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Turbulent Twin Jets in the Presence of a Turbulent Ambient

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ABSTRACT

This study aims to explore the influence of background turbulence on the mixing of twin round jets. Parallel twin jets, at two different jet spacing values, were emitted into quiescent conditions and also subjected to two distinct levels of background turbulence intensities. Concentration measurements were conducted using Planar Laser-Induced Fluorescence (PLIF) techniques. An increase in background turbulence intensity results in an earlier merging and combining of the twin jets, while also accelerating the rate of decay of the mean concentration of the jets with downstream distance.

Introduction

Understanding the mixing and dilution of parallel jets is essential when it comes to forecasting the release of pollutants into a turbulent environment. Parallel jets entrain ambient fluid, spread, and meet at the merging point (MP) on the line of symmetry. MP signifies the beginning of the merging region, where the initially observed double-peaked profile gradually transforms to a single peak as it progresses toward the combined point (CP), after which the flow exhibits the characteristics of a single jet (Harima et al., 2005; Naseri Oskouie et al., 2019; Laban et al., 2019), as illustrated in Figure 1.

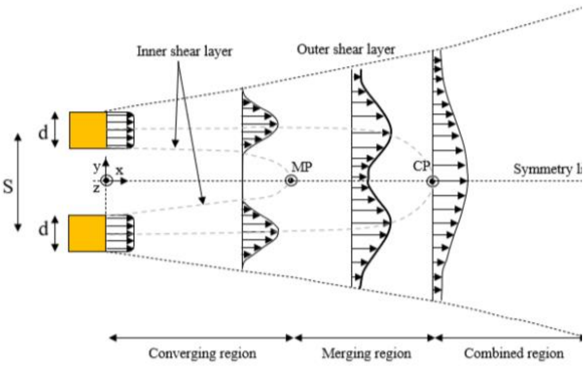

Figure1. Schematic of the streamwise development of two parallel jets. The coordinates and origin associated with the streamwise (x), transverse (y), and lateral (z) directions are shown.

In a quiescent ambient, when the distance between jets is increased, the merging takes place farther downstream (Okamoto et al. 1985; Harima et al. 2005). Furthermore, the dynamic behaviour is independent of the jet Reynolds number once it is above 10,000 (Aleyasin and Tachie, 2019).

The dynamics of twin jets are expected to change when they are released into a turbulent ambient. The effect of background turbulence on a single jet has been shown to increase the rate of decay of the jet and decrease entrainment (Gaskin et al. 2004; Khorsandi et al. 2013; Perez-Alvarado 2016; Sahebjam et al. 2022). Furthermore, a turbulent coflow advects the merging and combined points of twin jets. Nevertheless, increasing the coflow turbulence intensity leads to an earlier merging and combining of the twin jets, accompanied by an increase in turbulence intensity and a decrease in the magnitude of the integral length scale of the twin jets (Homayounfar et al. 2024). Most previous studies on the dynamics of twin jets investigated those emitted into a quiescent background. Moreover, scalar fields have been measured in multiple round jets (Hodgson et al. 1999; Wang and Davidson, 2003; Soltys and Crimaldi, 2015) in a quiescent background. The examination of twin jets in the presence of a turbulent ambient (with almost zero mean flow) has received much less attention.

Our primary objective is to investigate the influence of a range of levels of background turbulence on the structure and mixing patterns of two parallel round jets, with a specific emphasis on analyzing the passive scalar field. Meanwhile, our secondary objective is to explore the impact of varying the jet spacing. In the current study, twin turbulent round jets were released into a quiescent and homogeneous turbulence with negligible mean flow, building on the work of Khorsandi et al. (2013), Perez-Alvarado, (2016) and Sahebjam et al. (2022) in the Environmental Hydraulics Laboratory of McGill University.

Experimental approaches

The experiments were conducted within a 1.5×2.4×1 m^3 section of a larger glass water tank (1.5×6×1 m^3), which was open at the top (i.e., the free surface is under ambient pressure conditions). The water in the tank was either quiescent, having been allowed to settle for an adequate duration after a gradual filling process, or turbulent. A homogeneous turbulence with negligible mean flow was generated in the tank by a random jet array (RJA) (Perez-Alvarado, 2016).

The RJA consists of six rows and ten columns of bilge pumps (Rule 25D, 500 GPH) affixed to a vertical sheet of high-density polyethylene measuring 1.5×1 m^2 in size. Maintaining uniform spacing between the pumps both horizontally and vertically (at a center-to-center distance of M=15 cm) and applying a reflective boundary condition helps to minimize the development of secondary flows. The turbulence was generated by the RJA through an algorithm that independently activated and deactivated the jets for randomly selected time intervals, following a normal distribution. Downstream of the RJA, the jets combine and form an environment that approximates a condition of homogeneous turbulence without mean shear. Due to merging of the RJA jets, beyond y/M = 5, normal to the RJA plane, the background turbulence exhibits homogeneity within planes parallel to the RJA, which decays with distance from the RJA (Khorsandi, 2011). Therefore, the twin jets were positioned to issue parallel to the RJA sheet, positioned at a lateral distance of y/M=7.3, and y/M=9.3 (equivalent to 1.1, and 1.4 m), where the turbulent kinetic energy (TKE) of the surrounding environment was k_{RJA} = 4.44 cm^2/s^2, and k_{RJA} = 2.64 cm^2/s^2 (Perez-Alvarado, 2016).

Two parallel round jets with a Reynolds number (Re ≡ $U_j d/\upsilon$, where U_j is the jet average exit velocity, and υ is the kinematic viscosity of water) of 10,600 were released from two parallel round pipes of 10.0 mm diameter into the water tank aligned parallel to the RJA sheet, stacked vertically. This configuration ensured a constant turbulence intensity in the downstream direction along both jets and their symmetry line. The jets were composed of two L-shaped pipes, whose horizontal section extended 0.25 m to ensure a fully developed exit flow.

A constant-head reservoir located 3 m above the jets fed the jets flow, maintaining a constant Reynolds number. Two jet spacings (center-to-center distances of s/d= 2.8, and 7.1, where s is the center-to-center distance of the jets) were used to explore the influence of jet spacing on the flow field. The activation and deactivation of the jets were controlled by a solenoid valve. A list of laboratory experiments performed is presented in Table 1.

Table 1. Summary of laboratory experiments

Label	Jet spacing (s/d)	k_{RJA}	Re	Symbol
Q-2.8	2.8	---	10600	⊖
T1-2.8	2.8	2.64	10600	✡
T2-2.8	2.8	4.44	10600	▷
Q-7.1	7.1	---	10600	●
T1-7.1	7.1	2.64	10600	✶
T2-7.1	7.1	4.44	10600	▶

The planar laser-induced fluorescence (PLIF) technique was utilized to acquire the concentration field of a passive scalar along the twin jets. A laser sheet with a thickness of 1.5 mm, created through the use of an 8-sided polygonal rotating mirror, induced fluorescence in the dye (Rhodamine 6G) along the jets. A pco.dimax 4 Megapixel CMOS camera equipped with a 50 mm Pentax lens was used for the PLIF technique with a field of view (FOV) of 680 × 680 mm^2. The intensity profiles underwent a calibration process to determine the correlation between fluorescence intensity and concentration values. A laboratory image depicting the development of twin jets in a quiescent background, with a jet spacing of s/d=2.8 and 7.1, is presented in Figure 2.

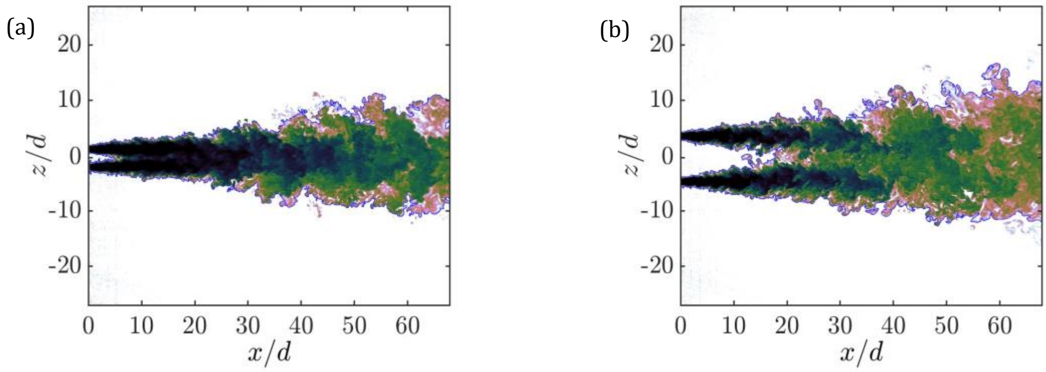

Figure 2. Instantaneous scalar concentration field of developing twin jets in a quiescent ambient, with a pipe spacing of (a) s/d=2.8, and (b) 7.1.

Results

The streamwise ensemble averaged mean concentration (Φ) contour plot is shown in Figure 3. The concentration and distance are normalized using their respective jet exit concentration (Φ_e) and pipe diameter (d). The variation of mean concentration is presented as a function of jet spacing and background turbulence level. As the jets develop downstream, the inner shear layers converge and the two jets undergo interaction and eventually converge at the symmetry plane, and the symmetry line concentration increases with downstream distance. The interactions between the jets, as well as the influence of the ambient fluid, influence the spreading of/entrainment into the jet. Concentration values decrease both longitudinally and laterally as the individual jets expand into the unconfined surrounding fluid and intrude into the confined space between them due to entrainment. Increasing the distance between the jets serves to reduce the mutual interaction between their inner layers and delays merging to a farther downstream distance as observable in the symmetry line profiles. Furthermore, the results indicate that increasing background turbulent intensity result in lower concentration values observed farther downstream of the jets. This phenomenon occurs due to the greater decay of concentration at higher background turbulence intensity, consistent with previous research on the effects of background turbulence on the dynamics of single jets (Khorsandi et al. 2013; Lai et al. 2019; Sahebjam et al. 2022).

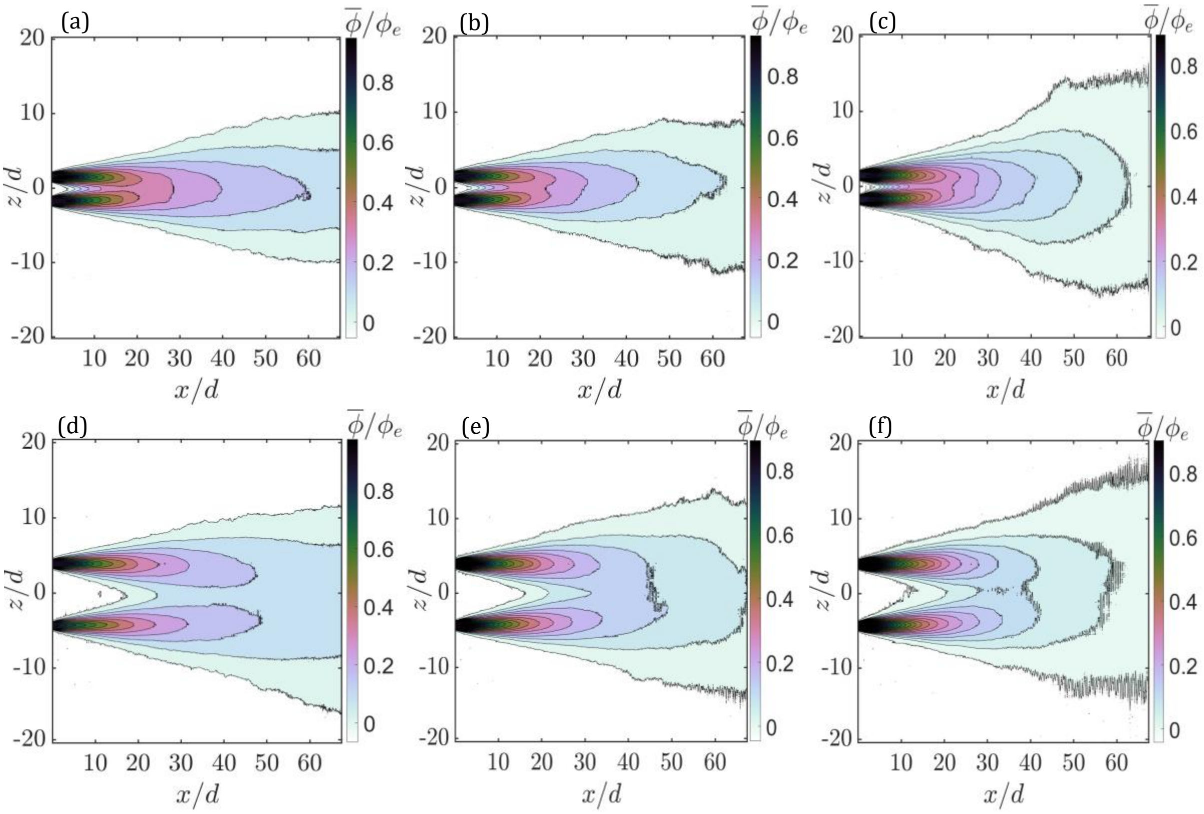

Figure 3. The mean concentration of the twin round jets for jet spacings of s/d=2.8, and 7.1 emitted into the quiescent and turbulent background. (a) s/d=2.8, quiescent background, (b) s/d=2.8, k_{RJA}=2.64, (c) s/d=2.8, k_{RJA}=4.44, (d) s/d=7.1, quiescent background, (e) s/d=7.1, k_{RJA}=2.64, (f) s/d=7.1, k_{RJA}=4.44.

According to previous studies (Okamoto and Yagita, 1985; Laban et al. 2019), the merging point, denoted as x_{MP}, is defined as the streamwise location where the concentration on the symmetry line exceeds zero (Φ_{sym}>0). Furthermore, the combined point, denoted as x_{CP}, is identified as the streamwise location where Φ_{cl} and Φ_{sym} intersect. The results show that the merging and combined points are located farther downstream with an increased distance between the twin jets. Increasing the jet spacing from 2.8 to 7.1 resulted in a 61% increase in x_{MP}/d and a 14% decrease in x_{CP}/d and a 85% increase in merging region length in quiescent background conditions. Furthermore, by increasing the level of the background turbulence intensity, the jets start to merge and combine earlier, i.e., when the jet spacing is 7.1 (s/d=7.1), increasing the background turbulent kinetic energy from 2.64 to 4.44 causes the merging point to shift upstream by 6% and 35% compared to twin jets in a quiescent background. Increasing the spacing between the jets amplifies the influence of background turbulence on both the merging and combined points. As an example, when the background turbulent kinetic energy is raised from zero to 2.64 and subsequently to 4.44, the combined point shifts upstream by 12% and 18% (in the case of s/d=7.1), and by 4% and 6% (in the case of s/d=2.8).

The merging behaviour of two parallel round jets is seen in the streamwise variations of ensemble averaged mean concentration along the symmetry line (Φ_{sym}) (normalized by their respective jet exit concentration, Φe) as a function of jet spacing and background turbulence level in Figure 5. We note that even in the converging region close to the jet exit, the external turbulence exerts a significant influence on the dynamics of the jets.

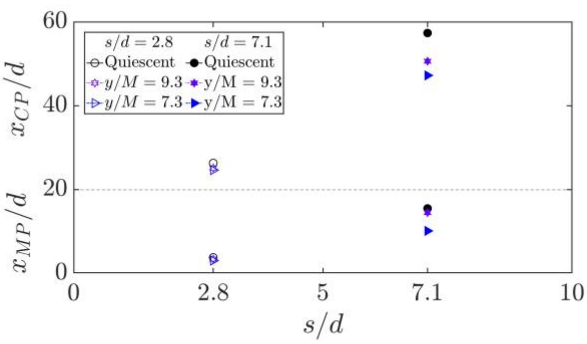

Figure 4. Merging and combined points variation as a function of two jet spacing and two background turbulence levels.

At the lower jet spacing (s/d=2.8), the jets merge rapidly to from a single jet whose mean concentration decreases as it decays ($\Phi_{sym} = \Phi_{cl} \sim x^{-1}$). Normalizing the ensemble averaged mean concentration along the symmetry line by its maximum mean value (inset to Figure 5) shows that merging occurs more rapidly and the decay is more rapid at smaller jet spacing. Increasing the background turbulence intensities has a minimal effect on merging. Jets subjected to higher background turbulence intensity exhibit a more rapid decay rate from their maximum values.

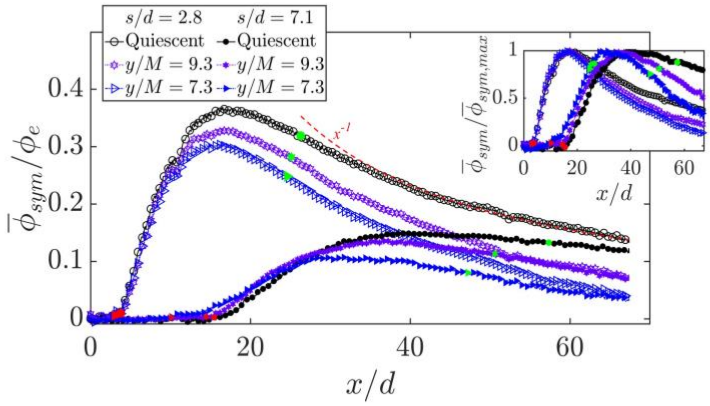

Figure 5. Symmetry line mean concentration of twin round jets as a function of two jet spacing and two background turbulence levels. The red symbols indicate the merging points, while the green symbols represent the combined points for each case.

The change in twin jet behaviour with jet spacing and turbulence level is evident in the log-log plot of the downstream variation of the ensemble averaged mean centerline concentration of twin round jets, normalized by their respective jet exit concentration. The rate of decay of the concentration for the twin jets at s/d=2.8 and 7.1 in a quiescent background beyond the combined point is that of a single jet (i.e. $\Phi_{cl} \sim x^{-1}$). Downstream of the combined point, increasing the background turbulence intensity leads to an increase in the decay rate of centerline concentration ($\Phi_{cl} \sim x^{-1.5}$ for k_{RJA} = 2.64 and $\Phi_{cl} \sim x^{-2.2}$ for k_{RJA} = 4.44) in the turbulence cases). This is consistent with the observations of Sahebjam et al. (2022) in a single jet. The increased decay rate of the mean concentration is due to the disruption of the jet structure caused by increasing background turbulence (Hunt 1994, Gaskin et al. 2004, Khorsandi et al. 2013, Perez-Alverado 2016, Sahebjam et al. 2022). Before the combined point, the centerline concentration decay rate of twin jets is lower than that reported for a single jet. This difference may be attributed to the suppression of entrainment on the inner side of the jets.

Figure 7 illustrates the degree of self-similarity of the ensemble averaged mean concentration in the twin jets by plotting the mean streamwise concentration along the symmetry line (Φ_{sym}), normalized by the maximum mean streamwise concentration along the same line ($\Phi_{sym,\ max}$), against the downstream distance (x) nondimensionalized by the location of $\Phi_{sym,\ max}$; (L_p) following the method for normalization for the velocity profile of twin jets released into a quiescent background and turbulent coflow (Taddesse and Mathew, 2022). Our results shows that the mean symmetry concentration may be self-similar for a range of background turbulence intensities at the close jet spacing (s/d = 2.8), but it is not self-similar for different background turbulence levels for larger jet spacing (s/d = 7.1). The earlier velocity data indicated independence with s/d (Taddesse and Mathew, 2022), and with s/d and jet to coflow velocity (Homayounfar et al. 2024).

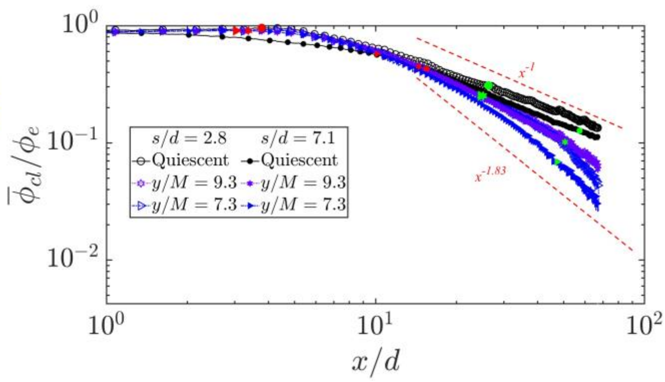

Figure 7. Decaying rate of mean concentration along the centerline of twin jets.

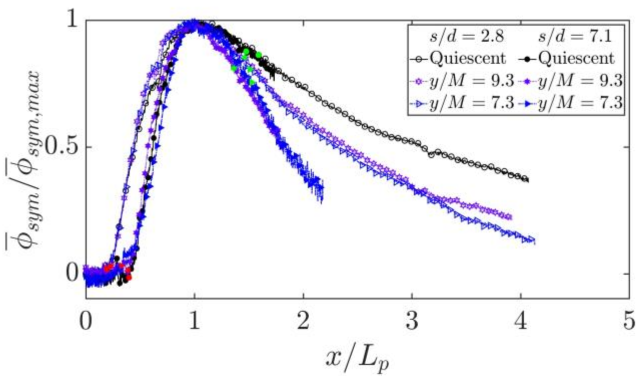

Figure 7. Development of streamwise mean concentration along the symmetry line scaled with peak concentration and its location.

The streamwise ensemble averaged root-mean-square (RMS) concentration (Φ_{rms}) contour plot is shown in Figure 8. The RMS concentration and distance are normalized using their respective jet exit concentration (Φ_e) and pipe diameter (d).
This figure investigates the effects of variations in jet spacing and background turbulence intensity levels on the turbulence intensity of twin jets. At the onset of the jet formation, a dual-peak RMS profile was observed within each of the twin jets. This phenomenon arises from the substantial velocity gradient between the jets and the surrounding background flow. As the jet spacing decreased, a reduction in the inner RMS peak values was observed relative to the outer RMS peaks. With increasing downstream distance in the jets, the inner RMS peaks merged and eventually vanished, while the outer shear layers continued to spread freely. Increasing the jet spacing leads to a more pronounced occurrence of this phenomenon at greater downstream distances.

By increasing the background turbulence intensity, at increasingly downstream distances, the two-peak RMS concentration profiles transition into a single-peak configuration, consistent with the results of Khorsandi et al. (2013) in the context of the velocity in single jet studies. The heightened background turbulence intensity amplifies the interaction between the turbulent structures of the jets and the background flow. Consequently, the turbulent structures within the jet undergo increased decay and mixing, while the position of the interface (TTI) turbulence has a greater range of positions (Kohan & Gaskin 2022). This facilitates the merging of turbulent structures, leading to the transition from a two-peak RMS profile to a single peak. Additionally, the results demonstrate that increasing the background turbulence intensity correlates with an expansion of the width of the twin jets. The background turbulent fluctuations contribute to the lateral spreading of the jet boundaries, further expanding the width of the twin jets.

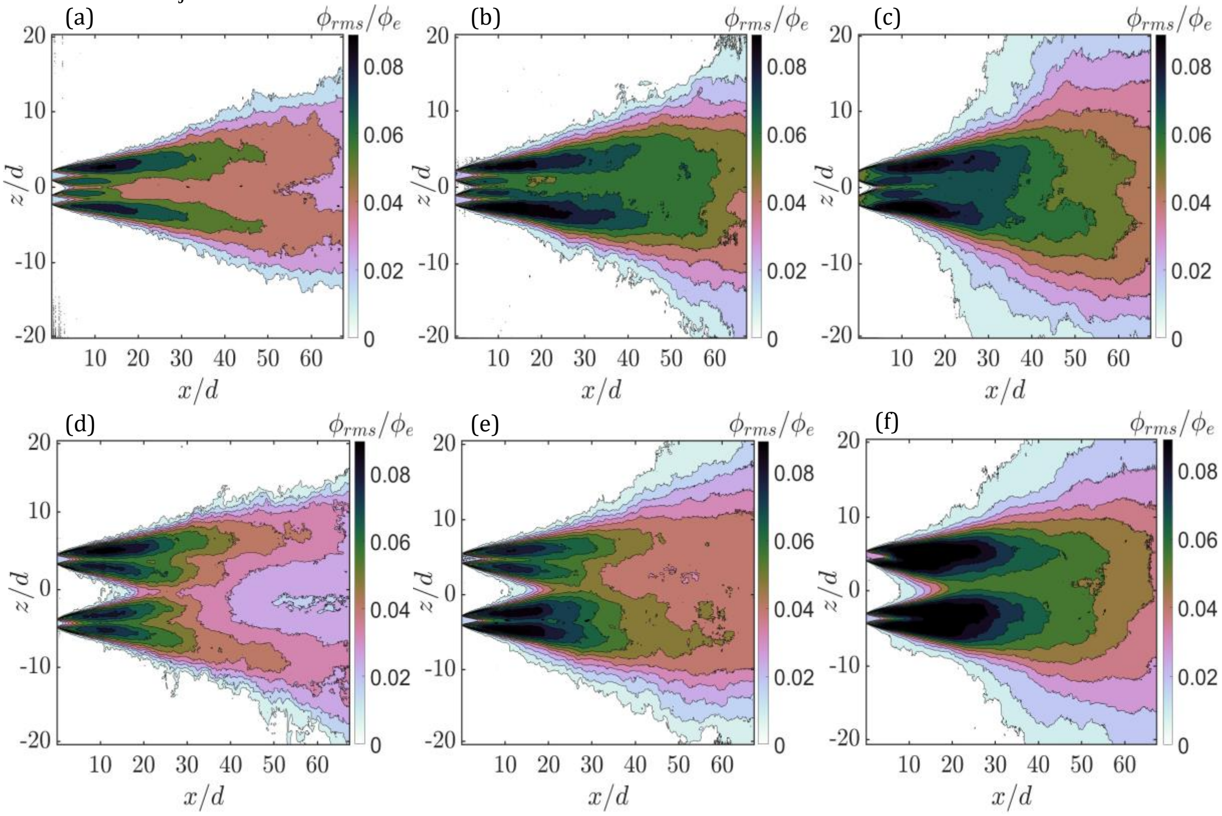

Figure 8. The RMS concentration of the twin round jets for the jet spacing of s/d=2.8, and 7.1 emitted to the quiescent and turbulent background. (a) s/d=2.8, quiescent background, (b) s/d=2.8, k_{RJA}=2.64, (c) s/d=2.8, k_{RJA}=4.44, (d) s/d=7.1, quiescent background, (e) s/d=7.1, k_{RJA}=2.64, (f) s/d=7.1, k_{RJA}=4.44.

Figure 9(a) depicts the downstream evolution of the symmetry line RMS concentration ($\Phi_{rms,sym}$) normalized by jet exit concentration (Φ_e) versus the downstream distance nondimensionalized by jet diameter as a function of jet spacing, and background turbulence level. Similar to the mean concentration, as the jets develop downstream, the inner shear layers converge, and the symmetry line RMS concentration increases to its peak values. The result demonstrates that as the turbulence level of the background increases, the RMS concentration increases with a greater increase for greater background turbulence level as seen for the single jet (Sahebjam et al. 2022). The centerline RMS variation along the jets is illustrated in Figure 9(b) using log-log coordinates. Results show that, the RMS decay rate beyond the combined point is approximately $x^{-0.7}$, which is consistent with previous reports in single jet studies.

Figures 9(c), and 9(d) present the turbulence intensity on the symmetry line of the twin jets as the RMS concentration ($\Phi_{rms,sym}$) normalized by the ensemble mean RMS concentration (Φ_{rms}). Beyond the combined point in a quiescent ambient, the turbulence intensity asymptotes to a constant (0.20 – 0.25) as expected. In the turbulent ambient, the turbulence intensity increases beyond the combined point as the relative contribution of the entrained turbulence relative to the jet turbulence to the RMS concentration increases as the jet decays. The high turbulence intensity before the merging point, are an artifact of the very low concentrations on the symmetry line before merging. Additionally, the results indicate that for both cases of s/d=2.8 and 7.1, similar turbulent intensities are observed at x/d distances greater than 60.

Conclusion

The impact of approximately homogeneous background turbulence intensity on the mixing of turbulent twin round jets was investigated experimentally using the PLIF technique to obtain ensemble mean and RMS concentrations. The study revealed that increasing background turbulence intensity led to a faster decay of the jets ($\Phi_{cl} \sim x^{-1.5}$ for k_{RJA} = 2.64 and $\Phi_{cl} \sim x^{-2.2}$ for k_{RJA} = 4.44), consequently facilitating earlier merging, and combining of the jets. The entrained background turbulence results in an increase in turbulence intensity in the jets and the more rapid breakdown of the jet. Universal self-similarity of the ensemble mean symmetry concentration is not demonstrated.

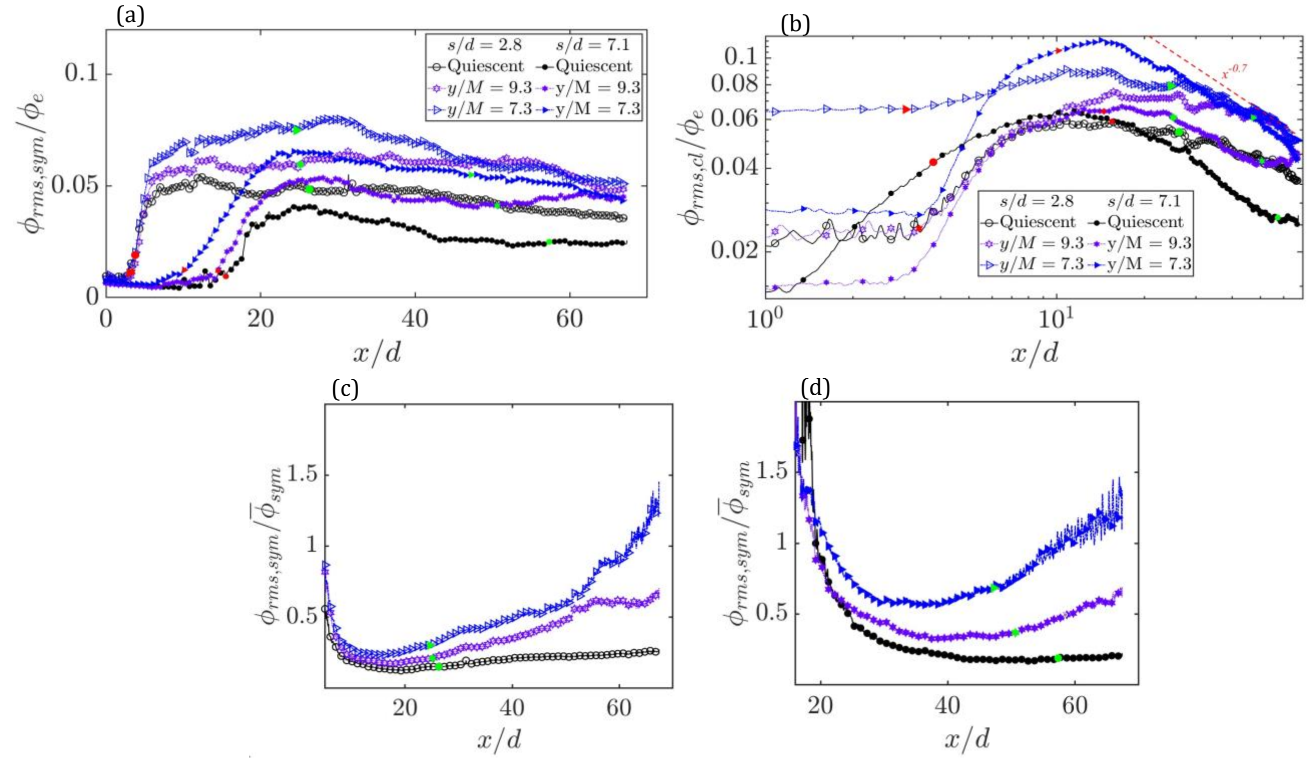

Figure 9. The effects of ambient turbulence on the downstream evaluation of symmetry line RMS concentration. Red symbols indicate the merging points, while the green symbols represent the combined points for each case. (a) symmetry line RMS concentration, (b) centerline line RMS concentration, (c) symmetry line turbulence intensity, s/d=2.8, (d) symmetry line turbulence intensity, s/d=7.1

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