve. Hence the local axial velocity on any plane parallel to the X-Y central plane can be represented by the assumption of Gaussian distribution as follow:

$$\frac{U_l}{U_{lc}} = \exp\left[-\left(\frac{Y_l}{\beta Y_{l1/2}}\right)^2\right] \quad (4.2)$$

Here, The subscript “ l ” denotes the local value on each plane that is parallel to the X-Y central plane and β is the empirical coefficient. For the X-Y central plane, the subscript “ l ” can be dropped without losing the generality. To determine the axial velocity at any location, the axial velocity on the centreline of each local plane U_{lc} must be determined first. Noting that U_{lc} is actually the value of the axial velocity on the X-Y central plane and parallel offset planes at $Y = 0$, and can be determined by the flow measurement obtained on the X-Z central plane (see Figure 4.8).

Figure 4.10: Comparison of self-similar curves of the axial velocity component for $Z/D = 0$ to 3.25 (Run C3)

Profiles of the mean axial velocity normalized by the centreline value U_c (at $Y = 0, Z = 0$) and jet half width $Z_{1/2}$ are shown in Figure 4.11 (a) at $X/D = 10, 12, 15, 17$ and $X/D = 17, 21, 25, 30$ in Figure 4.11 (b). Instead of the single peak of Gaussian distribution as on the X-Y plane, a double-peak distribution is observed on the X-Z plane. This is attributed to the injections of the two side jets which split the central jet into two radial symmetrical parts. As is shown in Figure 4.11 (a), and from $X/D = 10$ to 17 the magnitudes of the two crests decrease and the locations of the peaks are shifted further away from the central plane (X-Y). Downstream of $X/D = 17$, the location of the two peaks appear to remain steady at $Z/Z_{1/2} = \pm 0.54$, and the magnitude of the peaks are nearly constant at 1.26. Furthermore, the distributions at the central portion in between the two peaks are seen to evolve from that of a

convex through to that of a flattened, see Figure 4.11 (a). Self-similarity is attained after $X/D = 17$ on the X-Z plane which is consistent with that seen on the X-Y plane. By fitting the measurement data after $X/D = 17$, the normalized axial velocity on the X-Z plane can be described by the superposition of two identical Gaussian profiles as follows:

$$\frac{U}{U_c} = \alpha_1 \exp \left[- \left(\frac{Z/Z_{1/2} - \alpha_3}{\alpha_2} \right)^2 \right] + \alpha_1 \exp \left[- \left(\frac{Z/Z_{1/2} + \alpha_3}{\alpha_2} \right)^2 \right] \quad (4.3)$$

where α_1 is the amplitude of the peak (1.26 for C3), α_2 is the width of the original Gaussian profile used to in the superposition and α_3 denotes the locations of the peaks.

Figure 4.11: Normalized streamwise velocity component distribution at various downstream cross sections (run C3)

Combining Equations (4.1)-(4.3), it can be seen that after the velocity profiles attained self-similarity the axial velocity further downstream can be expressed as a function of $(X/D, Y/Y_{1/2}, Z/Z_{1/2})$. Hence, the three length scales play significant roles in dictating the magnitude of the axial velocity.

As observed elsewhere in the report, the converging jets depict necking at around $X/D \approx 7.5$ and a linear growth afterward. Figure 4.12 present the linear growth of $Y_{1/2}$ after $X/D = 8$ for $Z/D = 0 \sim 3.9$. It can be observed that the linear structure for both the central plane (X-Y) and the parallel offset planes collapsed onto the same curve.

Figure 4.12: Streamwise development of the Normalized jet half width $Y_{1/2}$ at $Z/D=0$ to 3.9 (C3)

Therefore one may anticipate that on any offset plane parallel to the X-Y plane ($Z = \text{constant}$) the local jet half width $Y_{l1/2}$ at various downstream locations can be solely determined by the streamwise coordinate X and described as:

$$\frac{Y_{l1/2}}{D} = K_y \left(\frac{X}{D} - \frac{X_{0y}}{D} \right) \quad (4.4)$$

in which K_y is the spreading coefficient (0.126 for C3) and X_{0y} is the location of the virtual origin. While on the X-Z plane the velocity spreading width $Z_{1/2}$ grow like a parabola with open-rim as shown in Figure 4.13. Similar parabola structures are also reported by Ashgriz (2011). The author has also suggested three modes of the expansion sheet on the X-Z plane and they are: closed-rim, open-rim and fully-developed. The mode of expansion is governed by the jets initial velocity and fluid viscosity, and small disturbance might be generated on the edge of the jet sheet, very much like the situation from $X/D = 26$ to 28 as shown in Figure 4.13. The best fitted curve for $Z_{1/2}$ can be expressed as:

$$\frac{Z_{1/2}}{D} = K_z \left(\frac{X}{D} - \frac{X_{0z}}{D} \right)^{1/2} \quad (4.5)$$

in which K_z is the spreading coefficient (2.046 for C3) and X_{0z} is the location of the virtual origin. It should be noted that for the central plane ($Y = 0$ or $Z = 0$) the local jet half width ($Z_{l1/2}$ or $Y_{l1/2}$) will have the same values as their values in the global coordinate ($Z_{1/2}$ or $Y_{1/2}$). Hence there will be no subscript "l" in Equations (4.3) and (4.5).

Figure 4.13: Streamwise development of the Normalized jet half width $Z_{1/2}$ at $Y/D=0$ (C3)

By considering Equations (4.1)-(4.5), the axial mean velocity U can be expressed as:

$$U = K_u U_e \left(\frac{X}{D}\right)^{-1} \cdot \alpha_1 \exp \left[- \left(\frac{Z/Z_{1/2} - \alpha_3}{\alpha_2} \right)^2 \right] + \alpha_1 \exp \left[- \left(\frac{Z/Z_{1/2} + \alpha_3}{\alpha_2} \right)^2 \right] \cdot \exp \left[- \left(\frac{Y}{\beta Y_{1/2}} \right)^2 \right] \quad (4.6)$$

In Equation (6), all the empirical coefficients can be determined based on the flow measurements on the two central planes ($Z = 0$ and $Y = 0$). In other words, the complex characteristic features of the compound flow can be prescribed by those on the two central planes. Henceforth, the subsequent demonstration and discussion will be focused mainly on the two central planes, i.e., (X-Y and X-Z planes).

4.3.4 Jet spreading

A commonly-used measurement that characterizes the jet growth and spread is the jet velocity-half width ($Y_{1/2l}$ and $Z_{1/2l}$), as shown in Figure 4.8. By definition $Y_{1/2l}$ and $Z_{1/2l}$ are determined based on the velocity profiles and then locating the distance to half of the centreline value U_c at ($Y/D = 0, Z/D = 0$). Noting the difference between the definitions between the two groups of length scales ($Y_{l1/2}$ and $Z_{l1/2}$) in Section 4.33 and ($Y_{1/2l}$ and $Z_{1/2l}$) in this section, the former one is determined by $U_l = 1/2 U_{lc}$ while the latter one is determined by $U_l = 1/2 U_c$. With the multiple-plane measurements, the jets development in the downstream direction could be further estimated on the Y-Z plane based on the measurements on the X-Y and X-Z planes. Figure 4.14 shows the cross-sectional shape by utilizing the jet half width as the boundary of the compound jet at $X/D = 18.5, 20.5, 21.5, 23, 24.5, 26$. It could be

observed that the compound jet depicts an elliptical cross-sectional shape instead of a circular one for a single round jet. Combining Equations (4.4) and (4.5), one can deduce that although the growth pattern of the jets half width ($Y_{1/2l}$, $Z_{1/2l}$) in the X-Y and X-Z planes are different, their magnitude eventually become comparable with each other in the far field ($X/D > 20$).

Figure 4.14: Variation of velocity spread width at various downstream cross sections (run C3)

4.3.5 Turbulence parameters

To further explore the interactions and mechanism involved among three converging jets, the turbulence parameters representative of series C (represented by C3) are presented in Figure 4.15 and Figure 4.16 on the X-Y and X-Z plane, respectively. Along the side jets (X-Y plane), the normalized streamwise Reynolds normal stress, $\overline{u'^2}/U_0^2$, the cross-stream Reynolds normal stress $\overline{v'^2}/U_0^2$ and the Reynolds shear stress $\overline{u'v'}/U_0^2$ are shown in Figure 4.15 (a)-(c) for single pipe jet and Figure 4.15 (d)-(f) for converging jets, respectively.

Figure 4.15: Reynolds stresses in the X-Y plane: a single pipe jet of (a) $\overline{u'^2}/U_0^2$, (b) $\overline{v'^2}/U_0^2$, (c) $\overline{u'v'}/U_0^2$ (run S3); three 45°converging jets of (d) $\overline{u'^2}/U_0^2$, (e) $\overline{v'^2}/U_0^2$, (f) $\overline{u'v'}/U_0^2$ (run C3)

For a single pipe jet or a “compound” jet without side jets-the benchmark jet (the single pipe jet), the distribution of the three Reynolds stresses are clearly different from that of a contraction (or an orifice) jet (see in Yule 1978, Tamburello and Amitay 2006). In contrast to the thin initial shear layer ($X/D = 2.5$, and $Y/D = \pm 0.4$) carrying the highest value of the turbulence quantities for a contraction jet, a “preserved core” is evident in the central portion with a maximum value of 0.08 and 0.05 for the two normal stress and 0.01 for the shear stress, respectively. Mi *et al.* (2007) found that the well-defined vortical and shear structures observed in a contraction jet is attributable to the natural instability of the thin shear layers, which is absent in a pipe jet at the exit. Vouros and Panidis (2013) stated that the absence of these structures delayed the entrainment of the ambient fluid and the mass flow rate is almost constant close to the exit. This observation is consistent with the constant value of the centreline velocity and half width of jet near the exit as observed in the present study (see in Figure 4.7). The normal stresses $\overline{u'^2}/U_0^2$ (0.08) are almost 1.5 times that of $\overline{v'^2}/U_0^2$ (0.05) for a single pipe jet in the present study. Whereas, in a contraction (or an orifice) jet the streamwise normal stress is almost twice that of cross-stream value (0.06 and 0.03, respectively) as reported by Tamburello and Amitay (2006). This difference is mainly attributed to the different initial velocity profiles at the jet exits between the pipe jets and non-pipe jets (orifice or contraction jets). The normalized turbulence shear stress field of the benchmark jet is symmetrical about the X-axis, with positive values along the right side shear layer and negative values (denoted by dashed lines) along the left side shear layer due to the opposite velocity gradients in the shear layers.

When the two side jets are injected into the central jet at 45 degree, all three turbulence parameters exhibit increased magnitudes (by almost 50%) at around $X/D = 5$. This observation is in contrast to the stabilizing trend which reduced the turbulence quantities as reported by Arakeri *et al.* (2003), and Tamburello and Amitay (2006). The latter's observation is probably due to the fact that the two side injections include minimal mass flux and low momentum flux (1% and 2%, respectively) compared to those of the central jet. In the present study, the momentum coefficients of the C Series are 1.00. The enhancement of turbulence was just around 50% and only appreciable near the impingement region (in Tamburello and Amitay 2006, the enhancement was throughout the measurement planes). Therefore the promotion of the turbulence level is associated with the momentum coefficient but not in a monotonic increasing relationship.

Different distributions of the two normal turbulent stresses are clearly evident in Figure 4.15 (d) and (e) as compared to that of the benchmark jet in Figure 4.15 (a) and (b). Note the very high concentration of $\overline{u'^2}/U_0^2$ and $\overline{v'^2}/U_0^2$ near the exits of the two side jets while the central jet shows relatively low values, especially for $\overline{v'^2}/U_0^2$ indicating that the central jet has been vectored or extruded into the perpendicular plane (X-Z plane). Further downstream, the streamwise normal stress $\overline{u'^2}/U_0^2$ showed a double-peak distribution for $X/D \geq 8$ where a core was found on the map of $\overline{v'^2}/U_0^2$ with maximum value of 0.035 at $8 \leq X/D \leq 12$, see Figure 4.15 (e). The distribution of $\overline{v'^2}/U_0^2$ resembles an elongated bulbous shape which is also observed when dual-jets interacted with each other, see Nasr and Lai 1997, and Wang and Tan (2007). For the shear stress $\overline{u'v'}/U_0^2$, a nearly zero region is observed near the exit of the central jet, see Figure 4.15 (f). In addition, low values of the two normal stresses could also be observed in the same region as shown in Figure 4.15 (d) and (e). Based on these observations one might suggest that prior to the impingement of the three converging jets, the merging of the outer layer of the central jet with its two neighbours would take place at a more upstream location. It is noted that the shear stress vanishes again at around $X/D \approx 5$ which corresponds to the centre of the jets impinging region. Moreover, the distribution of the shear stress downstream of this location shows positive values along the right side and negative values along the left side and is opposite to those upstream, but is similar to those of the benchmark jet, see Figure 4.15 (c). The change of signs of the shear stress indicates the penetrations and interactions of the two side jets with the central one.

The interactions of converging jets is further explored by examining the turbulence parameters on a plane across the jets' plane (X-Z plane), and compared with the benchmark case in Figure 4.16. When the two side jets are activated at $C\mu = 1.00$, the three turbulence parameters are slightly reduced in magnitude compared to their counterpart in the X-Y plane. The normal turbulence stresses $\overline{u'^2}/U_0^2$ and $\overline{w'^2}/U_0^2$ are almost symmetrical about the X-axis with a significant wider distribution. Instead of the single peak at the exit as that of the benchmark jet, the normal stress $\overline{u'^2}/U_0^2$ turns into a double-peak distribution at $X/D = 5$, and beyond until a core is formed at the central portion near $X/D = 8$ with significant values of $\overline{u'^2}/U_0^2$ of 0.05 at the centre. The location of the emergence of the double-peak distribution is in consistent with the impingement of the jets and formation of the core at $(X/D \approx 8, Z/D \approx \pm 0.4)$. The streamwise stress $\overline{u'^2}/U_0^2$ disperses almost isotropically until its value is reduced

down to about 0.005. The distribution of spanwise normal stress $\overline{w'^2}/U_0^2$ (Figure 4.16 (e)) is also wider and show significant peak value of 0.04 at the outer layers. It is also noted that the locations of the peaks is deflected away from the centreline from $X/D = 5$ to 15 and becomes steady at $Z/D \approx \pm 5$. These observations are attributable to the splitting of the central jet as a result of the impingement from the two side jets. The splitting could be further observed on the contour of the shear stress $\overline{u'w'}/U_0^2$ in Figure 4.16 (f). In the form of the large near-zero region at the central portion after $X/D = 8$. Similar observations have also been reported in Tamburello and Amitay (2006).

In general, the data on both the measurement planes (X-Y and X-Z) reveal that, for run C3 when three jets converge, the two side jets impinge onto the central one at around $X/D \approx 5$ and is reflected by the merged distribution of the normal stress or the near-zero region of the Reynolds shear stress on the X-Y plane and considerably high value and concentration of the Reynolds normal stresses at the same location on the X-Z plane. Further downstream, the side jets penetrate into the central jet, splitting it and displacing the mass to the perpendicular X-Z plane. The penetration and splitting processes are indicated by the change of the sign of $\overline{u'v'}/U_0^2$ distribution on the X-Y plane and large near-zero region of $\overline{u'w'}/U_0^2$ on the X-Z plane, respectively.

interpretation has not been as self-evident as its mathematical definition. Hence the identification of a vortex is always hindered by the lack of an accepted mathematical definition (Jeong and Hussain 1995). According to Jeong and Hussain (1995) there are two preliminary requirements in the identification of a vortex core. The first is that there must exist a net vorticity in the core and the second is that the geometry of the identified location should be Galilean invariant. Vollmers (2001) summarised the most general methods used in the detection of vortices and quantitative evaluation of them. Seven methods (integration of streamline; cross-sectional lines; moments of vorticity; fitting to an analytical model; opposite velocity direction; contour lines of vorticity; discriminant of non-real eigenvalues of gradient matrix) have been discussed along with the advantages and the drawbacks of each individual method. It can be seen that the three common intuitive indicators of vortices in deriving these methods are the pressure minimum point, closed or spiralling streamlines or pathlines and isovorticity surface. However, these indicators may be inadequate sometimes in detecting vortices especially in the case of an unsteady flow (Jeong and Hussain 1995).

In the literature, various methods have been proposed to identify the vortices from the velocity field obtained using PIV (Adrian 1991) and they include: 1). Galilean decomposition of velocity vector; 2). Instantaneous vorticity field and 3) λ_2 criterion proposed by (Jeong and Hussain 1995). These three methods have been used in combination in the interpretation of rotating (swirling) flow by Wang and Tan (2007). In the present study, the instantaneous spanwise vorticity ($\Omega_z = \partial v / \partial X - \partial u / \partial Y$) and cross-stream vorticity ($\Omega_y = \partial w / \partial X - \partial u / \partial Z$) are calculated using the least operations extrapolation scheme, which is suitable for processing PIV data (Raffel *et al.* 1998). The complex eigenvalues λ_2 proposed by Jeong and Hussain (1995) is the median of the three eigenvalues of the symmetric tensor $\hat{S}^2 + \hat{\Omega}^2$ in which $\hat{S}$ and $\hat{\Omega}$ are respectively the symmetric and anti-symmetric parts of the velocity gradient tensor ∇u . The two-dimensional form of λ_2 has been given by Vollmers (2001) as:

$$\lambda_2 = (\partial u / \partial X + \partial v / \partial Y)^2 - 4(\partial u / \partial X \cdot \partial v / \partial Y - \partial u / \partial Y \cdot \partial v / \partial X) \quad (4.7a)$$

$$\lambda_2 = (\partial u / \partial X + \partial w / \partial Z)^2 - 4(\partial u / \partial X \cdot \partial w / \partial Z - \partial u / \partial Z \cdot \partial w / \partial X) \quad (4.7b)$$

Equations 4.7 (a) and (b) is the two-dimensional form of λ_2 for cross-stream and spanwise plane respectively.

A snapshot of the decomposed instantaneous velocity vector (u, v) for a single pipe jet is presented in Figure 4.17 (a). Also superimposed in the figure are the contours of the calculated λ_2 , where the red and blue colors stand for regions of shearing ($\lambda_2 > 0$) and

swirling ($\lambda_2 < 0$), respectively. It can be seen that regions of swirling ($\lambda_2 < 0$) match the vortices that have been identified by the Galilean decomposed velocity vectors and show circular patterns. Whereas shearing ($\lambda_2 > 0$) would occur between two adjacent vortices. The vortices are standard Kelvin-Helmholtz (K-H) roll-up located in the shear layers. Contour of the normalized spanwise vorticity in terms of $\Omega_z D/U_0$ is presented in Figure 4.17 (b) for a single pipe jet. The shear layers are characterized by the elongated vorticity with positive and negative values on the right and left side, respectively. The maximum value of vorticity, $|\Omega_z D/U_0|_{max} = 1.4$ and 1.6 in the right and left shear layer, respectively, are lower than that of the single contraction round jet as reported by Tamburello and Amitay (2006) and the single plane jet as reported by Wang and Tan (2007). These lower values could be explained by the absence of well-defined vortical and thin shear structures that have been observed in contraction jets. As can be seen in Figure 4.17 the two layers of positive and negative vortices developed independently indicating that no appreciable interactions take place between the two shear layers.

Similarly, Figure 4.18 depicts a snapshot of the instantaneous field of the 45° converging jets in the X-Y plane (typical results of run C2). It can be seen that the shear layer of the central jets broke into small scale structure and merged with the inner layers of its two neighbours up to $X/D = 2$. From there until $X/D = 7$ downstream, i.e. at the necking region, the compound jet include well-defined K-H roll up in the right and left shear layer with the largest vorticity, $|\Omega_z D/U_0|_{max} = 2$, which is slightly higher than that of the benchmark case. Moreover, the shear layers appear sinuous and there are clear indication of mutual interactions at $X/D \approx 3, 7$, and 11 as can be seen by the synchronous swaying of the compound jets. Further downstream, shedding of the vortical structures can be observed at $(X/D, Y/D) = (11, 0.4)$. Beyond, the shear layers start to break and interact with each other and form larger-scale discrete vortices which are similar to the Karman-like vortices generated by the interaction between dual-jet as reported by Wang and Tan (2007). These flow patterns are also observed in reported numerical study of two parallel jets, see Soong *et al.* (1998).

Figure 4.19 is a snapshot of the instantaneous view of the converging jets in the X-Z plane. The normalized cross-stream vorticity distribution width increase significantly downstream of the merging point of the converging jets, and the observation is qualitatively in agreement with that observed by Tamburello and Amitay (2006). The two side jets penetrated and split the central jet flow field immediately downstream of the intersection between the

central jet and side jets. The splitting is clearly evident by the formation of large-scale structures around $(X/D \sim 0 \text{ to } 6; Z/D \sim 0 \text{ to } \pm 4)$ as shown in Figure 4.19 (b). Despite the enlarged scale of these structures compared to that in the benchmark single jet case as shown in Figure 4.17 (b), the two shear layers could still be described in shape as K-H like structures that are nearly symmetrical about the X-axis with thin irrotational flow in between. This K-H like structure begin to breaks down at $X/D = 7$. This location is consistent with the observation on the X-Y central plane. In addition, the distribution of instantaneous vorticity after this point is asymmetrical, indicating the swaying of the interacting shear layers. Consequently, one can deduce that the two shear layers were distinct before $X/D = 7$ and begin to breakdown and interact with each other after that. The interactions between the two sides shear layers resulted in distinct degree of turbulence ($|\Omega_Y D/U_0|_{max} = 2.4$) and the presence of random small scale counter-rotating vortices at the central portion ($Z/D \sim \pm 2$) after $X/D = 17$. Furthermore, the penetration of the two side jets into the central jet is evident by the presence of two large-scale counter-rotating vortices at $(X/D = 10, Y/D = 0.3)$. These two additional counter-rotating vortices were also observed by Tamburello and Amitay (2006) but with much smaller size due the weak side injections in their work (“weak” in both mass and momentum flux).

Figure 4.17: A snapshot of the instantaneous flow field for the single pipe jet a) velocity vector (u, v) superimposed with contours of λ_2 and b) contours plot of normalized spanwise vorticity $\Omega_z D/U_0$ (run S2)

Figure 4.18: A snapshot of the instantaneous flow field for 45° converging jets a) velocity vector (u, v) superimposed with contours of λ_2 and b) contours plot of spanwise vorticity $\Omega_z D/U_0$ (run C2)

Figure 4.19: A snapshot of the instantaneous flow field for 45° converging jets a) velocity vector (u, w) superimposed with contours of λ_2 and b) contours plot of cross-stream vorticity $\Omega_Y D/U_0$ (run C2)

4.4.2 Jet flapping

The “jets flapping” phenomenon has been reported by Spall (2003), based on his CFD investigation on the interactions of parallel plane jets. Spall’s (2003) results show that parallel jets that exhibit matching momentum flux would become unstable and such instability is characterized by “flapping” of the jet columns. The flapping of the vortex train closely resemble to the wake behind a bluff body (Anderson. *et al.* 2002, 2003). The flapping or oscillation frequency f , as defined in Strouhal number $St = f D/U_0$ is about 0.1–0.33 according to Bunderson and Smith (2005). It is noted that although the interactions between parallel jets is mainly driven by the deflection of jets towards to the centreline as a consequence of pressure difference across the vortex street. The frequency f has been estimated to be in the order of 10 Hz.

In the present study, the spanwise and cross-stream vorticity Ω_Z and Ω_Y are selected as the characteristic measurements because they clearly reflect the magnitude of the vortex in terms of the direction of swirl, vortex size and rotating strength. Figure 4.20 (b)–(d) show three instantaneous fields of Ω_Z subsequent to the snapshot shown in Figure 4.18 (b). Figure 4.20 (a)

is the same picture as Figure 4.18 (b) and is repeated here for easy comparison. It could be observed that the shear layers of the central jet are combined with the inner layers of the two side jets and forms a region of near-zero vorticity at $X \approx 2 \sim 3D$. The numbering of the jets, from left to right as shown in Figure 4.1 is adopted here for Figure 4.20 (a). On the left side of the X-axis, the inner layers of jets 1 and 2 correspond to layers 2 and 3 (numbered in Figure 4.20 (a)) of K-H roll up patches (see Figure 4.17 for single pipe jet). As jet 1 is injected toward jet 2, strong interactions take place between layer 2 and layer 3 and generate a vortex pair with opposite signs. The patch of K-H vorticity of layer 1 bends inward and elongates in the horizontal direction at $X = 2D, Y = \pm 0.6D$ as shown in Figure 4.20. Further downstream, layer 1 bends further inward and combine with layer 3. Layer 2 is ejected. Although the “flapping” phenomenon is difficult to be captured on video, one could infer from the bending of the outer layers 1 and 3 in the merging region. Assume there existed an imaginary probe installed at $X/D = 3.5, Y/D = 0$ and is marked by a “•” in Figure 4.20, The first moment in Figure 4.20 (a) show the right-hand layer (layer 6) over the left layer (layer 1). The opposite is in shown in Figure 4.20 (b), and the third moment in Figure 4.20 (c) show the transition between these two states. In Figure 4.20 (d) the right-hand flow over the left again like the situation shown in Figure 4.20 (a).

Figure 4.20: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) 0, b) $1/15s$, c) $2/15s$ and d) $3/15s$ (run C2)

Wang and Tan (2007) observed a row of discrete vortices with alternate signs at the interface of the shear layers of two interacting plane jets. In their work the size of the Karman like vortices was of the order of the nozzle width ($1D$) and with constant streamwise distance of $1.5D$ between two adjacent vortices.

In the present study, similar vortex shedding could be observed at around $X/D = 7$. The clockwise and counter-clockwise vortices are denoted by P and M, respectively. At $t = 0$ in Figure 4.20 (a), vortices M0, P1, M1 and P2 are formed and moved downstream while a larger vortex (M2 and M3) are just about to break off from the left side shear layer, with a smaller one, P4 being generated on the layer on right. At the next moment as shown in Figure 4.20 (b), the vortices, M1 and P1 have almost travelled out of the field of view and broken into smaller structures while two new vortices, M4 and P4 are on the verge of being shed from shear layer 1 and 6, respectively. Compare the shape and location of M1 and P1 in Figure 4.20 (b) with that of M0 and P0 in Figure 4.20 (a), it can be deduced that M0 and P0 could have been another pair of vortex that experience the same sequence of development like M1 and P1 at the moment $1/15s$ earlier than $t = 0$, i.e. at $t = -1/15s$. The M2 and M3 vortices have merged

at $t = 2 / 15s$ (Figure 4.20 c) but detached during the next frame ($t = 3 / 15 s$, Figure 4.20 d) while M2 has propagated and broken outside of the field of view. As M4 and P4 are being shed and travel downstream, two new and smaller vortices, M5 and P5 are being formed and are about to be shed. At $t = 3 / 15 s$, with M5 and P5 having been shed and stretched as compared to the last frame, M6 and P6 have almost coalesced into distinct vortices. Consequently, one may deduce that the vortex breaking and movement are periodic and reproducible, as illustrated by a well- ordered vortex sheet as P0, M0, P1, M1, P2, M2, P3, M3, P4 and M4 in sequence. The size of the distinct vortex is of the order of the nozzle diameter ($1 \sim 2 D$) and the distance between the center of two adjacent vortices is $2.5 D$ and is approximately constant. To estimate the vortex breaking frequency, an imaginary measurement probe was assumed to be installed at ($X / D = 13$, $Y / D = 0$), which was marked by a “*” symbol as shown in Fig 4.19 (a). From $t = 0$ to $t = 3 / 15 s$, the imaginary probe would have recorded the formation of the vortices, as the P1, M1, P2, M2, P3, M3, P4 and M4 in sequence. Hence, an equivalent frequency could be calculated as $f = 8/(3/15) = 40 (Hz)$, and the Strouhal number is estimated to be 0.4. The St Number obtained is higher than that of 0.25 in the case of dual-jets as reported by Wang and Tan (2007) and 0.11 by Bunderson and Smith (2005).

Note that although similar vortex structures are observed in the interaction between dual-jets by Wang and Tan (2007), the mechanism of jet interactions is quite different as the large-scale Karman-like vortices are actually derived from the inner layers of the dual jets. For the present study, the inner sides of the two neighbouring jets are merged as evident from the thin near-zero clearance in the central part and the small structures upstream of the jets being combined as can be seen in Figure 4.20 (b) and (c). A schematic representation of vortex/shear-layer interaction proposed shown in Figure 4.21 to illustrate jet interactions process described above. On the left side of the X-axis, the inner shear layer of jet 1 and 2 corresponds to shear layer 2 and 3. These patterns are analogous to the K-H roll up for single pipe jets as shown in Figure 4.17. As jet 1 meets jet 2, strong interactions take place between layers 2 and 3 in the form of vortex pairing. The nearby patch of K-H vorticity of shear layer 1 is bent inward and elongated its size in the horizontal direction at $X/D = 3, Y/D = \pm 0.6$ as shown in Figure 4.18 (b) and Figure 4.20. It can be seen that shear layer 1 is bent inward and combined with shear layer 3. Ejection of shear layer 2 takes place periodically. As a result, layer 1 with an initial K-H roll up becomes large-scale negative Karman-like flow accompanied with considerable interaction among shear layer 1, 2 and 3. Similar process is observed on the right side of the X-

axis and the result is the positive Karman-like flow ejecting toward the central core. The periodic interactions between the negative and positive Karman-like vortices finally enhance the mutual mixing among three converging jets.

Figure 4.21: Schematic diagram of the vortex/shear layer interaction in the X-Y plane

Figure 4.22 (b)–(d) depict three sequential instantaneous field of $\Omega_Y D/U_0$ subsequent to the snapshot shown in Figure 4.19 (b). Figure 4.22 (a) are actually the same figure as Figure 4.19 (b), but arranged in this manner for ease of comparison. The converging, merging and combining regions are denoted by straight lines drawn in Figure 4.22 (a). It can be seen that the vortical structures in the combining region are smaller and scattered while the distributions of the vorticity in the converging and merging region are much more distinct and steady. From Figure 4.22 (a)–(d), it can be seen that the time distribution of the vorticity Ω_Y consist of the K-H structures of a single jet (see Figure 4.17 b) albeit with slightly larger width due to the enhanced instability in the converging region ($X < 1.5D$). Merging of the jets is apparent and clearly indicated by the sudden expansion of the mixing layers in the merging and combining regions. As discussed before, the combining region could be divided into three subzones and the demarcation point of the necking zone is denoted as N.P, which is located at $X/D = 7.5$ for C3. As can be observed in Figure 4.22, the vorticity distribution begins to break up into smaller structures and the two mixing layers interact with each other in the central portion of the flow field. These interactions are clearly evident around $(X/D, Y/D) = (8, 0)$ as indicated by pairs of counter-rotating vortices. These are denoted by dashed circle in Figure 4.22. Similar observation has been reported by Tamburello and Amitay (2006). Therefore, one may infer the appearance of the counter-rotating vortices on the cross-stream plane as another indication of the establishment of fully developed flow.

Figure 4.22: A time series of contour plots of cross stream vorticity $\Omega_y D/U_0$ for $t =$ a) 0, b) $1/15s$, c) $2/15s$ and d) $3/15s$ (C3)

With reference to the mean velocity map shown in Figure 4.5, and the instantaneous velocity and vorticity map shown in Figure 4.19 and Figure 4.22 downstream of the necking

point ($X/D \geq 7.5D$), the mean velocity profile shows the distinct Gaussian profile and symmetrical about the X-axis while the instantaneous flow profile appears to be random and irregular in that region. Noting that the mean profile is actually the ensemble-averaged of the 1050 instantaneous snapshots as discussed in Chapter.3, one can conjecture that although the interaction of the two side mixing layers are difficult to describe exactly at any given instant moment, the fully developed flow would portray a cyclical pattern or at least one that has statistical periodicity. However, such period has neither been successfully established in the present work nor reported in the literature.

4.5 Effect of the momentum coefficient

In this section, the effects of the velocity ratio C_u ($1/4^2$, $1/3^2$ and $1/2^2$) between the side and central jets are deliberated. Two series of test cases with different Reynolds number (based on the central jet) of 6400 (D1-D3) and 8000 (D4-D6) at constant nozzle spacing ($4D$) are presented. The geometrical features of the flow are discussed in Section 4.5.1 in terms of the merging point (M.P), combining point (C.P), the necking point (N.P) and the “established flow” point (E.P) where the mean velocity profile attains self-similarity. As an aid to understand the effects, the integrated turbulent quantities (see in Tamburello and Amitay 2006) in the X-Y and X-Z planes are calculated and are presented in Section 4.5.2. The instability or the jet-flapping frequency as described in Section 4.4.2 is further discussed for different momentum flux ratio in Section 4.5.3.

4.5.1 Geometrical feature

Figure 4.23 shows the mean velocity fields in the converging and merging region. Also superimposed in the figure are contours of the mean spanwise vorticity Ω_z . When they are active with lower momentum coefficients, the two side jets approach the outer layer of the central jet a short distance downstream compared to that with higher momentum coefficients. In the latter case the reverse flow between adjacent jets vanishes around $X/D = 1.8$ in the X-Y plane as shown in Figure 4.23 (a) and (b). This feature is due to the pressure gradient in between the jets near the nozzle exits which is slightly elevated in the “higher momentum” cases as can be deduced from the Bernoulli equation. Whereas the location of the combining point is more upstream in the “lower momentum” cases. In other words, the higher the momentum the side jet has, the longer is the streamwise distance requires for the combining (or impinging) processes to take place. Further downstream, the mean velocity depicts a single

peak distribution and the shear layer is symmetrical about the centreline in the combining region. The necking process for cases with momentum coefficient less than 1 are not as clearly evident as shown in the mean vorticity map in Figure 4.23. To further investigate this, one may consider the jet half widths as denoted by $Y_{1/2}$ and $Z_{1/2}$ and presented in Figure 4.24 and Figure 4.25, respectively. It can be seen that for all the cases the jet spreading in the converging region ($X/D = 1.8$ for D4 and D5, 1.6 for D6 and C3) are similar to that of a single pipe jet (see Figure 3.11 in Chapter 3). The jet width is slightly expanded in the merging region and an obvious necking feature could be observed especially for case C3 at $X/D \approx 7.5$, see Figure 4.24. For lower momentum cases, the necking process commences further downstream with decreasing momentum coefficient ($X/D = 9.35$ for D4, ~ 8.5 for D5 and D6, and 7.5 for C3). Such narrowing of jet width has also been observed by Tamburello and Amity (2006). These authors have also reported that the rate of the spreading would increase after the narrowest point while the momentum coefficient of the side jets increase. This observation is also reflected in Figure 4.24. In the X-Z plane (Figure 4.25), activation of the side jets resulted in a much bigger jets width where the spreading of the jets increase with the momentum coefficient. In addition, the combined jet at the necking point (in the X-Y plane) expands significantly in the X-Z plane. This feature is attributable to the strong interactions between the central and side jets, forcing the flow to expand in the plane orthogonal to the jet plane. Based on the locations of the combining and necking points, one could deduce that the length of the necking zone decreases with increase momentum coefficient. Similar observation has also been reported by Tamburello and Amitay (2006). The jet appears stretched and depicts longer potential core. As has been described in Section 4.3.1, after the necking point the combined jet would assume linear and parabola structures in the X-Y and X-Z plane, respectively. Furthermore, the jet half width in the X-Y and X-Z plane $Y_{1/2}$ and $Z_{1/2}$ at various downstream locations are function of distance X as demonstrated in Section 4.3.3 and Equations 4.4 and 4.5.

To further explore the difference associated with the momentum coefficients, the downstream development of the centreline velocity U_c , normalized with respect to the centerline velocity at the exit U_e for momentum coefficients of 1/16, 1/9, 1/4 and 1 are presented in Figure 4.26. As discussed in the previous section and with reference to Figure 4.7 the rate of the centreline velocity decay $d(U_c/U_e)/d(X/D)$ for C3 ($C_\mu = 1$) is similar to that of a single pipe jet for $X/D > 20D$. This range is much wider than the value of $6D$ reported by Tamburello and Amitay (2006). The main reason for the difference is due to the relative mass

flux of the side jet compared to the central jet. For better observation and resolution in Figure 4.26 only the decay profiles for $X/D < 20D$ are presented. The normalized centreline velocity U_c/U_e increased slightly initially at $X/D \approx 1.5$ indicating the start of merging. Then the centreline velocity increases rapidly afterward until a peak value at $X/D \approx 4$ suggesting that the jets have combined. The centreline velocity decays rapidly after the peak.

Figure 4.23: Comparison of mean velocity map superimposed by the averaged spanwise vorticity $\overline{\Omega_z}$ with different momentum coefficients

Figure 4.24: Comparison of jet half width in the X-Y plane for 45° converging jets with different momentum coefficients (runs D4, D5, D6 and C3)

Figure 4.25: Comparison of jet half width in the X-Z plane for 45° converging jets with different momentum coefficients (runs D4, D5, D6 and C3)

It has been presented in Section 4.3.3 that after the three identical jets have converged, the mean velocity profile a certain downstream distance downstream would attain self-similarity and collapse onto the same Gaussian curve for that of a single jet. The writer also observed that when the momentum coefficients of the two side jets are reduced while maintaining that of the central jet at the same value as before, the normalized mean axial velocity U/U_c profiles against normalized lateral coordinates $Y/Y_{1/2}$ in the jets plane (X-Y plane) would still collapse onto a single curve as illustrated in Figure 4.27 (a). The cross-sectional distribution of the mean lateral velocity V/U_c is plotted in Figure 4.27 (b). The self-similar curves are found to be similar to that of a single jet in the central portion ($-1 < Y/Y_{1/2} < 1$) but with larger magnitude outside of this range. Note that the entrainment of the

ambient flow could be interpreted as the fluid exchange at the edge of the jet, which would result in a negative gradient of the lateral velocity as shown in Figure 4.27 (b) at $(-2.5 < Y/Y_{1/2} < -1)$ and $(1 < Y/Y_{1/2} < 2.5)$. Hence, the entrainment from the surroundings into the combining jets is slightly enhanced compared to that of a single jet. Moreover, with the larger momentum coefficient such enhancement is more evident. In the cross-stream plane (X-Z), the splitting of the central jet is less evident when the momentum coefficient of the side jets decrease, see Figure 4.28 (a) and (b). For lower momentum coefficients of $1/4^2$ and $1/3^2$, the two peaks of the streamwise velocity are located around $Z/Z_{1/2} \approx \pm 0.5$ and expanded to ± 0.52 and ± 0.54 for higher momentum coefficients of $1/2^2$ and $1/1^2$, respectively. The peak value of the double-peak distribution is 1.26 when two identical side jets are applied (see in Figure 4.11). When the lowest momentum coefficient is applied at $1/4^2$ (D4) the peak value is only 1.1 and increases to 1.15 for $1/3^2$ (D5) and 1.2 for $1/2^2$ (D6), respectively. Another effect of the momentum coefficients is on the streamwise distance to the location where self-similarity of mean velocity is observed. For a single pipe jet, the flow attained self-similar after $X/D = 8$ (see Figure 3.9 in Chapter 3) and this distance increases with the momentum coefficients of side jets: $11.5D$, $13.5D$ and $15D$ for D4, D5 and D6, respectively. Based on these observations, one may deduced that the side injection would result in the onset of self-similarity of the mean velocity at a further downstream location and with a larger momentum coefficient the self-similarity of the mean velocity would commerce further downstream.

Figure 4.26: Comparison of centreline velocity decay for 45° converging jets with different momentum coefficients (runs D4, D5, D6 and C3)

Figure 4.27: Comparison of cross sectional distributions of a) streamwise velocity U and b) lateral velocity V for 45° converging jets with different momentum coefficients in the X - Y plane (runs D4, D5, D6 and C3)

Figure 4.28: Comparison of cross sectional distributions of a) streamwise velocity U and b) lateral velocity W for 45° converging jets with different momentum coefficients in the X-Z plane (runs D4, D5, D6 and C3)

4.5.2 Turbulence quantities

The integrated turbulent quantities in the X-Y and X-Z planes are calculated and shown in Figure 4.29 (a)-(c) and (d)-(f), respectively. The definitions of these integrated turbulent quantities are the same as those proposed by Tamburello and Amitay (2006), and are expressed by the following equations:

$$\tilde{u}'^2 = \frac{\int_{Y-5\%}^{Y+5\%} \overline{u'^2} d\left(\frac{Y}{D}\right)}{\int_{Y-5\%}^{Y+5\%} \overline{U^2} d\left(\frac{Y}{D}\right) \Big|_{\frac{X}{D}=0}} \quad (4.8)$$

$$\tilde{v}'^2 = \frac{\int_{Y-5\%}^{Y+5\%} \overline{v'^2} d\left(\frac{Y}{D}\right)}{\int_{Y-5\%}^{Y+5\%} \overline{U^2} d\left(\frac{Y}{D}\right) \Big|_{\frac{X}{D}=0}} \quad (4.9)$$

$$\widetilde{w'^2} = \frac{\int_{Y-5\%}^{Y+5\%} \overline{w'^2} d\left(\frac{Y}{D}\right)}{\int_{Y-5\%}^{Y+5\%} \overline{U^2} d\left(\frac{Y}{D}\right) \Big|_{\frac{X}{D}=0}} \quad (4.10)$$

$$\widetilde{u'v'} = \frac{\int_{Y-5\%}^{Y+5\%} \overline{u'v'} d\left(\frac{Y}{D}\right)}{\int_{Y-5\%}^{Y+5\%} \overline{U^2} d\left(\frac{Y}{D}\right) \Big|_{\frac{X}{D}=0}} \quad (4.11)$$

$$\widetilde{u'w'} = \frac{\int_{Y-5\%}^{Y+5\%} \overline{u'w'} d\left(\frac{Y}{D}\right)}{\int_{Y-5\%}^{Y+5\%} \overline{U^2} d\left(\frac{Y}{D}\right) \Big|_{\frac{X}{D}=0}} \quad (4.12)$$

For each downstream location in the combining region, the integrations are calculated from the spanwise (or cross-stream) position where the velocity is 5% of the maximum mean velocity to the corresponding 95% position. This value was chosen to assure the integral bounds could be found farther downstream where the jet would be much wider (Tamburello and Amitay 2006). Changing the integral boundary location to 1% of the maximum velocity would increase the integral values by less than 4%. In the present study, the integral bounds setting at 1% to 4% of the maximum velocity increase the final values to around 5% while setting at 5% and 7% of the maximum velocity resulted in an almost equivalent value (within ~1%). Hence the boundary of integration is chosen as 5%. For the calculation before the combining region, the velocity distributions are non-single peak profiles, hence to include all the effect from the three interaction jets the integration bounds are chosen to be the outer bounds of the side jets (jet 1 and 3) where the velocity reached 5% of the local maximum value.

The integrated streamwise stress $\widetilde{u'^2}$ in the X-Y plane increases with downstream distance due to the growth of the vortex ring as discussed in Section 4.3.5 and Section 4.4.1 (also suggested by Tamburello and Amitay 2006). The more rapid growth rate for $X/D < 1.5$ is attributable to the fact that integration in this range include all three jets. In addition, the first peak at around $X/D = 1.5$ is consistent with the merging point mentioned before. A sudden drop afterward indicates that the jet flow has become more stable in the short distance after the merging point. Similar observation has also been made by Tamburello and Amitay (2006). A second peak appeared at $X/D \approx 3.5D$ which denotes the two side jets have penetrated into the mixing layers of the central jet. This location would appear a little bit upstream than the

combined point (C.P). The magnitude of these two peaks increase with the momentum coefficients as can be seen in Figure 4.29 (a). Similar trends could also be observed for the spanwise stress $\tilde{v}^2$ in the converging and merging regions except for the second peak of case C3 (matched momentum case) which is significantly bigger than that of other cases (D4-D6). Downstream of the combining region, the integrated streamwise stress in the X-Y plane appears saturated and levels off at ~ 0.07 (Figure 4.29 (a) and (b)). This value is slightly higher than the reported value of 0.05 reported by Tamburello and Amitay (2006).

On the cross-stream plane (X-Z plane), the three integrated turbulence quantities are lower in the converging and merging region but higher in the combining region than the corresponding values in the X-Y plane.

The distributions of the integrals of the shear stress $\tilde{u}\tilde{v}'$ and $\tilde{u}\tilde{w}'$ on the X-Y and X-Z planes are presented in Figure 4.29 (c) and (f), respectively. The general trends are similar for all the four cases. The effects of the momentum coefficients show higher stresses levels at the corresponding merging and combining points.

Figure 4.29: Comparison of downstream distribution of the integrated Reynolds stress for 45° converging jets with different momentum coefficients in (a-c) X-Y and (d-f) X-Z planes (runs D4, D5, D6 and C3)

4.5.3 Momentum Induced Jet flapping

In Section 4.4.2, the observed instability in the form of jet flapping for identical momentum fluxes (runs C1-3) are discussed. The combining jets appear to “flap” periodically at ~ 40 Hz (run C3, $St = 0.4$). The frequency is estimated by using the relationship of $f = n/t$, here n is the vortices pass by and t is the time duration between two successive frames. The instability is known to be a function of the jets’ spacing and the momentum flux ratio, with the most prominent flapping for cases with the matched momentum flux. When the momentum flux of the interacting jets is different by a factor of three, the flow becomes steady (Bunderson and Smith 2005). To further investigate the effect of the momentum coefficient, snapshots of a time series of the instantaneous vorticity field for cases with side jets of different momentum flux are analysed and presented in Figure 4.30 to Figure 4.32. At the lowest momentum coefficient of $1/16$ as in Figure 4.30, one can observe that the shear layers of the central jet combine with the inner layers of the two side jets at $X \approx 2 \sim 3D$. The interaction takes place between shear layers 2 and 3 is not as intense as that for the matched momentum case (C3) as shown in Figure 4.20. The central jet appears to play a dominant role in the merging process, see Figure 4.30 (c). This is consistent with the observation reported by Bunderson and Smith (2005). The stronger jet appears to draw the weaker side jets inward and the inner shear layers (shear layers 2 and 5) are diverted and elongated in the horizontal direction at $X/D = 2, Y/D = \pm 2$. However, since the lateral contributions of the side jets are much smaller in the lowest momentum case (D4), the flapping phenomenon is not as clearly evident until $X/D = 11$. The

amplitude of the flapping is in range of $Y = \pm 2D$ which is smaller than that in C3. The vortex shedding frequency for D4 is 20 Hz and the Strouhal number is 0.2. When the momentum coefficient is 1/9, the two side jets appear to split the central jet and direct the split jet into the X-Z plane, resulting an almost zero value of cross stream vorticity at the central jet there. Larger momentum coefficient of the side jets also lead to larger lateral component of momentum flux which initiate the flapping process at a location further upstream.

Figure 4.30: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for 45° converging jets at $C_\mu=1/16$ (D4) for $t =$ (a) 0, (b) $1/15s$, (c) $2/15s$ and (d) $3/15s$

Figure 4.31: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for 45° converging jets at $C_\mu=1/9$ (D5) for $t =$ (a) 0, (b) $1/15s$, (c) $2/15s$ and (d) $3/15s$

preserving core and necking are more noticeable for larger momentum coefficients. With lower momentum coefficients and lower Reynolds number, the two side jets produce more pronounced effects on the main jet (see Figure 4.33 (a) and (b)) as compared to those with larger momentum coefficients and higher Reynolds (see Figure 4.33 (e) and (f)). The combined jet is narrower at the necking point in the X-Y plane. However, such difference became less evident with larger momentum coefficients. The contours of the mean velocity in the X-Z plane correspond to those with the highest C_μ (C2 and C3) are shown in Figure 4.34 (a) and (b), respectively. The penetration of the side jets and the splitting of the central jet are pronounced in both runs.

Figure 4.33: Comparison of the mean velocity field of 45°converging jets at various Reynolds number in the X-Y plane

Figure 4.34: Comparison of the mean velocity field of 45° converging jets with various Reynolds number in the X-Z plane

The effectiveness of the side jets at different Reynolds numbers is also demonstrated clearly examining the downstream development of the centreline axial velocity, normalized by the centreline velocity at the nozzle exit, as shown in Figure 4.35. The case of C1 with the lowest Reynolds number of 4240 and a single jet are also included for comparison. It can be observed in Figure 4.35 that when the momentum of the side jets matches that of central jet, the normalized centreline velocity increases rapidly in the merging region and decays rapidly in the combining region. The location and value of the peak of the centreline velocity differed marginally for various Reynolds numbers. In the combining region, the centreline velocity at different Reynolds numbers decays in the same manner and can be described by Equation 4.1. The decay is more rapid compared to a single jet at $X/D < 20$.

Figure 4.35: Comparison of centreline velocity decay for 45° converging jets with various Reynolds number (runs C1, C2 and C3)

The cross-sectional distribution for the mean velocity in the X-Y plane and X-Z plane at different Reynolds numbers are presented in Figure 4.36 and Figure 4.37, respectively. It is noted in Section 4.3.3 that when the three jets converge the axial velocity profile would attain self-similarity at a certain distance downstream. With reference to Figure 4.36 (a) one can observe that the axial velocity distribution for converging jets at different Reynolds actually collapse onto the same Gaussian profile. Similar observation can also be made in the X-Z plane, where the normalized axial velocity depicts a double peak distribution, as shown in Figure 4.37 (also in Figure 4.11 (b)). This distribution highly resembles the corresponding profiles in cases C1, C2 and C3 in both the X-Y and X-Z planes. Therefore, one may deduce that once the momentum coefficients is known the axial velocity in any downstream section could be described by a function of the chosen velocity and length scale (U_c , $Y_{1/2}$ and $Z_{1/2}$ in the present study) as described by Equation (4.2) and (4.3). The axial velocity is independent of the Reynolds number ($Re=4240\sim 8000$). However, the lateral and transverse velocity V and W are more sensitive to the Reynolds number. The negative gradient for the lateral velocity V at ($-2.5 < Y/Y_{1/2} < -1$) and ($1 < Y/Y_{1/2} < 2.5$) increases slightly with Reynolds number, see Figure 4.36 (a) Whereas the transverse velocity W shows larger magnitude in the outer mixing layer and the location of the peak is somewhat further off from the centerline. The magnitude of the Reynolds number also affected where or how “fast” the combined flow approaches the established state. At lower Reynolds number (C1 and C2) the velocity approaches self-similarity at $X/D \approx 14$ which is more upstream than the higher Reynolds number case (C3) of 17D as shown in Figure 4.9 to Figure 4.11.

Figure 4.36: Comparison of distribution of mean velocity for 45° converging jets with various Reynolds number in the X-Y plane (runs C1, C2 and C3)

Figure 4.37: Comparison of distribution of mean velocity for 45° converging jets with various Reynolds number in the X-Z plane (runs C1, C2 and C3)

The downstream development of the converging jets in terms of the jet half width $Y_{1/2}$ and $Z_{1/2}$ in the X-Y and X-Z planes at different Reynolds numbers are presented in Figure 4.38 and Figure 4.39, respectively. It can be observed the data show scattered the most within the range on $5 < X/D < 14$ which is also the location of the first two subzones of the combining region. In other words, Reynolds number mainly influences the transition processes and development of the combined flow. Further downstream, the half widths of the combined jets appear to be independent of the Reynolds number.

The effect of the Reynolds number on the downstream development of the integrated turbulence stresses (discussed in Section 4.5.2) for runs C1, C2 and C3 are discussed further here. The integrated turbulence stresses in X-Y and X-Z planes are presented in Figure 4.40 (a-c) and (d-f), respectively. It can be observed that when the side jets are at a momentum coefficient of 1, the three integrated turbulence stresses are increased only slightly with the Reynolds numbers. This is consistent with the observation on the centreline velocity and the jet half width. However, the magnitudes of the three turbulence quantities on the X-Z plane are larger with Reynolds number at $X/D < 8$ indicating the jet flow has become more unstable in the corresponding converging and merging regions. At Reynolds number of 8000 (run C3), the integrated streamwise stress $\widetilde{u'^2}$ is slightly enhanced in the transition zone of the combining region ($8.5 < X/D < 11$) and decays afterwards. The decay rate appears to be the same as that for the lower Reynolds number cases (C1 and C2). The integrated normal stress $\widetilde{v'^2}$ experiences a plateau in the transition zone. Other than the peak value, the general trend of the Reynolds

stress $\widetilde{u'v'}$ appears to be invariant with Reynolds number within the present range of Reynolds numbers considered.

Figure 4.38: Comparison of streamwise development of the jets half width for 45° converging jets with various Reynolds number in the X-Y plane (runs C1, C2 and C3)

Figure 4.39: Comparison of streamwise development of the jets half width for 45° converging jets with various Reynolds number in the X-Z plane (runs C1, C2 and C3)

Figure 4.40: Comparison of downstream distribution of the integrated Reynolds stress for 45° converging jets with different Reynolds number in (a-c) X-Y and (d-f) X-Z planes (runs C1, C2 and C3)

4.7 Effects of the jet spacing ratio

In the present study, three jet spacing ratio of $S/D = 2, 3$ and 4 are investigated. The periodic behaviors are elucidated by examining the time series of instantaneous vorticity maps. The methodology used is discussed in Sections 4.4.1 and 4.4.2.

4.7.1 Geometrical effect

Tanaka (1970) showed that for the cases of two parallel jets, the interaction of the two jets would attract each other and the axis of each jet follows an arc of a circle. The radius of the jet axis and the cavity length increases in proportion to the nozzle distance. However, such behaviour is not observed in the present study, perhaps due to the different jet configuration used. As discussed in Section 2.3.1 and 4.5.1, the entrainment of adjacent jets of set in a parallel configuration are due to the pressure gradient in between the jets while the effect of such pressure gradient is minor in the present study of two side jets converging on the central jet. Here the jet axes before the jets combine follow a straight line, as shown in Figure 4.41.

The velocity maps for cases C5 and C8 at $Re = 6400$ at $S/D = 3$ in Figure 4.41 (a), (c) and $S/D = 2$ in Figure 4.41 (b) and (d) on both the X-Y and X-Z planes are used to illustrate the effects of spacing ratio on the flow development. Note that the velocity vector maps for $S/D = 4$ are shown in Figure 4.4 and 4.5. When the jet spacing ratio is 4 (cases C1-3), the merging and combining points are located at around $X/D = 1.5$ and 4.5, respectively. With smaller spacing ratio of 3, the jets start to merge at $X/D = 0.7$. The combining of the converging jets also takes place earlier, at $X/D \approx 3$, see Figure 4.41 (a). At the corresponding combining location in the X-Z plane, the velocity is significantly larger in the central portion ($Z/D \sim \pm 1.5$). The splitting of the central jet is more obvious as indicated by the narrower distribution in the X-Y plane but wider in the X-Z plane. When the spacing ratio is smaller and equal to 2, it could be observed that the jets almost started to merge with each other immediately after leaving the nozzle at $X/D = 0.4$, and the jets combine at $X/D = 2$ for C7, see Figure 4.41 (b) and (d).

Figure 4.41: Mean velocity field for 45° converging jets at various jet spacing ratio in the X-Y and X-Z plane (runs C5 and C8)

The downstream development of the centreline velocity U_c , normalized by the centerline velocity at the exit U_e for momentum coefficient of 1/16, 1/9, 1/4 and 1 at $Re = 6400$ are presented for $S/D = 3$ and $S/D = 2$ in Figure 4.42 (a) and (b), respectively. For the convenience of comparison and to improve the frame resolution, the velocity decay for C2 ($S/D = 4, Re = 6400$) is also included in the figures as black line (see also Figure 4.7 and Figure 4.35). Compared to $S/D = 4$ and 2, the jet interactions appear to be more sensitive to the momentum coefficient at $S/D = 3$. At this spacing ratio, the centerline velocity decays far more rapidly for high momentum cases at the beginning of the combining region ($3 < X/D < 8$). Despite the lowest momentum coefficient case (D7), a minor peak of U_c/U_e could be seen near $X/D = 8$ for D8 and D9, and at $X/D = 6$ for C8. Similar secondary peak could be also seen for C2 but with smaller magnitude. This is attributed to the fact that when three jets combined, most part of the side jets have been vectored off to the X-Z plane. With the increase of momentum, the two side jets penetrate into the central jet resulting in a sudden drop in the velocity along the jet centreline. However, such penetration lasts only for a short distance, and the velocity decays linearly afterward. The intensity of such penetration is reduced with larger jet spacing, resulting in a small, median and notable secondary peak (and a drop) for $S/D = 4, 3$ and 2, respectively.

The effect of the jet spacing ratio is explored further in terms of the jet half widths denoted by $Y_{1/2}$ and $Z_{1/2}$ and they are presented in Figure 4.43 and Figure 4.44. The illustration is based on the cases with matched momentum at $Re = 6400$ in the X-Y and X-Z planes. As can be seen in the vector maps (see Figure 4.4), the jets at larger spacing merge and combine

further downstream than those with closer spacing. Moreover, the narrowest part of the jets is observed further downstream (at $X/D \approx 7.5$, 5.2 and 4.2 for C2, C4 and C7, respectively) and with smallest value of $Y_{1/2} = 0.23D$ for $S/D = 2$. Beyond this point, the jet half width starts to grow linearly. It has been found that although the value of the jet half width for bigger jet spacing might be slightly large than that of jets at smaller spacing, the growth rate $dY_{1/2}/dx$ and $dZ_{1/2}/dx$ appears to be independent of the spacing ratio after $X/D = 20$. In the X-Z plane, the injection of the side jets result in a wider combining flow, where the spreading rate of the jets increases as the jet spacing decreases (at $2 < X/D < 8$). Similar to that on the X-Y plane, the jet half width in this plane for different jet spacing ratios reached almost the same value suggesting the effect of the jet spacing is pronounced only before $X/D = 20$.

Figure 4.42: Comparison of centreline velocity decay for 45° converging jets at various jet spacing ratios (runs C2, C5 and C8)

Figure 4.43: Comparison of streamwise development of the jets half width for 45° converging jets at various jet spacing ratios on the X-Y plane (runs C2, C5 and C8)

Figure 4.44: Comparison of streamwise development of the jets half width for 45° converging jets at various jet spacing ratios on the X-Z plane (runs C2, C5 and C8)

4.7.2 Temporal flow characteristics

When the interacting jets have the same initial momentum flux, the combining jet flow would depict an instability characterized by a sinuous “flapping” and enhanced mixing of the jets’ with the ambient fluid (Bunderson and Smith 2005). The frequency and amplitude of such flapping are a function of the momentum coefficient and jet spacing ratio. Moreover, the oscillatory behaviour in the near field has been shown to be characterized by periodic large-scale Karman-like vortices as reported by Wang and Tan (2007). The dynamics processes are represented by vortex shedding at a frequency of 25 (Hz) in Wang and Tan (2007). The present

study includes combining jets which appear to “flap” periodically at a frequency of 40 Hz ($St = 0.4$) at $S/D = 4$.

Figure 4.45 depicts a time series of instantaneous field of $\Omega_z D/U_0$ for $S/D = 3$ represented by test case C4. The K-H structures for each individual jet are hardly detectable compared to that in C3 ($S/D = 4$). The inner shear layers of the side jets (layer 2 and 5) interact with those of the central jet (layer 3 and 4) and produce irregular and smaller vortical structures in the converging and merging region ($0 < X/D < 2$). Meanwhile, the outer layers of the two side jets propagate inward and interact with each other. Consequently, the combining jet flapped from the left side to the right due to the expansion of one side layer and compression of the other as shown in Figure 4.45 (a) and (b). The vortex shedding processes are more appreciable by the row of discrete vortices for $S/D = 3$ as shown in Figure 4.45 (d). The clockwise and counter-clockwise vortical structures are denoted using the same notation as in 4.4.2, i.e. using “P” and “M”, respectively. At $t = 0$, it can be seen in Figure 4.45 (a) that vortices M1, P1, M2 and M3 are formed and move downstream while a larger vortex P2 is just about to be shed from the right side shear layer. $1/15$ s later, as can be seen in Figure 4.45 (b), the vortices M1 and P1 have already travelled out of the field of view while a new one M3 is about to be shed from the stretching shear layer 1. The vortices M3 and M4 are merged at $t = 1/15$ s but are detached in the next frame ($t = 2/15$ s) by “truncating” P3, see Figure 4.45 (c). Meanwhile, two new small vortices M5 and P5 are being formed and at the verge of being shed. At the same moment P4 is bending inward and M4 is about to be shed from M5. At $t = 3/15$ s, with M5 and P5 having been shed, a row of discrete vortices with alternate signs are formed at the interface of the shear layers. Then the process is repeated. Hence one can infer that the breaking up of vortex and movement of the vortices are periodic. The size of the vortical structures is of the order of the nozzle diameter ($1.5 \sim 2 D$) and the vortex breaking frequency, is estimated at $f = 9/(3/15) = 45(\text{Hz})$. The Strouhal number is calculated to be 0.68 ($St = 45 \text{ Hz} \times 0.008\text{m}/0.53 \text{ m/s}$).

When the jets are located closer to one another at $S/D = 2$, the flapping of jet is limited to $4 < X/D < 8$. The interaction between the two shear layers of the combining jets downstream of $9D$ is not discernible. Although discrete vortices could still be observed, the mechanism of these vortical structures is perhaps associated more with advection by the mean flow. The equivalent frequency is estimated to be $f = 2/(2/15) = 15(\text{Hz})$, and the Strouhal number is 0.22 ($St = 15 \text{ Hz} \times 0.008\text{m}/0.53 \text{ m/s}$).

It could be deduced that the St number is not a monotonic function of the jet spacing ratio. As illustrated in the present study the St number reaches the highest value of 0.68 for $S/D = 3$ and reduces to 0.4 when the jet spacing ratio is equal to 4. However, when the jet spacing ratio is lower and equal to 2, the St number is reduced significantly to a value of 0.15.

Figure 4.45: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for 45° converging jets at $S/D = 3$ (run C4)

Figure 4.46: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for 45° converging jets at $S/D = 2$ (run C7)

4.8 Effects of the inclined angle

In the present study, the effects of converging angle on the interaction among converging jets is elaborated further by comparing the flow characteristics based on the incline angle of 45° and 30° degree.

4.8.1 Ensemble-averaged flow characteristics

Figure 4.47 shows the mean velocity field in the converging and merging region for $\alpha = 30^\circ$ from test series T2 ($Re = 6400, S/D = 3$). The two side jets approach the outer layer of the central jet after $X/D \approx 2$ (M.P), as shown in Figure 4.47 (a). The individual characteristics of the three jets attenuate and finally merge into a combined distribution at $X/D \approx 5.4$ (C.P). Compared to the 45° side jets at the same jet spacing ratio ($S/D = 3$), one

can see that the 30° side jets start to merge at $X/D = 0.7$ and combine around $X/D = 3$ (see Fig 4.41 (a)). The 30° side jets impinge on the central jet at a location further downstream. Hence the length of the converging and merging region is lengthened. The merging and combining of the jets could be identified in the X-Z plane. At $0 < X/D < 2$, the velocity vector map resembles that of a single pipe jet. Downstream of the merging point, the mean velocity distribution is wider in the streamwise direction until $X/D = 5.4$ where the two side jets are fully merged with the central jet forming a double peak distribution in the X-Z plane.

To further investigate the effect of the converging angle, the jets half widths denoted by $Y_{1/2}$ and $Z_{1/2}$ exemplified using the test series T1, T2 and T3 are shown in Figure 4.48 and Figure 4.49. In the converging region the jet spreading ($0.7D$ for 45° and $2D$ for 30° at $S/D = 3$) is similar to that of a single pipe jet (see Figure 3.11 in Chapter 3). The jet widths are slightly expanded in the merging region (from $0.5D$ to $0.7D$). It could be observed that when the side jets are set at a smaller incline angle with respect to the central jet, the necking process in the X-Y plane is not observable (compared to the 45° jets). Instead, the jet half-width remains constant at $0.7D$. The difference is mainly attributable to the less contribution of the side jets in the lateral direction for 30° jets compared to that for 45° jets. As shown in Figure 4.48, the linear flow structures appear at $X/D = 12$, which is located further downstream compared to that for 45° jets ($X/D = 5.5$). In the X-Z plane, the injection of the side jets result in a wider combining flow, where the spreading rate of the jet is increased slightly as the jet Reynolds number increases ($Re = 4240, 6400$ and 8000 for T1, T2 and T3). Compared to the 45° jets, the expansion takes place further downstream and with narrower $Z_{1/2}$ in the corresponding combining regions as shown in Figure 4.49.

Figure 4.47: Mean velocity field for 30° converging jets on the (a) X-Y and (b) X-Z planes (run T2)

Figure 4.48: Comparison of streamwise development of the jets half width between 30° and 45° converging jets on the X-Y plane

The decay of the normalized centreline velocity U_c/U_e is shown in Figure 4.50 for 30° jets. The result of a single pipe jet and 45° jets (represented by C4) are included for comparison. It can be seen that when the side jets are set at smaller incline angle the centreline velocity U_c/U_e at $X/D < 2$ almost collapsed on the curve of a single pipe jet indicating the merging has not happened upstream of this point. Further downstream, the centreline velocity increases due to the merging of the three jets and reaches a peak at the combining point ($X/D = 5.4$). Intuitively, the peak value would be bigger in magnitude for 30° jets than that of 45° jets according to the vector decomposition in the streamwise direction. However, the peak value of 1.22 for T1-3 was slightly smaller than that of 1.29 for C4 as depicted in Figure 4.50.

The difference is mainly attributable to the fact that at the same jet spacing ratio, smaller incline angle results in a larger distance between the origins of the side jets to the centreline of the measurements. Consequently, the axial velocity of each individual jet would have decayed to a lower value before the jet combination takes place.

Figure 4.49: Comparison of streamwise development of the jets half width between 30° and 45° converging jets on the X-Z plane

The cross-sectional distribution for the mean velocity on the X-Y and X-Z plane at different Reynolds are presented in Figure 4.51 and Figure 4.52, respectively. When three jets collided or impinged convergingly the axial velocity profile would attain self-similarity at certain downstream location. As is shown in Figure 4.51 (a) one may find the streamwise velocity distribution for converging jets at different angles actually collapse onto the same Gaussian profile as that of a single pipe jet at $|Y/Y_{1/2}| < 2$. The minor difference at $|Y/Y_{1/2}| > 2$ is mainly attributable to the fact that the streamwise component of the axial velocity of the two side jets is marginally bigger for smaller incline angle at lateral locations away from the centreline. The cross-sectional distribution of the normalized mean lateral velocity V/U_c is plotted in Figure 4.51 (b). Compared to 45° jets, the negative gradient for 30° jets at $1 < |Y/Y_{1/2}| < 2.5$ is smaller indicating the entrainment of the ambient flow would be more effective for converging jets with bigger incline angle.

Figure 4.50: Comparison of centreline velocity decay between 30° and 45° converging jets

In the X-Z plane, the normalized axial velocity depicts a double peak distribution as seen in Figure 4.52 (a). The distribution are similar for the 30° and 45° jets. The peak value of U/U_c is 1.31 in 30° jets which is slightly bigger than that of 1.29 in 45° jets. Compared to the streamwise velocity U/U_c , the transverse velocity W/U_c is altered greatly due to the effect of the incline angle. With the larger incline angle of 45°, the magnitude of W/U_c is almost 1.5 times larger than that of 30°. This is attributable to the splitting of the central jet is much more effective for the 45° converging jets.

Figure 4.51: Comparison of the cross-sectional distribution of (a) mean streamwise velocity and (b) mean lateral velocity between 30° and 45° converging jets on the X-Y plane

Figure 4.52: Comparison of the cross-sectional distribution of (a) mean streamwise velocity and (b) mean transverse velocity between 30° and 45° converging jets on the X-Z plane

The Reynolds stresses for 30° jets base on test series T2 are presented in Figure 4.53 and Figure 4.54 for the X-Y and X-Z plane, respectively. Along the side jets (X-Y plane), the normalized streamwise Reynolds normal stress, $\overline{u'^2}/U_0^2$, the cross-stream normal $\overline{v'^2}/U_0^2$ and the Reynolds shear stress $\overline{u'v'}/U_0^2$ are shown in Figure 4.53 (a)-(c) for single pipe jet and (d)-(f) for 30° converging jets, respectively.

When the two side jets are injected into the central jet at 30 degree the two normal turbulent stresses show distinctly different distributions, see Figure 4.53 (d) and (e) as compared to that of the benchmark case (the single pipe jet) in Figure 4.53 (a) and (b). The streamwise normal stress $\overline{u'^2}/U_0^2$ shows a double-peak distribution for $X/D \geq 8.5$ while the distribution of $\overline{v'^2}/U_0^2$ resembles an elongated bulbous shape with the maximum value of 0.025 at $8 \leq X/D \leq 12$, see Figure 4.53 (e). For the shear stress $\overline{u'v'}/U_0^2$, a nearly zero region is observed near the exit of the central jet as shown in Figure 4.53 (see Figure 4.15 (f) for the 45° jets). In addition, low values of the two normal stresses could also be observed in the same region as shown in Figure 4.53 (d) and (e). It is worth noting that the shear stress vanishes (nearly zero) again around $X/D \approx 5.4$ which corresponds to the center of the jets impinging region.

The interaction of converging jets is explored further by examining the Reynolds stresses in the cross-stream plane (X-Z plane). When the two side jets are set at 30°, the normal turbulence quantities $\overline{u'^2}/U_0^2$ and $\overline{w'^2}/U_0^2$ depict symmetrical distribution about the X-axis but with a significantly wider distribution than that of a single pipe jet. Compared to the double-peak distribution of $\overline{u'^2}/U_0^2$ in the X-Y plane, the second peaks are observed nearer to the outer

layer. In addition, a significant value of $\overline{u'^2}/U_0^2 = 0.04$ at $X/D \approx 6$ is observed. The high streamwise fluctuations at this region coincide with the impingement of the converging jets. The distribution of spanwise normal stress $\overline{w'^2}/U_0^2$ (Figure 4.54 (e)) is also wider and has the second peaks located at the outer layer. Downstream of $X/D = 6.5$, high values of normal stresses are found near the centreline while the corresponding values on the centreline are relatively low. It can also be seen that there is a larger near-zero region of shear stress $\overline{u'w'}/U_0^2$ at this location. These observations could be explained by the splitting of the central jet by the side jets. Similar phenomenon is also reported in Tamburello and Amitay (2006). The shear stress distribution (Figure 4.54 (f)) shows more regions of positive and negative shear stress along the combined jet centreline compared to that in the X-Y plane (Figure 4.53 (f)). This observation further clarifies the splitting of the central jet during the jets interaction.

For converging jets with the smaller incline angle of 30° , the general distribution of the Reynolds stresses are similar to the 45° jets (see Figure 4.15 and Figure 4.16 for the X-Y and X-Z plane, respectively). The magnitudes are found to be slightly lower.

Figure 4.53 : Reynolds stresses on the X-Y plane: a single of (a) $\overline{u'^2}/U_0^2$, (b) $\overline{v'^2}/U_0^2$, (c) $\overline{u'v'}/U_0^2$; 30°converging jets of (d) $\overline{u'^2}/U_0^2$, (e) $\overline{v'^2}/U_0^2$, (f) $\overline{u'v'}/U_0^2$ (run T2)

Figure 4.54: Reynolds stresses on the X-Z plane: a single jet of (a) $\overline{u'^2}/U_0^2$, (b) $\overline{w'^2}/U_0^2$, (c) $\overline{u'w'}/U_0^2$; 30°converging jets of (a) $\overline{u'^2}/U_0^2$, (b) $\overline{w'^2}/U_0^2$, (c) $\overline{u'w'}/U_0^2$ (run T2)

4.8.2 Temporal flow characteristics

Figure 4.55 shows a snapshot of the instantaneous flow field of the 30° converging jets in the X-Y plane. It can be seen that, before $X/D = 3$ the shear layer of the central jet breaks into small scale structures which merge with the inner layers of its two neighbours. From $X/D = 3$ to 8 which corresponds to the necking region, the compound jet retains the K-H roll up in the right and left shear layer with maximum vorticity, $|\Omega_z D/U_0|_{max} = 1.6$, and is higher than that of a single pipe jet as shown in Figure 4.17 (b) but lower than that of 2.4 for 45° jets as shown in Figure 4.45. Beyond $X/D = 8$, the K-H roll up in the shear layers start to break up and interact with each other to form large-scale discrete vortices. The discrete vortices could be discerned as the regions of isolated and concentrated vorticity in Figure 4.55 (b). An alternate row of negative (anticlockwise) and positive (clockwise) vortices periodically propagate downstream, forming a well-organized vortex sheet. These vortices become weaker with downstream distance as could be appreciated from the vorticity contour values.

Figure 4.56 shows a snapshot of the instantaneous flow field of the converging jets on the X-Z plane. Similar to the 45° jets the normalized cross-stream vorticity distribution width is increased significantly downstream of the impingement location of the converging jets. The coherent K-H structures begin to break down at $X/D \approx 8$, and are similar to that on the X-Y plane. In addition, the distribution of instantaneous vorticity in this plane is highly asymmetrical reflecting the oscillation of the sides of the shear layers. The strong interactions between the two sides of the shear layers result in the enhancement of turbulence ($|\Omega_y D/U_0|_{max} = 2.2$) and the presence of random small scale vortices after $X/D = 10$. The turbulence level for the 30° jets is slightly lower than that of the 45° jets ($|\Omega_y D/U_0|_{max} = 2.4$ for $S/D=4$ and 3 $S/D=3$). Furthermore, the penetration of the two side jets into the central jet is evident by the presence of two large-scale counter-rotating vortices at ($X/D = 9$, $Y/D = 0.3$).

By examining the 1050 images of instantaneous flow field, the evolution of the flow is found to be periodical. Figure 4.57 (a)–(d) depict a random time series of instantaneous fields of Ω_z (note that Figure 4.57 (b) is actually Figure 4.55 (b), and reproduced here for ease of comparison). It can be seen that the size of the discrete vortices at $8 < X/D < 16$ is of the order of the nozzle diameter ($2D$) and the streamwise distance between adjacent vortices (synclastic, either positive or negative) appears to be constant at about $3D$, see Figure 4.57 (a) at $X/D=9, 12$ and 15 for negative vortices and $X/D=10$ and 13 for positive ones. The size of

the discrete vortices is marginally larger than that of the 45° converging jets. In Figure 4.57, the clockwise and counter-clockwise vortices are denoted by “P and M”, respectively. One may argue whether the vortices M2 at $X/D = 12, t = 0$ in Figure 4.57 (a) could have been one and the same as that located at $X/D = 15, t = 1/15s$ in Figure 4.57 (b). This deduction is supported by the estimation of the translational velocity of these vortices. According to Lyn *et al.* (1995), Wang and Tan (2007) and Zheng *et al.* (2014), the translational velocity of such vortices in the near wake is estimated to be 60~80% of the average efflux velocity U_0 . Based on this estimation, given that U_0 for the representative case T1 is 0.53 m/s , one can yield a translational velocity of $0.3\sim 0.4 \text{ m/s}$. Therefore, after a time duration of $1/15 \text{ s}$ (15Hz frame frequency), the discrete vortices would have travelled downstream by a distance of $20\sim 26\text{mm}$, i.e, around $3D$. Similar approach could be used to assess the dynamic processes for the 30° converging jets. To estimate the vortex shedding frequency, an imaginary measurement probe was assumed to be installed at $(X / D = 14, Y / D = 0)$, which is marked by a “*” sign in Figure 4.57 (a). From $t = 0$ to $t = 3 / 15 \text{ s}$, the probe could detect and record these vortices, namely M1, P2, M2, P3, M3, P4 and M4 in sequence. Hence, an equivalent frequency may be calculated as $f = 7/(3/15) = 35 \text{ (Hz)}$, and the corresponding Strouhal number is estimated to be 0.53. The St Number of 0.53 for the 30° converging jets is lower than that of 0.68 for the 45° converging jets.

Figure 4.55 : A snapshot of the instantaneous flow field for 30° converging jets a) velocity vector (u, v) superimposed with contours of λ_2 and b) contours plot of spanwise vorticity $\Omega_z D/U_0$ (run T1)

Figure 4.56 : A snapshot of the instantaneous flow field for 30° converging jets a) velocity vector (u, w) superimposed with contours of λ_2 and b) contours plot of spanwise vorticity $\Omega_y D/U_0$ (run T1)

Figure 4.57: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) $1/15s$, b) $2/15s$ and c) $3/15s$ (run T2)

4.9 Summary

The results of an experimental investigation on the converging jet are presented in this chapter. The centreline of the converging jet coincides with the jet central axis along which one could locate the impinging point. The decay of the centreline maximum velocity is similar to that of a single pipe jet near the jet exit. The centreline velocity experiences a sudden amplification upon merging of the three converging jets and then drops rapidly, and finally decays linearly in the combining region. The cross-sectional profiles of the streamwise velocities on both the central planes and the parallel offset planes are presented, and examined with respect to jets merging and mixing processes. The findings indicate that the mean streamwise velocity can be prescribed by the measurements on the two jet central planes (X-Y and X-Z). The jet spread width based on velocity profile reveals the linear growth of the converging jet on the X-Y plane. The contours of the turbulence intensity and Reynolds shear stress yield insight on the flow characteristics and the mechanism by which the side jets influence and affect the development of the central jet and flow instabilities. The effects of the momentum coefficients, Reynolds number, jet spacing ratio and incline (converging) angle are deliberated as well. Based on the experimental results, the geometric characteristics of the converging jets, including the location of the merging point, combining point, necking point and flow established point are discussed. Furthermore the dynamic characteristics have been illustrated by a time series of instantaneous flow fields. Galilean decomposition of the instantaneous velocity vectors and calculation of λ_2 in conjunction with the vorticity fields

have been used to discriminate difference between the swirling and the shearing in the evolution of the flow. The free shear layers of a single pipe jet are standard K-H roll-ups while the combined jet is dominated by periodic Karman-like vortices. The breaking of the roll-up and the movement of the Karman-like vortices have been revealed to be the result of the interactions of the shear layers from each individual jet. The empirical coefficients that relate to the effect of the investigated parameter in the present study have been summarised in Table 4.2.

Table 4-2 : Summaries of the empirical parameters

Exp. No.	Inclined Angle θ	Spacing ratio S/D	Momentum Coefficient C_μ	Reynolds Number Re_a	K_y	K_z	β	α_1	α_2	α_3	Strouhal Number S_t
C1	45°	4	1	4240	0.126	2.047	0.779	1.24	0.826	0.545	0.4
C2	45°	4	1	6400	0.126	2.045	0.779	1.24	0.826	0.54	0.4
C3	45°	4	1	8000	0.126	2.046	0.779	1.26	0.826	0.54	0.4
C4	45°	3	1	4240	0.1245	2.231	0.779	1.29	0.818	0.649	0.68
C5	45°	3	1	6400	0.1241	2.233	0.779	1.3	0.818	0.648	0.68
C6	45°	3	1	8000	0.1248	2.233	0.779	1.29	0.818	0.65	0.68
C7	45°	2	1	4240	0.123	2.46	0.779	1.25	0.798	0.57	0.22
C8	45°	2	1	6400	0.1233	2.45	0.779	1.25	0.798	0.57	0.22
C9	45°	2	1	8000	0.1235	2.464	0.779	1.27	0.798	0.57	0.22
D1	45°	4	1/16	6400	0.122	1.787	0.779	1.103	0.826	0.51	0.2
D2	45°	4	1/9	6400	0.1237	1.801	0.779	1.135	0.826	0.5	0.3
D3	45°	4	1/4	6400	0.125	1.95	0.779	1.197	0.826	0.51	0.3
D4	45°	4	1/16	8000	0.1231	1.8	0.779	1.1	0.826	0.52	0.2
D5	45°	4	1/9	8000	0.1235	1.901	0.779	1.15	0.826	0.5	0.3
D6	45°	4	1/4	8000	0.1254	1.96	0.779	1.2	0.826	0.5	0.3
D7	45°	3	1/16	6400	0.1205	2.221	0.779	1.19	0.818	0.607	0.3
D8	45°	3	1/9	6400	0.123	2.223	0.779	1.193	0.818	0.613	0.35
D9	45°	3	1/4	6400	0.1237	2.223	0.779	1.23	0.818	0.63	0.45
D10	45°	2	1/16	6400	0.119	2.236	0.779	1.181	0.798	0.53	Na
D11	45°	2	1/9	6400	0.1213	2.233	0.779	1.183	0.798	0.54	0.11
D12	45°	2	1/4	6400	0.1225	2.236	0.779	1.2	0.798	0.56	0.15
D13	45°	2	1/16	8000	0.118	2.238	0.779	1.187	0.798	0.55	Na
D14	45°	2	1/9	8000	0.1211	2.24	0.779	1.193	0.798	0.573	0.11
D15	45°	2	1/4	8000	0.122	2.243	0.779	1.21	0.798	0.577	0.15
T1	30°	3	1	4240	0.1233	1.98	0.779	1.31	0.82	0.64	0.53
T2	30°	3	1	6400	0.1237	1.991	0.779	1.31	0.82	0.64	0.53
T3	30°	3	1	8000	0.1240	2.096	0.779	1.314	0.82	0.65	0.53
S1	0	Na	Na	4240	0.085	0.085	0.779	Na	Na	Na	Na
S2	0	Na	Na	6400	0.084	0.084	0.779	Na	Na	Na	Na
S3	0	Na	Na	8000	0.085	0.085	0.779	Na	Na	Na	Na

Chapter 5. Conclusions and Recommendations

5.1 Conclusions

Specific findings and conclusions have been drawn and discussed at various sections of the report. The main conclusions of the present study are summarised as follows.

General flow characteristics

When three jets are set to converge in a co-planar manner, the converged flow depicts certain unique flow characteristics. The cross-sectional profiles of the streamwise velocities show strong resemblance on both the central planes and the parallel offset planes. Therefore the mean streamwise velocity for converging jets may be prescribed by the corresponding velocity on the two central planes (X-Y and X-Z). The flow field may be divided into three regions: the converging region, the merging region and the combining region.

The cross-sectional profiles of the mean streamwise velocity U on the X-Y plane fit the Gaussian distribution in the combining region, and are similar with those of a single pipe jet. The self-similar curve of the mean lateral velocity V is also similar with that of a single jet in the central portion ($|Y/Y_{1/2}| \leq 1$) but with significant deviation at the two limbs ($|Y/Y_{1/2}| > 1$). On the cross-stream plane (X-Z), the mean streamwise velocity U shows wider and double-peak distribution compared to that of a single jet in the combining region.

Entrainment of ambient fluid from the surroundings into the combined jets is enhanced compared to that in a single jet, as indicated by the steeper negative gradient of the mean lateral velocity V at the edge of the combined jet in the X-Y plane, and significant values of mean transverse velocity W (almost 3 times larger than V in magnitude) in the X-Z plane. In addition, one may observe further enhancement of entrainment base on the jet spreading features. The linear spreading of such flow in the X-Y plane is elucidated by checking the jet half width based on the cross-sectional profile of the mean streamwise velocity. In the X-Z plane, the complex flow is bounded by smooth parabolic curve with open rim. The spreading rate is significantly elevated compared to that of a single pipe jet in both the X-Y and X-Z central planes, at around 30% and 150% respectively.

Cross-sectional profile

The cross-sectional shapes of the converging jets at various downstream locations in the combining region are estimated by utilizing the jet half width as the boundary of the compound jet. The compound jet depicts an elliptical cross-sectional shape instead of a circular one for a single round jet. The lengths of the long and short axis of such elliptical cross-section eventually become circular in the far field.

Centre line velocity

The decay profile of the centreline velocity U_c/U_e is found to collapse onto one that is similar to that of a single pipe jet in the converging region. The magnitude of U_c/U_e is then amplified and peaks in the merging region. After the peak, the centerline velocity U_c/U_e depicts a rapid decrease in the combining region. The decay rate of the converging jets is marginally larger than that of a single pipe jet until $X/D = 20$. After that the decay rates of the combined or single jets are almost of the same magnitude. The centerline velocity U_e/U_c decreases linearly in the whole combining region. Therefore, one may conclude that the interactions of converging jets do not alter the decay patterns of the centreline velocity ($\sim X^{-1/2}$ for plane jets and $\sim X^{-1}$ for round jets).

Turbulence parameters

For the turbulence parameters, the merging process is reflected by the merged distribution of the normal stress or the near-zero region of the shear stress on the X-Y plane and considerably higher value and concentration at the same location on the X-Z plane. Further downstream, the side jets penetrate into the central jet, splitting it and displacing the mass to the orthogonal X-Z plane. The penetration and splitting processes are reflected in the change of the sign of Reynolds shear stresses $\overline{u'v'}/U_0^2$ distribution on the X-Y plane and large near-zero regions of Reynolds shear stresses $\overline{u'w'}/U_0^2$ on the X-Z plane, respectively.

Dynamic characteristics of a combined jet

Galilean decomposition of the velocity vectors and calculation of λ_2 in conjunction with the vorticity fields are used to discriminate the swirling and shearing in the evolution of the flow. The dynamic characteristics of converging jets are illustrated by a time series of instantaneous vorticity in the X-Y plane. In the merging region, the inner layers of the two side jets the shear layers of the central jet are combined with the shear layers of the central jet

forming a near-zero region of vorticity. The free outer shear layers depict the standard K-H roll-ups similar with that of a single pipe jet for a short streamwise distance. Further downstream, the K-H structures in the shear layers become unstable gradually and the instability is characterized by the “sinuous” flow motions. The two shear layers interact with each other, forming large-scale discrete vortices. The translational velocity of these discrete vortices is estimated to be about 60~80% of the average efflux velocity U_0 . The combined jet is then dominated by the periodic Karman-like vortex. The periodic nature of the interactions between the negative and positive Karman-like vortices enhances mixing among three converging jets.

Momentum coefficients

When the momentum coefficients of the side jets are reduced and is lower than 1, the side jets tend to merge and combine with the central jet at a more upstream location resulting in a shorter length of the converging and merging region in the streamwise direction. However, the length of the necking zone in the combining region is increased when the momentum coefficients is decreased. The centreline velocity shows similar decay patterns for different value of momentum coefficients but with larger peak value and more rapid decay rate for the higher momentum cases. The mean velocity distributions achieve self-similarity at more upstream locations for lower momentum cases. The self-similar curves of the streamwise velocity U/U_c collapse onto the same Gaussian profile for all cases on the X-Y plane. Whereas for the lateral velocity V/U_c , larger velocity gradient appears at the edge of the converging jets at higher momentum coefficients indicating enhanced entrainment from the surrounding fluid. On the X-Z plane, splitting of the central jet is less evident at lower momentum coefficient. The distributions of the three turbulence stresses ($\overline{u'^2}/U_0^2, \overline{v'^2}/U_0^2$ and $\overline{u'v'}/U_0^2$) and ($\overline{u'^2}/U_0^2, \overline{w'^2}/U_0^2$ and $\overline{u'w'}/U_0^2$) are similar at different momentum coefficients. The overall trends show high resemblance for all the four momentum coefficients. The effects of the momentum of the side jets are mainly reflected by the higher stress levels at the corresponding locations of merging and combining regions.

Jet spacing ratio

When the converging jets are set at different jet spacing ratios S/D , the geometrical features of the flow field are altered. The merging and combining of the converging jets take place earlier with smaller jet spacing. In addition, the splitting of the central jet is more evident

in the lower jets spacing cases as indicated by the narrower streamwise velocity distribution in the X-Y plane but wider in the X-Z plane. At the low spacing ratio of 2, the converging jets are observed to merge with the adjacent jets immediately after issuing out of the nozzle. The jet interactions appear to be more sensitive to the momentum coefficient at the jet spacing ratio of 2. At this spacing ratio, the centreline velocity decays far more rapidly for high momentum cases. A minor peak of U_c/U_e could be observed in the corresponding necking zone, which is attributable to the penetration of the two side jets. In addition, the intensity of such penetration is reduced with larger jet spacing. In terms of jet “flapping”, the instability may be characterized by the vortex shedding frequency, in terms of a non-dimensional St number. It is found that the St number is not a monotonic function of the jet spacing ratio. The findings of the present study show that the St number reaches the highest value for jet spacing ratio $S/D = 3$ and decreases slightly when S/D is increased to 4, but is reduced significantly when S/D is equal to 2.

Jet inclination angle

The incline angle of the two side jets, with respect to the central jet, also influences the interactions among the converging jets. For 30° converging jets, the two side jets impinge onto the central jet at a further downstream location than that for 45° converging jets. The length of the converging and merging region is lengthened with smaller incline angle. For 30° converging jets, the necking processes on the X-Y plane is not distinct compared to that for 45° jets. The jet half width remains constant and appears independent of the jet angle. The linear flow structures developed beyond the necking zone are similar for both 30° and 45° jets. The spreading rate of the jet half width $Y_{1/2}$ increases with larger incline angle. On the X-Z plane, the injection of the side jets at larger incline angle of 45° results in a wider combining flow, where the spreading rate of the jet is increased slightly with jet Reynolds number. Compared to 45° jets, the expansion of 30° jet takes place further downstream. The cross-sectional distributions of the streamwise velocity U/U_c are similar for both 30° and 45° jets. A larger velocity gradient is observed at $1 < |Y/Y_{1/2}| < 2.5$ in the cross-sectional distribution of the lateral velocity V/U_c for 45° jets, indicating that the entrainment of the ambient flow would be more effective for converging jets with bigger incline angle. On the X-Z plane, the transverse velocity W/U_c is altered greatly by the effect of the incline angle. With the larger incline angle of 45°, the magnitude of W/U_c is almost 1.5 times larger than that for 30°.

Moreover, the St number is larger for the 45° jets, which is attributable to the fact that the 45° jets penetrate the central jet at a location closer to the nozzle (than 30° jets) where the central jet's instabilities have not yet developed, making the central jet more receptive to the influence from the two side jets.

5.2 Recommendations

Measurements on the two central planes for each test case have been separated into two steps in the present study. Despite the fact that the initial conditions of every test have been carefully calibrated to ensure that the best experimental results are obtained, the accuracy of the combined flow fields (the X-Y plane and X-Z plane) is imperfect to a certain degree. This is primarily due to the uncertainties in the test conditions since the measurements have been carried out at different time. Although the results obtained are useful in terms of determining the gross behaviour of the converging jets, further efforts to measure the flow field in the orthogonal planes simultaneously and concurrently will improve the data continuity. This approach appears desirable and necessary.

The present study focuses on the enhancement in the transverse growth of the jet and suppression of the interaction processes on the two central planes beyond the point of impingement. Measurements further downstream have not been attempted. From the contours of the relevant turbulence quantities, one may observe the occurrence of second peak at the edge of our measurement domain. It would be of interest to conduct further observation and explore the potential effects of such feature in a future study. It is also worth noting that in the present study only the two central-planes of the complex flow field are observed while the exact shape of the cross-section of the converging jet is still not defined clearly. To further explore the dilution efficiency of the converging jet, LIF image of instantaneous velocity or concentration field in cross-section is essential.

In future work, a wider range of the pertinent parameters affecting the converging jets are to be investigated, and they include some extreme angle of inclination (for example at 180°) of the side jets with respect to the central jet, and much large Reynolds number of the central jet ($\sim 10^5$).

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Appendix A Experimental Data Post-processing Routines

A.1 Mean field. M

```
%% change the column to row (if needed)

a=100; b=75; % length and width of the velocity vector field grids

for i=1:a,j=1:b;

B{i}(j,:)=data((j-1)*a+i,:);

B=B'; end

%% centerline velocity

while abs(B{i}(j,3)-max(B{i}(:,3)))>0

    j=j+1;

end

Vc(i,:)=B{i}(j,:);

end

%% find the boundary & centerline of the jets

Vu=zeros(100,4);

for i=1:100; j=1;

while B{i}(j,3)<0.5*Vc(i,3)    % 0.5 for half width (0.368 for e notation)

    j=j+1;

end                                % find the upper boundary

Vu(i,:)=B{i}(j,:);

end;

Vd=zeros(100,4);

for i=1:100; j=75;
```



```

while B{i}(j,3)<0.5*Vc(i,3)    % 0.5 for half width (0.368 for e notation)
    j=j-1;
end
    Vd(i,:)=B{i}(j,:);
end;                          %find the lower boundary
for i=1:100
    bu(i)=abs(Vu(i,2)-Vd(i,2))/2;
end                            % find jet velocity spreading width bu
%% output the cross-sectional axial velocity
hold on
for i=5
    while i<65
        plot(B{i}(:,2)/bu(i),B{i}(:,3)/Vc(i,3),'*')
        i=i+5;
    end;
end

```

A.2 λ_2 and instantaneous fields. m

```

Clc;
Clear;
Close all;
%% Load vorticity data file
for i=1:150,j=1:200;
    c{i}(j,:)=data((8*(j-1)+1)+1600*(i-1)*8,:);
    c=c';
end
for i=1:150
    Vor((200*(i-1)+1):(200*i),:)=c{i,:};
end; % reduce from 1600 × 1200 to 200 × 150
%% Load instantaneous velocity data file
a=100; b=75;
for i=1:a,j=1:b;
    C{i}(j,:)=data((j-1)*a+i,:);
    C=C';
end
for i=1:a-1;
    D{i}(:,1)=0.5*(C{i}(:,1)+C{i+1}(:,1));
end;
for i=1:a-1;j=1:b-1;
    D{i}(j,2)=0.5*(C{i}(j,2)+C{i}(j+1,2));
end;
for i=1:a-1;
    D{i}=D{i}(1:b-1,:);
end;
D=D';
%% start
%% x,y,u,v for 74*99
E=D;
for i=1:a-1;j=1:b-1;

```

```

E{i}(j,3)=0.25*(C{i}(j,3)+C{i}(j+1,3)+C{i+1}(j,3)+C{i+1}(j+1,3));
E{i}(j,4)=0.25*(C{i}(j,4)+C{i}(j+1,4)+C{i+1}(j,4)+C{i+1}(j+1,4));
end;
for i=1:a-1;
    insV(((b-1)*i-b+2):(b-1)*i,:)=E{i};
end;
%% du/dy
for i=1:a-1;j=1:b-1;
    D{i}(j,4)=(C{i}(j,4)+C{i+1}(j,4)-C{i}(j+1,4)-C{i+1}(j+1,4))./(C{i}(j,1)-C{i}(j+1,1)));
end;
%% dv/dx
for i=1:a-1;j=1:b-1;
    D{i}(j,3)=(C{i}(j,3)+C{i}(j+1,3)-C{i+1}(j,3)-C{i+1}(j+1,3))./(C{i}(j,2)-C{i+1}(j,2)));
end;
%% du/dx
for i=1:a-1;j=1:b-1;
    D{i}(j,6)=(C{i}(j,4)+C{i+1}(j,4)-C{i}(j+1,4)-C{i+1}(j+1,4))./(C{i}(j,2)-C{i+1}(j,2)));
end;
%% dv/dy
for i=1:a-1;j=1:b-1;
    D{i}(j,5)=(C{i}(j,3)+C{i+1}(j,3)-C{i}(j+1,3)-C{i+1}(j+1,3))./(C{i}(j,1)-C{i}(j+1,1)));
end;
%% vor
for i=1:a-1;
    D{i}(:,7)= D{i}(:,4)- D{i}(:,3);
end;
%%  $\lambda_2$ 
For i=1:a-1;
D{i}(:,8)=(D{i}(:,5)+D{i}(:,6)).*(D{i}(:,5)+D{i}(:,6))-
4*(D{i}(:,5).*D{i}(:,6)D{i}(:,3).*D{i}(:,4));
end;
%% dim  $\lambda_2$ 

```

```
for i=1:a-1;  
    dimV(((b-1)*i-b+2):(b-1)*i,:)=D{i};  
end;
```

Appendix B More Graphical Illustrations

B 1: Mean velocity field on the X-Y central and offset planes (C1)

B 2: Mean velocity field on the X-Z central and offset planes (C1)

B 3: Mean velocity field on the X-Y central and offset planes (C2)

B 4: Mean velocity field on the X-Y central and offset planes (C2)

B 5: Development of the cross-sectional axial velocity on the X-Y plane in initial region

B 6: Development of the cross-sectional lateral velocity on the X-Y plane in initial region

B 7: Centerline velocity decay for 45° converging jets at various momentum coefficients, $S/D=4$ (C2)

B 8: Centerline velocity decay for 45° converging jets at various momentum coefficients, $S/D=2$ (C9)

B 9: Cross-sectional distribution of axial velocity on the X-Y plane with various momentum coefficients, $S/D=4$ (C2)

B 10: Cross-sectional distribution of axial velocity on the X-Y plane with various momentum coefficients, $S/D=3$ (C5)

B 11: Cross-sectional distribution of axial velocity on the X-Y plane with various momentum coefficients, $S/D=2$ (C8)

B 12: Cross-sectional distribution of lateral velocity on the X-Y plane with various momentum coefficients, $S/D=4$ (C2)

B 13: Cross-sectional distribution of lateral velocity on the X-Y plane with various momentum coefficients, $S/D=3$ (C5)

B 14: Cross-sectional distribution of lateral velocity on the X-Y plane with various momentum coefficients, $S/D=2$ (C8)

B 15: Cross-sectional distribution of axial velocity on the X-Z plane with various momentum coefficients, $S/D=4$ (C2)

B 16: Cross-sectional distribution of axial velocity on the X-Z plane with various momentum coefficients, $S/D=3$ (C5)

B 17: Cross-sectional distribution of axial velocity on the X-Z plane with various momentum coefficients, $S/D=2$ (C8)

B 18: Cross-sectional distribution of lateral velocity on the X-Z plane with various momentum coefficients, $S/D=4$ (C2)

B 19: Cross-sectional distribution of lateral velocity on the X-Z plane with various momentum coefficients, $S/D=3$ (C5)

B 20: Cross-sectional distribution of lateral velocity on the X-Z plane with various momentum coefficients, $S/D=2$ (C8)

B 21: velocity spreading width (e notation) on the X-Y plane with various momentum coefficients

B 22: velocity spreading width (e notation) on the X-Z plane with various momentum coefficients

B 23: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) $1/15s$, b) $2/15s$ and c) $3/15s$ (C3)

B 24: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) $1/15s$, b) $2/15s$ and c) $3/15s$ (D7)

B 25: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) $1/15s$, b) $2/15s$ and c) $3/15s$ (D8)

B 26: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) $1/15s$, b) $2/15s$ and c) $3/15s$ (D9)

B 27: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) $1/15s$, b) $2/15s$ and c) $3/15s$ (D10)

B 28: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) $1/15s$, b) $2/15s$ and c) $3/15s$ (D11)

B 29: A time series of contour plots of spanwise vorticity $\Omega_z D/U_0$ for $t =$ a) $1/15s$, b) $2/15s$ and c) $3/15s$ (D12)