Effect of Turbulent Coflows on the Dynamics of Turbulent Twin Jets

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Abstract

The impact of turbulent coflows on the dynamics of turbulent twin round jets is investigated experimentally. Parallel twin jets, at three jet spacing values and two Reynolds number/jet-to-coflow velocity ratios, were released into turbulent coflows with two distinct levels of turbulence intensity. Velocity measurements were made using acoustic Doppler velocimetry. An increase in the coflow turbulence intensity leads to an earlier merging and combining of the jets and also accelerates the rate of decay with downstream distance of the mean centerline excess velocity of the jets. The mean velocity on the symmetry line, for different values of jet spacing, ratios of jet exit velocity to coflow mean velocity, and coflow turbulence intensity is self-similar when scaled by the maximum mean velocity on the symmetry line and the corresponding streamwise distance. Moreover, as the turbulence level of the coflow intensifies, the turbulence intensity along the symmetry line of the jets increases. The longitudinal integral length scale on the symmetry line of the twin jets decreases as the coflow turbulence intensity increases. The energy spectra of the coflowing twin jets show that the turbulence in the coflow transfers the energy contained by the

larger scales to the smaller scales at a greater rate than that which occurs for jets in a quiescent background. However, as the jet spacing increases, less energy is transferred to the smaller scales.

1-Introduction

Turbulent round jets are created by a momentum-driven fluid that is discharged either from a single or multiple outlets into the surrounding medium of similar density. Instead of a single large jet outlet, multiple smaller outlets can be employed to achieve the necessary mass flow rate and enhance fluid mixing (Naseri Oskouie et al., 2019). Multiple jet diffusers have many environmental and industrial applications, such as discharging pollutants into water bodies, for fuel injection, in mixing chambers, in heating, ventilation and air conditioning (HVAC) systems, and for the launching of vehicles (Aleyasin et al., 2017; Naseri Oskouie et al., 2019; Laban et al., 2019; Li et al., 2022).

Due to the mutual interactions between adjacent shear flows of the jets, the flow properties and turbulence characteristics of multiple jets are more complex than those of a single jet (Aleyasin and Tachie, 2019). The simplest type of multiple jets are twin jets, which consist of two parallel single jets. Research on twin jets helps with understanding the physics of the interaction of multiple jets and enables the validation of numerical models. A comprehensive review of the flow dynamics of twin jets can be found in Miller and Comings (1960), Tanaka (1970), Zang and New (2015), Aleyasin and Tachie (2019) and Naseri Oskouie et al. (2019).

Figure 1 shows a schematic representation of twin round jets issuing from twin circular pipes with a diameter of d and a center-to-center jet spacing of s. The x, y, and z directions represent the streamwise (or downstream), transverse, and vertical directions, respectively. Initially, upon exit from the pipes, each of the two jets behaves like a single jet. The inner and outer shear layers are produced by the velocity difference between the high-velocity jet and the surrounding fluid. The centerline velocity (the local maximum of streamwise velocity, U_{cl}) of each jet decreases with increasing streamwise distance due to the conservation of mean momentum as ambient fluid is entrained into the jets across the shear layers. As the jets spread in the downstream direction, the inner shear layers of the two jets converge (Laban et al., 2019) and meet at the socalled "merging point" (MP) located on the symmetry line of the jets. The region extending from the pipe exit to the merging point is known as the converging region. The local maximum velocity paths for each jet curve towards the symmetry line due to the entrainment flow demand of both jets from the restricted region between them (Naseri Oskouie et al., 2019). As the distance beyond the MP increases, the transverse two-peak profile of the mean streamwise velocity gradually transforms into a single-peak pattern at the "combining point" (CP) (Aleyasin and Tachie, 2019). The region between the MP and CP is referred to as the "merging region." Downstream of the CP (combined region), the single-peaked mean streamwise velocity profile is comparable to that of a single self-similar jet (Harima et al., 2005; Naseri Oskouie et al., 2019; Laban et al., 2019).

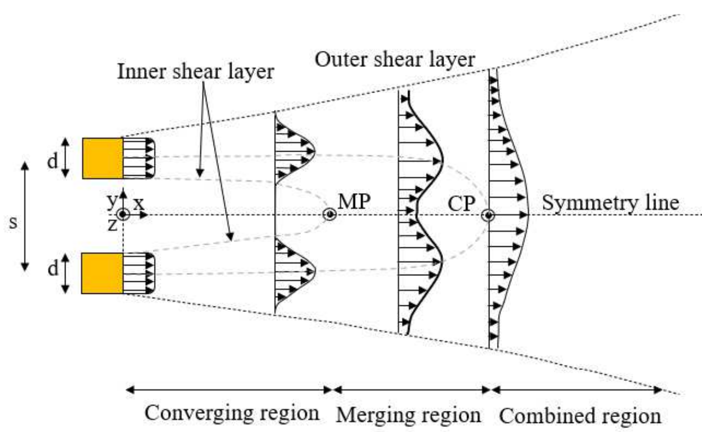

Figure 1. Schematic representation of the twin-jets configuration

Several studies have been conducted over the past few decades on the dynamics of twin round jets emitted into quiescent backgrounds (e.g., Tanaka, 1970; Okamoto et al., 1985; Lin and Sheu, 1990; Harima et al., 2005; Durve et al., 2012; Anderson and Spall, 2001; Zhang and New, 2015; Laban et al., 2019; Aleyasin and Tachie, 2019; Naseri Oskouie et al., 2019; Oskouie et al., 2020). An important aspect investigated is the effect of jet spacing on the behavior of twin round jets in quiescent backgrounds. The maximum velocity of the twin jets shifts from the axis of the jets to the symmetry line between the jets once they merge (Laban et al. 2019). The inner shear layer interactions between twin round jets are highly dependent on their separation distance (Zang and New, 2015). The distance to the merging and combining points grows linearly with the jet spacing (Okamoto et al., 1985; Harima et al., 2005; Laban et al., 2019), i.e., at reduced jet spacing merging occurs earlier and vice-versa. Moreover, a reduction in jet spacing increases the interference between two jets and their interaction, while decreasing the velocity decay rate before the combined point (Laban et al., 2019). Interestingly, the maximum values of streamwise turbulent intensity along the centerline of the jet were found to be in the merging region and independent of jet spacing (Harima et al., 2005).

For Reynolds numbers greater than 10,000, it has been observed that the velocity decay rate, location of the combined point, and the spreading rate are all independent of Reynolds number (Aleyasin and Tachi, 2019). However, as the Reynolds number increases, the location of the merging point shifts downstream. It has also been observed that when the jets initially start to merge, they have an elliptical cross-section, which evolves into a circular cross-section farther downstream (Okamoto, 1985). Furthermore, velocity fluctuations remain uniform within a central half-width as the merged jets continue to expand within the merging region (Taddesse and Mathew, 2022).

The dynamics of a jet depend on the jet parameters and those of the surrounding fluid. The presence of ambient flow and its turbulence level is expected to significantly affect the dynamics and mixing of jets. Despite the fact that in both environmental and industrial applications of twin jets, the surrounding fluid is rarely quiescent, the vast majority of earlier research only investigated cases in which twin jets were released into a stationary environment. Historically, it was considered to be conservative to neglect the effect of background turbulence and difficult to generate in a laboratory setting. However, more recent research indicates that background turbulence reduces dilution. Furthermore, the primary direction of ambient flow relative to the jet axis also influences the jet dynamics. The flow is referred to as a coflow if the jet and the ambient flow are flowing in the same direction. Understanding the complex interplay between the twin jets and a turbulent ambient flow, and the impact thereof on their mixing is crucial for the design of efficient and effective industrial mixing systems and of outfalls for effluent dilution. The present study focuses on the dynamics of twin round jets in turbulent coflows.

The behavior of a single coflowing jet depends on the excess velocity of the jet (Antonia & Bilger 1973), which transitions from a strong jet to a weak jet (Gaskin & Wood, 2001). Unlike Reynolds stresses, the evolution of mean velocities and scalar concentrations display self-similarity for coflowing jets (Antonia and Bilger, 1973; Nickels and Perry, 1996; Smith and Hughes, 1977). Furthermore, the width of the velocity and concentration fields vary nonlinearly (Chu et al., 1999), because of the transition from a strong jet ($U_{cl} \propto x^{-1}$) to a weak jet ($U_{cl} \propto x^{-\frac{2}{3}}$) (Gaskin & Wood 2001). Another important aspect of coflowing jets is the effect of the surrounding channel boundaries on the entrainment into the jet. Recent research has demonstrated that the effect of channel boundaries on entrainment only occurs once the jet occupies more than 15% of the cross-sectional area (Gaskin & Wood 2001). Furthermore, the characteristics of the coflowing stream has been shown to affect a number of important flow parameters, including the spreading rate, mass flow rate, and entrainment of the jet. Specifically, it has been found that the presence of a coflowing stream with a low level of turbulence ($\frac{u_{rms,coflow}}{u_{rms,jet}} = 0.04 - 0.17$, where u_{rms} is the root-mean-square (RMS) velocity measured over the downstream range of x/d = 45–105) leads to an increase in the spreading rate, mass flow rate, and entrainment of a coflowing jet (Moeini et al., 2021). On the other hand, the decay rate, spreading rate, and outward mean lateral velocity of a wall jet were reduced in the presence of a turbulent coflow (Kazemi et al., 2022). The decay and spreading of a plane jet in a shallow turbulent coflow also resulted in more rapid velocity decay and reduced entrainment (Gaskin et al., 2004). While for a single jet in a zero-mean background turbulence, the ambient flow disrupts the jet structure leading to increased velocity decay and reduced entrainment, and finally leading to a rapid break-up once the jet turbulence intensity has decreased twice that of the background (i.e., relative turbulence intensity of background to jet of 0.5) (Sahebjam et al., 2022).

An experimental evaluation of the effects of turbulence in the coflow on the dynamics, mixing, and interaction of twin turbulent round jets was performed. The present experimental research provides a new database for studying the effects of a range of coflow turbulence intensities, jet-to-coflow velocity ratios, and different jet spacing values on the flow field of twin turbulent jets. The results of the current research can pave the way for a better understanding of the dynamics of twin jets under different conditions.

The remainder of the paper is arranged as follows. The experimental apparatus and measurement techniques are described first, followed by a discussion of the coflow characteristics and a validation against prior research. The experimental measurements of twin round jets in turbulent coflows are then presented and analysed. Finally, discussions and conclusions are drawn.

2-Apparatus and Experimental setup

The experimental setup of the jets in a coflowing flume and the velocity measurement instrumentation are described. Point velocity measurements were performed using a SonTek MicroADV acoustic Doppler velocimeter (ADV) operating at 16 MHz. During the experiments, the maximum sampling frequency of 50 Hz was used. The cylindrical sampling volume is located 5 cm below the transmitter of the probe, which is vertically oriented, to ensure flow disturbance by the ADV probe was negligible. The diameter of the sampling volume was 6 mm, and its height was set to 9.1 mm (maximum) to reduce Doppler noise. The velocity range of the ADV was optimally set to span the full range of measured velocities and avoid phase wrapping (Homayounfar and Khorsandi, 2022). The ADVs measure the phase shift of the return signal reflected from particles suspended in the water. To increase the signal-to-noise ratio of the ADV measurements in the present study, neutrally buoyant particles (talcum powder) were added to the water. The data post-processing was carried out using the phase-space thresholding method (Goring and Nikora, 2002; modified by Wahl, 2003). Moreover, data with signal-to-noise ratio and correlation of less than 15 and 70%, respectively, were eliminated from the data set, as recommended by the ADV manufacturer (SonTek, 2001).

Figure 2 provides a sketch of the experimental setup. The experiments were conducted in a (0.5 m × 1 m × 9 m) recirculating flume with a Plexiglas (polymethyl methacrylate) weir at the end of the flume to keep the water depth at 0.42 m for the experiments in the quiescent background. The base and side walls of the flume were composed of tempered transparent glass. Initially, experiments of twin jets discharged in a quiescent background were performed for validation purposes. This was followed by the experiments of coflowing twin jets.

For the experiments of coflowing twin jets, water flowed from an upstream basin into the flume and overflowed into a stilling basin located downstream from which it was recirculated to the upstream basin with a pump. The inflow was made uniform by passing it through a perforated steel plate with a mesh size of approximately 10.0 mm. The curved, symmetric contraction connecting the upstream basin to the flume improves the uniformity of open-channel flow. The channel flow was approximately uniform as verified by measurements of the mean and RMS velocities across the width and over the depth of the channel (not shown). The twin jets were released into a turbulent open-channel flow with two levels of turbulence intensity. The flow rate and mean velocity (U_∞) were approximately 0.05 $\frac{m^3}{s}$ and 0.125±0.005 m/s, respectively, and the two turbulence intensities ($TI \equiv \frac{u_{rms}}{U_{mean}}$) were 7 and 11%, which are herein referred to as low and high TI, respectively. The low TI was produced with a honeycomb at the inlet, and the turbulence intensity decreased in the downstream direction from the jet exit as $x^{-0.03}$. The TI of the channel flow was increased from 7 to 11% using two passive square-mesh grids placed perpendicular to the flow (at a spacing of 0.25 m) at the inlet of the flume. The turbulence intensity, in the case of high TI, decayed as $x^{-0.33}$ within the measurement field of the present study. The mesh size (M=0.11 m) and the grid bar thickness (d_b=0.02-m) were selected to get a solidity coefficient ($\sigma = \frac{d_b}{M} \times (2 - \frac{d_b}{M})$) of 0.33. Note that to prevent the generated flow from becoming unstable, the solidity coefficient must be kept below 0.5 (Comte-Bellot and Corrsin, 1966).

The twin jets were released from two parallel round pipes of 10.0 mm diameter (d) positioned at the midpoint of the flume cross section to minimize boundary effects. The jets were composed of two L-shaped pipes mounted on a traversing mechanism, whose horizontal section extended 0.25 m to ensure a fully-developed exit flow. The jet Reynolds numbers of 10,600, and 15,400 ($Re \equiv U_j d/\upsilon$, where U_j is the jet average exit velocity, and υ is the kinematic viscosity of water) were set using a ball valve upstream of a flowmeter (Georg Fischer) with 1% accuracy. $Re \geq 10^4$ were chosen so as to be above the mixing transition (Dimotakis 2000). The nondimensional excess velocities of the jets, $\lambda \equiv \frac{U_j - U_\infty}{U_\infty}$, defined by Antonia and Bilger (1973) and Nickels and Perry (1996), corresponding to Re=10,600, and 15,400 were 7 and 11, respectively. Three jet spacings of s/d= 2.8, 5.5, and 7.1, where s is the center-to-center distance of the pipes, were used to explore the influence of jet spacing on the flow field. The jets were fed by a constant-head tank (with an elevation of 2.8 m) supplied from the flume. Consequently, the water temperature of the jets and the ambient flow were the same, ensuring that there were no buoyancy effects. The intersection of and the jet exit plane served as the origin of the coordinate system. The x-direction of the ADV probe was parallel to the direction of the jet axis and the coflow, and the y- and z-directions of the probe (referred to as the lateral and vertical directions, respectively) were in the radial direction of the jets. The ADV probe was carefully aligned with the symmetry line and axis of the jets to minimize errors. Point velocity measurements were made at 17 points along the symmetry line and 25 points along each of 7 radial profiles. To ensure convergence of statistics up to the second order, 48,000, and 30,000 data points were recorded by the ADV for the twin jets issued to the quiescent background and into the coflow, respectively. Note that the shorter convergence time in the coflowing jets was due to reduced intermittency of the jets.

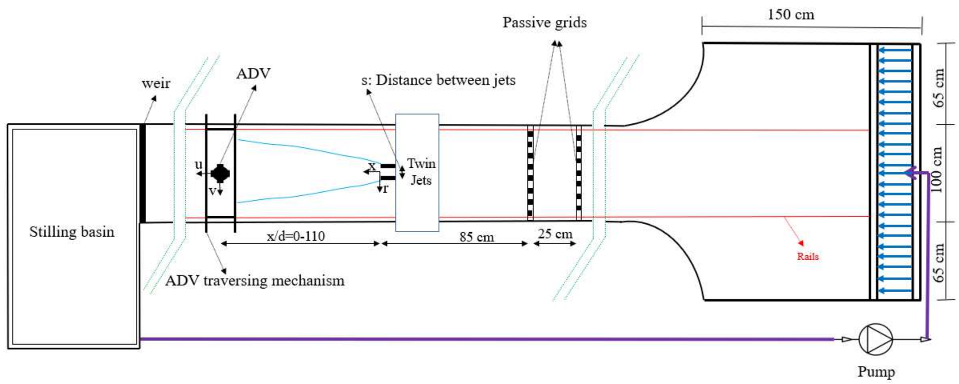

Figure 2. Schematic top view of the experimental setup and its components

3-Results

The statistics of the velocity field of the twin jets emitted into a quiescent background and coflowing streams are presented in this section. The measurement technique is first validated and the results pertaining to coflowing twin jets are then presented and discussed.

3.1- Validation

The velocity measurements technique (ADV) was validated in twin round jets emitting into a quiescent background. The results are compared to those of Aleyasin et al. (2019) and Laban et al. (2019), who used the same jet spacing values and Reynolds number and employed particle image velocimetry (PIV) for the measurements.

Figure 3 presents the downstream variation of streamwise mean and RMS velocities of twin round jets (in a quiescent ambient with zero mean flow). The mean and RMS centerline velocity (U_{cl}, $u_{rms,cl}$), and mean and RMS symmetry velocity (U_{sym}, $u_{rms,sym}$) measured with pipe spacings of s/d=2.8 and 7.1 are shown in Figures 3(a) and (b), respectively. The mean and RMS velocities are normalized by the exit velocity of the jet, and the downstream distance (x) is nondimensionalized by the inner diameter of the jets. (Note that the centerline velocity is the local maximum of streamwise velocity and the symmetry velocity is the streamwise velocity on the symmetry line of the twin jets.) It can be seen that the mean and RMS velocities measured for different jet spacing ratios agree well with those of the previous studies. Similarly to a single jet, the mean centerline velocity decays with the downstream distance due to the conservation of mean momentum as a result of the entrainment of ambient fluid into the jets. Along the symmetry plane, the mean and RMS velocities in the streamwise direction start at near zero and increase with downstream distance as the inner shear layers merge. The symmetry velocities then reach a maximum value that remains almost constant over a short distance before evolving into the centerline velocity of the merged jets. The jet spacing does not significantly influence the centerline velocities, however, it affects the velocities along the symmetry plane. Specifically, the mean and RMS velocities along the symmetry line measured at the smaller jet spacing ratio exhibit a more rapid ascent to their maximum values and have higher peak values, compared to those measured at the larger jet spacing. The results presented in Section 3.1 validate the apparatus and accuracy of ADV measurements in the twin round jets.

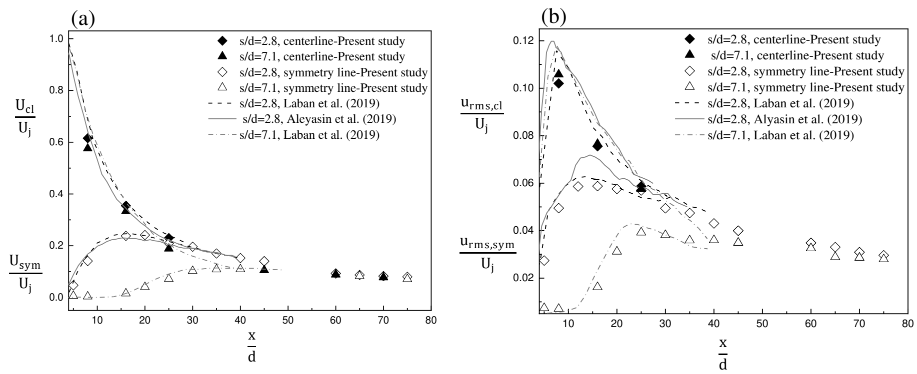

Figure 3. Downstream variations of (a) mean velocities, and (b) RMS velocities, along the centerline and symmetry line of twin round jets.

3.2. Twin jets in turbulent coflows

The location of the merging point (x_{MP}) and of the combined point (x_{CP}) describe the evolution of the flow behavior of the twin jets with downstream distance having nondimensional excess velocities of 7 and 11 in coflows with turbulence intensities of 7% and 11%.

Before presenting the results, it is necessary to first define the downstream location of the merging point (x_{MP}) and combined point (x_{CP}) for coflowing twin jets. x_{MP} has been defined differently in the literature as the location where (i) $U_{sym} = 0.1U_{cl}$ (Meslem et al., 2010; Vouros, and Panidis, 2008; Ghahremanian, and Moshfegh, 2015), (ii) $U_{sym} > 0$ (Okamoto and Yagita, 1985), and (iii) U_{sym}=0.015$U_{max,PIV}$, where, $U_{max,PIV}$ is the velocity at which the streamwise velocity initially increases from the exit value reaching a peak value at x/d ≈ 0.5 (Aleyasin et al., 2019; Laban et al., 2019). In the present study, x_{MP} is designated as the streamwise position where $U_{sym,excess} > U_\infty$, ($U_{\alpha,excess} = U_\alpha - U_\infty$, where U_α represents the mean symmetry or centerline velocity in the downstream direction). This point signifies the beginning of inner shear layer mixing. Furthermore, the streamwise location where the U_{sym} reaches its maximum value was defined as x_{CP} in the previous studies (Nasr and Lai, 1997; Anderson and Spall, 2001). In our work, there is a substantial difference between the location of the maximum value of $U_{sym,excess}$ and the precise location where the dual peak velocity profile evolved to a single peak profile, which can be attributed to the decay of the velocity before the convergence of dual velocity peaks to a single peak. Consequently, x_{CP} is defined as the downstream location along the symmetry line where $U_{sym,excess}$ reaches the local maximum velocity along the transverse profile ($U_{cl,excess}$), i.e., the point where the transverse profile becomes single peaked.

The position of the dimensionless merging ($\frac{x_{MP}}{d}$) and combined ($\frac{x_{CP}}{d}$) points versus jet spacing for λ = 7 and 11, and ambient turbulent intensities of 7% and 11% are shown in Figures 4(a) and 4(b), respectively. The location of the merging point varies linearly with jet spacing similarly to the twin jets in quiescent background. The jets emitted into a coflow merge farther downstream than in a quiescent ambient due to the advection of the jets by the coflow. However, with increasing turbulence intensity in the coflow, the merging points are located farther upstream. The effect of the coflow magnitude and turbulence intensity increases with increased jet spacing. At a jet spacing ratio of 7.1, for example, when the background turbulence is raised from 7 to 11%, the merging point is 25% closer to the jet exit. The strength of the jet contributes to its ability to maintain its structural integrity and reduces its susceptibility to the influence of turbulent background conditions, as seen from the comparison of the λ = 7 to λ = 11 cases.

The location of the combined points of the coflowing twin jets are located farther downstream (by a factor of ~2) relative to those of the twin jets in a quiescent background, especially for the larger jet spacing values, as seen in Figure 4(b). Moreover, the higher λ values result in the double-peak profiles combining at farther upstream for both coflow turbulence intensities (by a factor of [0.77 – 0.95]). While the greater coflow intensity results in the combining point being farther upstream, due to the greater jet strength, and therefore, less disruption by the background turbulence (see Sahebjam et al. 2022), the effect decreases with increased jet spacing. It is worth noting that the effect of the coflow on the location of the combined points is more significant than that on the location of the merging points, likely attributable to the greater contribution of coflow advection.

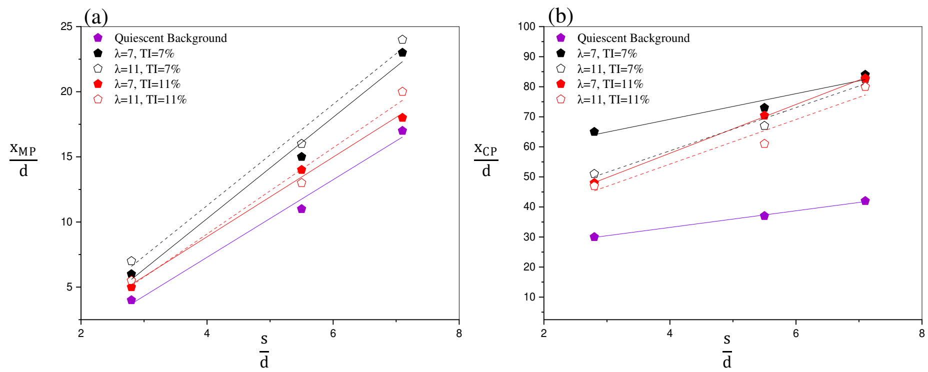

Figure 4. Evaluation of (a) merging points, and (b) combined points along the symmetry line of coflowing twin jets for various jet spacing values, turbulence intensities, and λs.

The variation in the mean streamwise excess velocity along the symmetry line of the twin round jets (normalized by their respective jet exit velocities) as a function of jet spacing, coflow turbulence level, and λ are presented in Figure 5. As the twin jets develop downstream, the inner shear layers converge, and the excess velocity along the symmetry line increases. In the merging region (at the end of which the symmetry line becomes the jet centerline), the mean excess velocity on the symmetry line increases to reach its maximum values before the combined point. Downstream of the combined point, the two jets have combined to form a single jet, thus, downstream of this point, decay is as for a single jet. At smaller jet spacings, the mean excess velocity of the symmetry line reaches the maximum more rapidly (as merging happens more quickly). The higher coflow turbulence intensity has the greatest effect on the twin jet with the smallest spacing (s/d=2.8). The impact of the increase in turbulence intensity from 7 to 11% is small but does indicate for jet spacing of 5.5 and 7.1 that the symmetry line velocity has decreased in the coflow with greater turbulence. Moreover, the symmetry line velocity decreased as the values of λ decreased from 11 to 7. One can conclude that, overall, the disruption of the jet by the background turbulence leads to a decrease in mean velocity, which is greater when the background turbulence is greater.

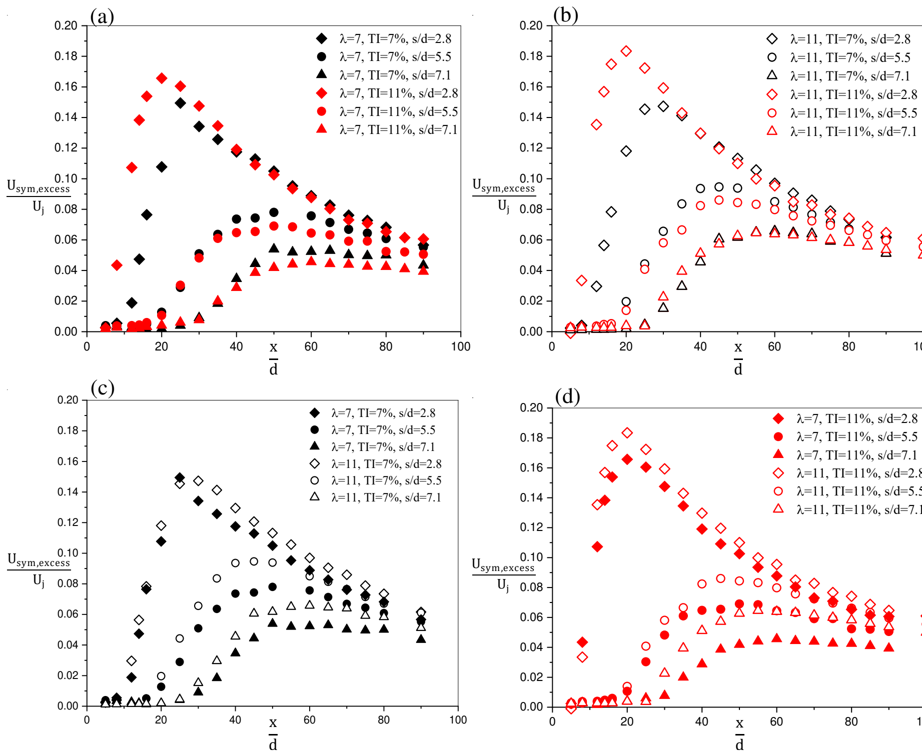

Figure 5. Mean excess velocity variation along the symmetry line of coflowing twin jets: (a) $\lambda = 7$, (b) $\lambda = 11$, (c) TI=7%, and (d) TI=11%.

The downstream decay of the centerline excess velocity of the coflowing twin jets follows a power-law relationship,

$$\left(\frac{\mathrm{U_{cl,excess}}}{\mathrm{U_j}}\right) = A\left(\frac{x}{d}\right)^n \qquad \text{Eq.1}$$

where A is the decay constant and n is the decay exponent). Note that, for the twin jets in the quiescent background a similar relationship holds except that $\mathrm{U_{cl,excess}} = \mathrm{U_{cl}}$). The downstream variation of the centerline excess velocity of twin round jets (normalized by their respective jet exit velocities) is plotted in Figure 6 in log-log coordinates. It has been shown that a strong jet in a coflow decays as x^{-1}, while a weak coflowing jet decays more slowly as $x^{-\frac{2}{3}}$ (Gaskin and Wood, 2001). It can be observed in Figure 6 that the twin jet with s/d=2.8 has reached the single strong jet behaviour (decays as x^{-1}) within the measurement range, for both λ = 7 and λ = 11 at both turbulence levels. While at greater jet spacing (s/d=5.5, and 7.1), the merged single jet behaviour is approaching the weak single jet behaviour (decays as $x^{-\frac{2}{3}}$). However, the confirmation of the latter would require a greater measurement range.

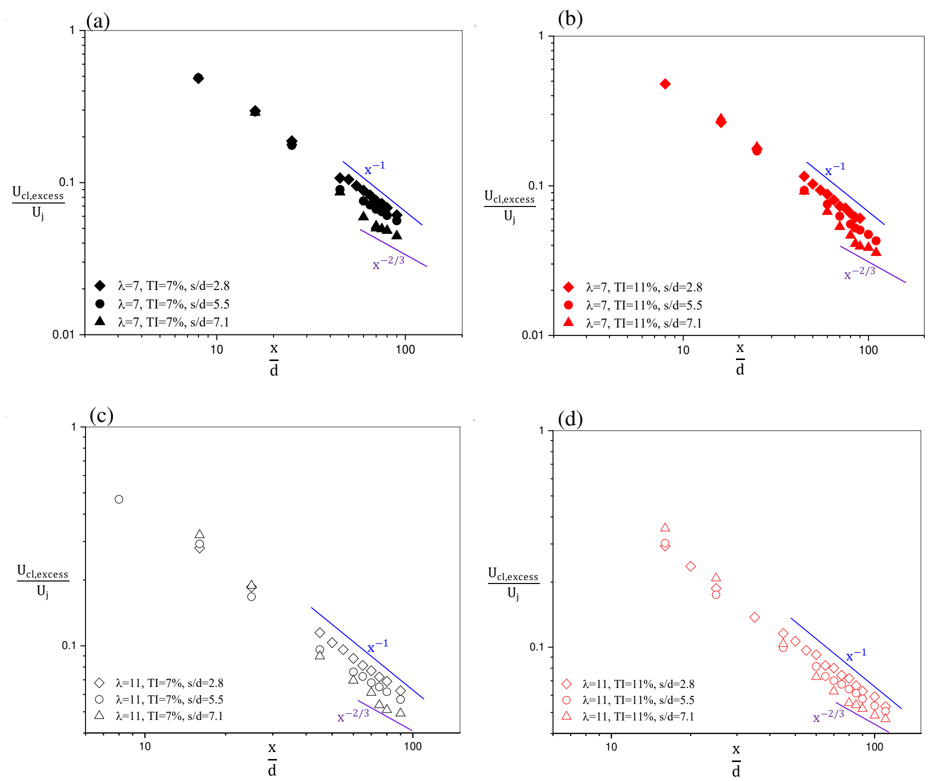

Figure 6. Downstream variations of the mean centerline excess velocity: (a) λ = 7, TI = 7%, (b) λ = 11, TI = 7%, (c) λ = 11, TI=7%, and (d) λ = 11, TI=11%.

The twin jet behaviour is initially that of two separate jets, which merge over the merging region between the MP and the CP into a single larger jet. Therefore, the twin jet behaviour can be observed in the regions up to and beyond the combined point. The evolution of this behaviour can be documented from the decay exponents presented in Table 1. One finds that before the combined point, the decay rate increases as jet spacing increases. Beyond the combined point, the jet decay rate decreases as jet spacing increases, exhibiting a similar trend to the decaying rates observed in the twin jets in a quiescent background. It can be seen that the turbulent coflows generally lead to higher decaying rates of mean velocity both before and after the combined points. This result conforms to Hunt (1994)'s hypothesis that any disruption of the jet structure, in this case by the coflow turbulence, will result in a more rapid jet decay. It also confirms the experimental findings of Gaskin et al. (2004), Khorsandi et al. (2013), Moeini et al. (2021), and Sahebjam et al. (2022), for the self-similar region of a single round or plane jet. Note that contrary to the other cases, the decay rates of coflowing twin jets with s/d = 7.1 decreased after the combined points compared to that of the twin jet in a quiescent background. The reason may be that, at the greater jets spacing, the background turbulence has a stronger influence on the jets before the combined points (n ~ -1.2), resulting in the disruption of the entrainment mechanism of the jets, and therefore, smaller decay rates after the combined points. Furthermore, an increase in the jet λ values (in this case, equivalently an increase in jet Reynolds number) does not significantly impact the decay rates. This is similar to the results reported for twin round jets in a quiescent background, indicating that the velocity decay rate becomes independent of the Reynolds number for Re ≥ 10,000 (Aleyasin et al., 2019).

Table 1. Summary of decay constant (A) and decay exponent (n) for the power-law relationship $\frac{U_{cl,excess}}{U_j} = A(\frac{x}{d})^n$.

Region	jet spacing	Quiescent		TI=7%				TI=11%			
				λ = 7		λ = 11		λ=7		λ=11	
		A	n	A	n	A	n	A	n	A	n
Before CP	2.8	2.6	-0.8	2.9	-0.9	2.8	-0.8	3.2	-0.9	4.3	-1.0
	5.5	3.9	-0.9	4.1	-1.0	3.5	-0.9	4.8	-1.0	4.5	-1.0
	7.1	7.2	-1.0	7.5	-1.2	7.5	-1.1	8.6	-1.2	8.9	-1.2
After CP	2.8	3.0	-0.8	3.2	-0.9	3.1	-0.9	3.6	-0.9	3.1	-0.9
	5.5	1.4	-0.7	1.6	-0.8	1.5	-0.7	2.0	-0.8	1.5	-0.7
	7.1	0.2	-0.6	0.4	-0.5	0.4	-0.5	0.2	-0.3	0.7	-0.6

The self-similarity of the mean excess velocity in the twin jets is shown by graphing (Figure 7) the mean streamwise excess velocity on the symmetry line normalized by the maximum mean streamwise excess velocity along the symmetry line ($U_{p,sym,excess}$) versus the downstream distance non-dimensionalized by the location of $U_{p,sym,excess}$ (L_p). Similar normalization for twin jets released into a quiescent background was shown to collapse the data, indicating independence with s/d (Taddesse and Mathew, 2022). The mean symmetry velocities of coflowing twin jets are approximately self-similar for different values of jet spacing and nondimensional excess velocity.

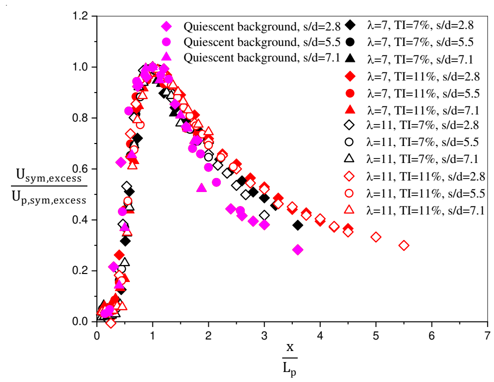

Figure 7. Downstream evolution of the mean streamwise excess velocity along the symmetry line, normalized by the maximum mean streamwise excess velocity.

The downstream evolution of the symmetry line turbulence intensity (RMS velocity normalized by U_{sym}) versus the downstream distance nondimensionalized by L_p over the range of jet spacings, coflow turbulence levels, and λs is shown in Figure 8. Note that at $x/L_p \sim 0$, the turbulence intensity is that of the coflow (i.e. before the jets have merged), having a value of 0.07 at TI=7% and 0.11 at TI=11%. Figures 8(a) and 8(b) present the measurement results for $\lambda = 7$ and 11, respectively. The ($x/L_p > 0$) turbulence intensity along the symmetry line, $u_{rms,sym}/U_{sym}$, increases (i.e., as the jet moves relative to the symmetry line, the measurement is made at locations increasingly closer to the jet centreline) with downstream distance to reach its maximum values before the combined point. Downstream of this location, the symmetry line turbulence intensity decreases. It is probable that the turbulence intensities will asymptote to the coflow turbulence intensity at far downstream distances. Moreover, the symmetry line turbulence intensity decreases as the jet spacing becomes larger, with the highest turbulence intensity occurring at the smallest jet spacing, s/d=2.8. From this, it can be inferred that the highest mixing probably occurs for the coflowing twin jets with the smallest jet spacing. In addition, as the turbulence intensity of the coflow increases, the symmetry line turbulence intensity also increases. A similar observation was reported for single coflowing jets (Moeini et al. 2021) and jets released into a turbulent background with zero mean flow

(Khorsandi et al. 2013). Figures 8(c) and 8(d) show the symmetry line RMS velocities for TI=7% and 11%, respectively. It can be seen that increasing λ for twin jets in the same coflow turbulence intensity results in higher jet turbulence intensity.

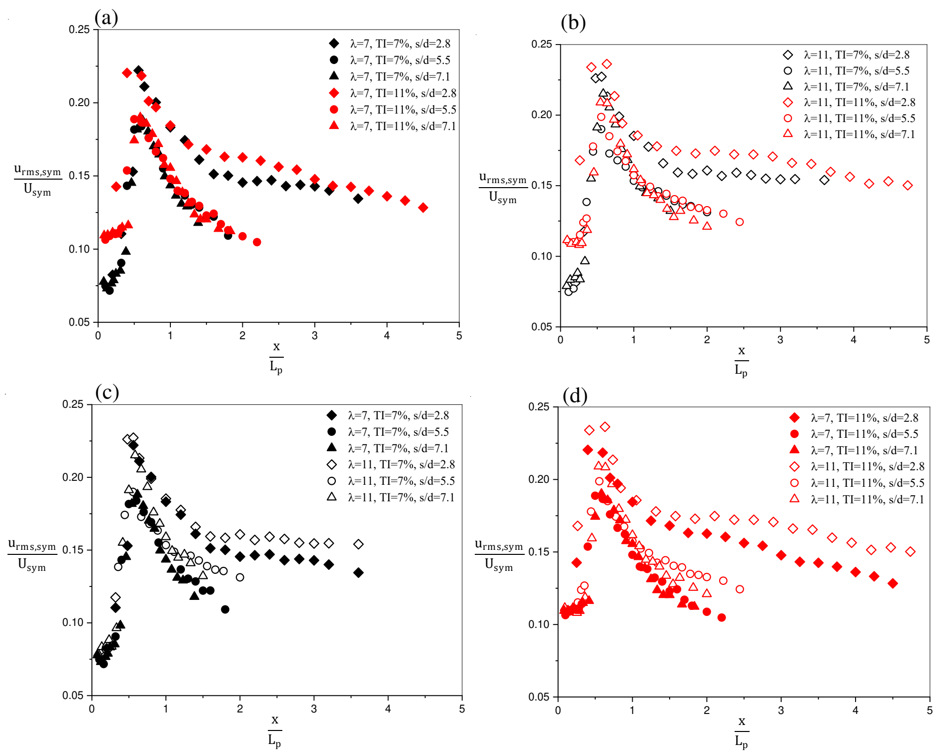

Figure 8. Downstream evolution of the turbulence intensity along the symmetry line for (a) λ=7, (b) λ=11, (c) TI=7%, and (d) TI=11%.

The integral length scale (ILS) indicates the size of the largest eddies in the flow. In a jet in a quiescent ambient, ILS can be approximated by the jet width, which increases with downstream distance (Hussein et al. 1994). The ILS on the symmetry line of the twin jets (with three different jet spacing values) in both a quiescent background and a coflow with a low and a high turbulence intensity for $\lambda = 7$ and 11, is plotted in Figure 9. The ILS was computed by multiplication of the symmetry mean velocity by the integral time scale obtained from the integration of the autocorrelation function (Antonia and Bilger, 1973), using Taylor's frozen flow hypothesis as

$u_{rms}^2/U^2 << 1$ (in this case it is < 0.1). In the quiescent background, the ILS increases with increasing jet spacing, e.g., at x/d = 75, for s/d = 2.8 to 5.5 and 2.8 to 7.1, the length scale increases by 78% and 111%, respectively. The two coflow cases vary in turbulence intensity and length scale. We note that the coflow with the higher turbulence intensity (11%, produced by passive grid) has lower ILS compared to that of the lower turbulence intensity (7%). When the twin jets are released into a turbulent coflow, the integral length scale is reduced and its rate of increase with the downstream distance is much reduced compared to the quiescent case, but similar over a range of jet spacings [2.8 – 7.1]. The reduced rate of increase of the ILS is dependent on the coflow length scale, which is reduced in the higher intensity coflow compare to the lower intensity coflow. This can be explained by the disruption of the jet structure (or jet eddies) by the higher ambient turbulence. The large effect of the coflow length scale is in contrast with the research on wakes in a turbulent coflow, indicating that in the far-field ($37 \leq x/d \leq 41$), the effect of ambient turbulence is more notable on the turbulence intensity than on the length scale (Kankanwadi and Buxton, 2020; Chen and Buxton, 2023). A slight decrease in ILS is seen for an increase in λ from 7 to 11, with the effect increasing slightly at the greatest jet spacing.

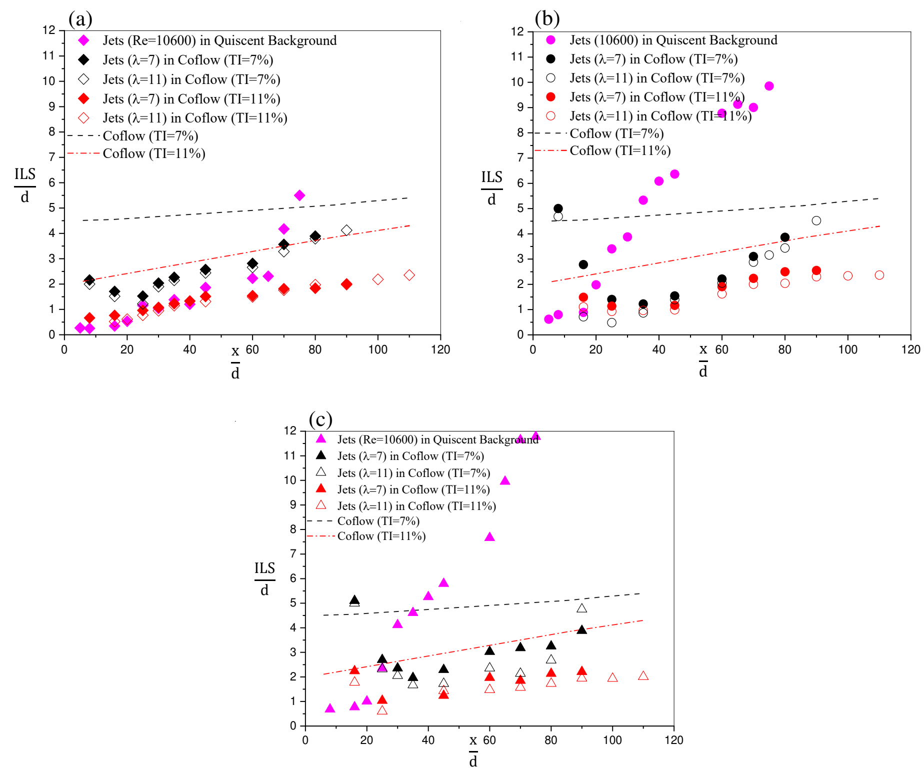

Figure 9. Evolution of the symmetry line integral length scale of twin jets with different λs issued into the coflows with various turbulence intensities for (a) s/d=2.8, (b) s/d=5.5, and (c) s/d=7.1.

The Eulerian temporal velocity spectra of the coflow and of the twin round jets emitted into both the quiescent background (Figure 10(a)) and coflow (Figure 10(b) and (c)), measured on the symmetry line of the jets at x/d=70 is presented to examine the transfer of energy between the turbulent velocity scales. The vertical velocity (w) spectra are presented as they have a lower noise level. The velocity spectra were captured at 50 Hz, and according to the Nyquist criteria, they extend to 25 Hz. Both the coflow and the jets show the expected -5/3 power-law spectrum in the inertial range.

In the quiescent background (Figure 10(a)), the velocity spectra of the twin jets are similar, but slightly higher at the smaller jet spacing (s/d=2.8), a difference that increases with increased frequency, as predicted by their considerably greater RMS velocities (or velocity variances which correspond to the area under the curves). The velocity spectra of the twin round jets emitted into a turbulent coflow with two different turbulence intensities are compared to those of the twin jets in the quiescent background and to that of the coflow, in Figure 10(b) for s/d = 2.8 and in Figure 10(c) for s/d = 7.1. At the lower frequencies (i.e., larger scales, frequencies < 1 Hz), the spectra of the coflowing twin jets resemble those of the coflow and are lower than that of the twin jets in the quiescent background, whose large eddies have not been disrupted. Therefore, it may be concluded that the coflow has a more significant effect on the larger jet structures. On the other hand, the coflowing jet spectra have higher values than the spectra of the coflow and twin jets in a quiescent background at the intermediate and high frequencies. These results indicate a greater transfer of energy from the large scales to the smaller scales in the coflowing twin jets, compared to that which occurs in the twin jets in a quiescent background, due to the effect of the background turbulence disrupting the jet structure. Furthermore, as the coflow turbulence level increases, the spectra of the coflowing twin jets slightly increases. In general, the effect of increasing jet spacing is to decrease the velocity spectra values.

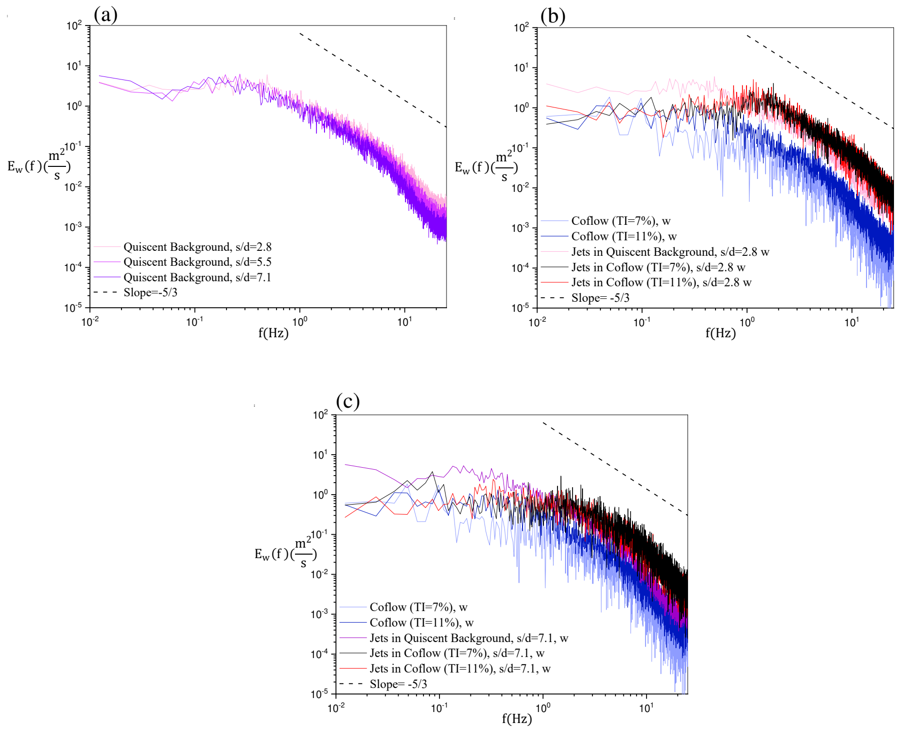

Figure 10. Vertical velocity spectra on the symmetry line at x/d = 70 for (a) twin jets issued to the quiescent background, (b) coflowing twin jets with s/d=2.8, and (c) coflowing twin jets with s/d=7.1.

Discussion

The preceding results clearly indicate that, when twin jets are emitted into a coflow, their merging and combining occur farther downstream compared to a quiescent ambient, owing to the advection of the jets by the coflow. An increase in the turbulence level of the coflow results in an earlier merging and combining of the jets, and this effect becomes more pronounced with an increase in jet spacing. Furthermore, Aleyasin et al. (2019) revealed that in a quiescent background, the combining point becomes independent of Reynolds number when Re ≥ 10,000. The current findings demonstrate that the higher λ values lead to the double-peak profiles combining at an earlier stage for both coflow turbulence intensities.

According to Gaskin and Wood (2001), in a coflow, a strong jet ($U_{cl,excess}$ varies as x^{-1}) transitions to a weak jet, where $U_{cl,excess}$ varies with $x^{-\frac{2}{3}}$. In this study, for all jet spacings, the jet behaviour before the combined point approaches that of a strong jet in a coflow as seen by the non-dimensionalized velocity approaching a power law with an exponent of ~ -1. On the other hand, the combined jet behaviour appears to follow that of a strong jet for the closest jet spacing (s/d = 2.8), while it follows that of a weak jet for the larger jet spacing values (s/d=5.5, and 7.1). Also, it can be inferred, based on the measurements, that the key parameter influencing the transition from a twin jet to a combined jet is the jet spacing followed by the nondimensional excess velocity.

By normalizing the mean streamwise excess velocity on the symmetry line by the maximum mean excess velocity along the symmetry line ($U_{p,sym,excess}$) and also normalizing the downstream distance by the location of $U_{p,sym,excess}$ (L_p), it is evident that the mean symmetry line excess velocities exhibit self-similarity across a range of jet spacing values, nondimensional excess velocities, and turbulence intensities. Similar normalizations were employed by Taddesse and Mathew (2022) in a quiescent background, revealing that the mean symmetry line velocity is approximately independent of jet spacing values.

The results indicate that with an increase in the turbulence intensity of the coflow, the symmetry line turbulence intensity of the twin jets also increases. This observation aligns with similar findings reported for both single coflowing jet (Moeini et al., 2021) and a jet emitted into a turbulent background with zero-mean flow (Khorsandi et al., 2013). Moreover, the scaled turbulence intensity is not found to be self-similar, in contrast to the mean velocities.

In this study the coflow with the higher turbulence intensity (11%, produced by passive grid) has lower ILS compared to that of the lower turbulence intensity (7%). The findings indicate that upon introducing twin jets to the coflow, the growth rate of the integral length scale has nearly similar values for a range of jet spacing (s/d=2.8–7.1) and is significantly influenced by the size of the coflow integral length scale.

Previous research hypothesized that any external forcing, such as ambient turbulence, that breaks up a jet or plume, leads to a reduction in entrainment (Hunt, 1994). The experimentally demonstrated reduction in entrainment observed for a shallow jet in a coflow (Gaskin et al., 2004) was subsequently validated for both an axisymmetric jet (Khorsandi et al., 2013; Pérez-Alvarado et al., 2016; Sahebjam et al., 2022) and a buoyant jet (Lai et al., 2019). In the present study, the turbulent coflow results in the increased decay rate and reduced integral length scale (or width) of the jets. From these observations, it can be inferred that the mass flow rate of the jets, and therefore, entrainment into the jets is reduced in the presence of coflow turbulence. This confirms the findings of the aforementioned previous studies.

For a relative turbulence intensity of $\xi = u_{rms,background}/u_{rms,cl,jet} < 0.5$, the ambient turbulence disrupts the structure of a free jet but it maintains self-similarity, while for $\xi > 0.5$, the jet is completely broken down and any scalar only undergoes turbulent diffusion (Sahebjam et al. 2022). The relative turbulent intensity of the ambient coflow to jets, ξ ($= u_{rms,coflow}/u_{rms,\ cl,jet}$) increases with downstream distance mainly due to the decrease in turbulence intensity in the jets with downstream distance. The relative turbulent intensity calculated at the centerline of the jets (with three different jet spacing values) in a coflow with a low and a high turbulence intensity for $\lambda = 7$, and 11 is shown in Figure 11. It can be seen that $\xi > 0.5$ for the twin jets with λ=7 released into the coflow with TI=11% at x/d > 70. This suggests that at this specific region, the jets are likely to have undergone breakup. The integral length scales remain approximately constant in this region, which can also serve as evidence in support of this finding.

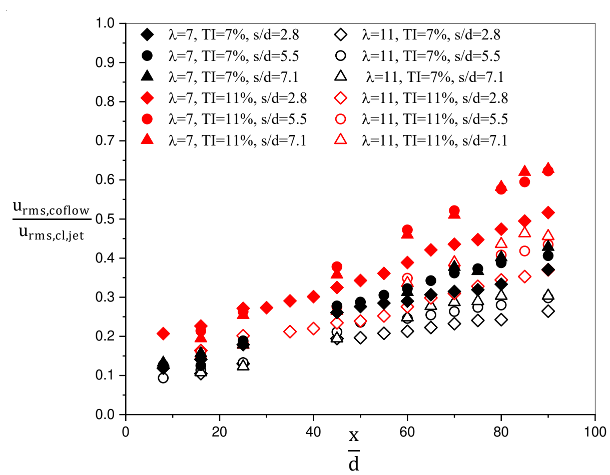

Figure 11. The relative turbulent intensity of the coflow to the jet

Conclusions

The effect of turbulent coflows on the dynamics and mixing of the turbulent twin round jets was experimentally investigated. After benchmarking the measurement technique, acoustic Doppler velocimetry, for the twin jets in a quiescent background and characterizing the coflow, measurements were conducted in the coflowing twin round jets. The experiments were carried out for twin jets, with nondimensional excess velocities of $\lambda = 7$ and 11 and three jet spacing values (s/d=2.1, 5.5, 7.3), introduced into coflows with two different turbulence intensities (7 and 11%). It was shown that, due to the advection of jets by the background coflow, the twin jets emitted into the turbulent coflows merged and combined farther downstream than those emitted into the quiescent background. The twin jets also decayed faster in the presence of turbulent coflows. Increasing coflow turbulence intensity resulted in an earlier merging and combining, an increase in the turbulence intensity, a reduction in the magnitude of the integral length scale of the twin jets, and a greater transfer of energy from the larger scales of the jet to the smaller scales compared to that which occurs in the quiescent background. The mean symmetry velocity of twin round jets in a coflow was shown to be self-similar (over the range of jet spacing values, excess jet velocity ratios, and turbulence intensities) when non-dimensionalized by the maximum mean velocity along the symmetry line and plotted against the downstream distance normalized by the location of the maximum mean symmetry velocity. On the other hand, the scaled turbulence intensity of the coflowing twin jets was not found to be self-similar. The mass flow rate of the jets, and therefore, entrainment into the jets was inferred to be reduced in the presence of coflow turbulence.

The results presented in this study can be used to optimize the design of parallel jets in both environmental and industrial applications, to improve pollution dispersion models, which ignore the impact of coflow turbulence, and to validate numerical models of parallel jets. The degree and dynamics of the mixing processes could be further investigated through future studies of the scalar field.

Author Declarations

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Conflict of Interest

The authors have no conflicts to disclose.

AIP Publishing Data Sharing Policy

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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