Author accepted version. Final publication as:
Gaskin, S.J., McKernan, M. & Xue, F. (2004) The effect of background turbulence on jet entrainment: an experimental study of a plane jet in a shallow coflow. Journal of Hydraulic Research, 42(5): 531-540.

The effect of background turbulence on jet entrainment: an experimental study of a plane jet in a shallow coflow.

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Abstract

Many effluents are released into water bodies or into the atmosphere, and dilution is relied on to minimize the toxic effects of the pollutants on the environment. Dilution occurs due to entrainment and subsequent mixing of the “clean” (or cleaner) ambient fluid and the effluent stream. In the near field, dilution occurs due to momentum or buoyancy driven entrainment into the effluent stream, which is proportional to a characteristic velocity of the jet or plume. Whereas in the far field, dilution occurs due to turbulent diffusion at a rate dependent on the level of turbulence in the receiving fluid. In order to predict the expected dilution of an effluent stream, it is necessary to answer the question, at what point does the dilution mechanism change and how does it affect dilution rates. An experimental study examining the velocity and concentration decay of plane jets released into shallow coflows with increasing levels of external turbulence, indicated that levels of external turbulence just large enough to disrupt the jet structure reduced dilution rates significantly. This indicates that models, in which the jet dilution and turbulent diffusion are superimposed, will not always give a conservative estimate of effluent dilution.

Keywords
Background turbulence, entrainment, jet, turbulent diffusion, coflow.

Introduction

Many effluents are released into water bodies or into the atmosphere and dilution is relied on to minimize the toxic effects of the pollutants on the environment. Dilution occurs due to entrainment and mixing of the "clean" (or cleaner) ambient fluid and the effluent stream. Entrainment can be defined as the net transport of a fluid from a less turbulent to a more turbulent fluid (McClimans 1994). In the near field, where the effluent stream can be described as a buoyant jet, momentum or buoyancy driven entrainment increases the volume flux of the effluent stream, hence increasing its dilution. In this near field region, the jet is more turbulent than its surroundings, hence jet turbulence dominates. Therefore the entrainment occurs as an inwards entrainment velocity, u_α, normal to the interface between the buoyant jet and the ambient fluid, and it is proportional to a characteristic jet velocity (Morton et al. 1956), resulting in an entrainment flow, q_α,

$$q_\alpha = u_\alpha b_\ell \tag{1}$$

where b_ℓ is defined as the length of the interface between the buoyant jet and the ambient fluid, *e.g.* $2\pi r$ for an axisymmetric jet. This inwards entrainment flow will continue until the magnitude of the jet turbulence is less than that of the background turbulence.

The near field region is defined as the region in which the jet momentum (or energy) dominates the flow dynamics. The primary entrainment mechanism is large scale engulfment by eddies, which scale with the width of the jet or plume (Turner 1986). The engulfed fluid is subsequently mixed by the small scale turbulence and by diffusion within the jet. As the jet or plume entrains fluid, its volume flux increases and its time averaged mean velocity decreases. The self-similarity of the jet or plume flow indicates that the internal jet turbulence decreases proportionally with the decrease in mean velocity (Fisher et al. 1979). Once the jet turbulence is less than the background turbulence, detrainment of the jet fluid into its surroundings occurs by turbulent diffusion and the effluent behaves as a passive tracer advected by the background flow. This is the dilution mechanism for the far field

In order to frame the question of how the background turbulence can affect entrainment into the jet, the pure axisymmetric jet in a stagnant ambient fluid is considered. In the near field the entrainment into the pure axisymmetric jet is driven by the jet momentum. The integrated momentum equation to the first order has contributions only from the mean velocity and is given by,

$$M = 2\pi \int_0^\infty U^2 r dr \qquad (2)$$

where U is the mean velocity, and r is the jet radius. The momentum integral to the second order also includes the contributions to the streamwise momentum flux from turbulence and pressure,

$$M = 2\pi \int_0^\infty \left[U^2 + u'^2 - \tfrac{1}{2}\left(v'^2 + w'^2\right)\right] r dr \qquad (3)$$

where u', v' and w' are the turbulent jet velocities in the axial and transverse directions (Hussein et al. 1994). The first term is due to the mean jet velocity, the second to the jet turbulence and the third to the streamwise mean pressure variation. Experimental measurements of the jet in a stagnant ambient fluid show that the contribution of the jet turbulence is approximately 10% of that of the mean velocities in the near field (Wygnanski & Fiedler 1969, Rodi 1982, Hussein et al. 1994). This indicates that the turbulent intensity in the jet influences the entrainment rate into the jet.

It can clearly be seen, that in the far field, the level of turbulence in the receiving fluid (or background turbulence) will determine the turbulent diffusion of the effluent. However, in the near field, some questions remain unanswered. Is background turbulence entrained into the jet and does it affect the turbulent component of the jet velocity, thereby increasing entrainment? Does the background turbulence affect the magnitude of the mean jet velocity or disrupt the jet structure altogether, thereby decreasing entrainment? At what point does the transition from jet entrainment to turbulent diffusion occur? These questions must be answered in order to improve on many numerical models used to predict the effluent dilution for field conditions, in which some background turbulence is always present. Currently many models either superimpose the dilution effects of the jet's internal turbulence and the effects of the background turbulence, or ignore the effect of the background turbulence in the near field region.

The aim of the present experimental study is to get a better understanding of the effect of different levels of background turbulence on jet entrainment and jet structure. Changes to jet structure and entrainment are observed using flow visualization and from measurements of the mean and fluctuating properties of jet velocities and concentrations. The plane jet issuing horizontally into a shallow coflow was chosen for study as it is a relatively simple configuration, in which an increase in background turbulence can be produced by increasing the bed friction. The geometry of the shallow flow limits the large scale turbulence to two dimensions. Comparison to the control case, of the jet in a shallow coflow with no background turbulence, allows the effects of different levels of background turbulence on the structure and entrainment of the jet in a shallow coflow to be determined. This study begins to address the questions posed above about the effect of background turbulence on jet entrainment.

Literature review

Hunt (1994) presents theoretical arguments to support his hypothesis that background turbulence can reduce the rate of dilution in the near field. In general, a positive forcing of a jet or plume will increase entrainment, whereas any tendency of the plume to break up into distinct eddies decreases entrainment. Near the source, when the entrainment velocity into a jet is larger than the root mean square velocity of the background turbulence, the background turbulence is entrained and does not affect the growth rate of the jet. Weak eddies with the root mean square velocity of the background turbulence do not perturb the strong eddies of the internal turbulence until the internal turbulence has decreased to the order of magnitude of the background turbulence. At this point, the root mean square velocity of the background turbulence strongly affects the internal structure of the jet and the self-preserving structure of the jet breaks down relatively suddenly. This results in an entrainment velocity into the jet that is greatly reduced by the background turbulence, and dilution then occurs at a reduced rate due only to turbulent diffusion.

On the other hand, the work of Ching et al. (1995) suggests that background turbulence will increase dilution. They investigated line plumes in a stagnant fluid with oscillating grid turbulence and found that at a certain distance the background turbulence destroyed the plume structure and resulted in an increased rate of spread due to high levels of turbulent diffusion. In their analysis they suggest that eddies will only make a significant contribution to plume growth when their advection timescale T_a is greater than their overturning timescale T_0. For an eddy of size l,

$$T_a \approx l / u_\alpha \qquad (4)$$
$$\text{and} \quad T_0 \approx l / u_{eddy}$$

where u_{eddy} is the characteristic velocity of the eddy, which is proportional to the background turbulent intensity, u'_∞, and u_α is the entrainment velocity. When $T_a < T_0$, the background turbulence does not affect plume growth as the eddies are advected by the entrainment flow and distort within the plume similarly to a passive substance. When $T_a > T_0$, the background turbulence will break down the plume. This point was experimentally found to occur when the convective velocity of the plume was less that about 1.6 times the background turbulence.

For jets in a stagnant fluid, Guo. et al. (1999) found that the jet structure was destroyed when the background turbulent intensity was 12.5 % of the centerline velocity. Law et al. (2001) found an increased decay of the mean properties of an axisymetric jet beyond a certain downstream point due to background turbulence, as did Gaskin & Wood (1993) for an advected line thermal. Wright (1994) found that, for an axisymmetric buoyant jet in a crossflow, background turbulence increased the rate of decay of mean properties and destroyed the jet structure at a certain downstream point. He attempted to relate the increased rate of decay to the level of background turbulence, produced in the open channel flow by beds of different roughness, by increasing the entrainment coefficient by a term, which scaled with the background turbulence level. This assumes that the effects of the background turbulence are superimposed on the normal jet entrainment.

The flow dynamics of a axisymmetric and plane jet in an unbounded coflow have been studied in detail (Nickels & Perry 1996, Bradbury 1965, Bradbury and Riley 1967). The momentum excess is invariant with downstream distance (there is some loss in the shallow flow case due to bed friction). The excess mean velocities are self preserving, however the product of the turbulent velocities are not self preserving at large downstream distances. The entrainment into the plane jet in a coflow varies gradually with the relative magnitude of the jet excess velocity, U_m, and coflow velocity, U_∞, whose asymptotic behavior is a strong jet for

$U_m >> U_\infty$ and the weak jet for $U_m << U_\infty$ (Bradbury & Riley 1967, Gaskin & Wood 2001). The decay of the mean velocity is proportional to $x^{-½}$, where x is the downstream distance, but the rate of decay is greater for the weak jet. The width growth is proportional to x for the strong jet and proportional to $x^{½}$ for the weak jet.

In the shallow flow case, the plane jet is bounded resulting in quasi two dimensional motion. The large scale motions scale with the jet width, while small scale three dimensional turbulence is generated by bed friction (Jirka 1994, Chen & Jirka 1995). The bed friction, which is a source of external turbulence, "stabilizes" or breaks down the large scale transverse motions (Babarutsi et al. 1989) resulting in a reduced centerline velocity, hence reducing entrainment and limiting dilution efficiency (Dracos et al. 1992).

Experimental Method

The present laboratory study investigates the effect of different levels of background turbulence on dilution, and hence entrainment, by observing the structure and velocity of a plane jet issuing horizontally into a shallow coflow. A sketch of the flow configuration is shown in Figure 1. The 4 m long and 0.6 m wide flume had a flow depth, h, of 25 mm controlled by a downstream weir. A coflow in the channel of $U_\infty = 50$ mm/s with a coflow Reynolds number of $\mathrm{Re}_\infty = U_\infty h / \nu = 1250$ was maintained with a pump. The jet outlet, constructed of plexiglass, had a width, d, of 6.5 mm and a height, h, of 25 mm. Wire grid was inserted inside the outlet normal to the flow direction to ensure a uniform exit velocity. A constant head tank, regulated by a rotameter provided a jet exit velocity of 180 mm/s with a jet Reynolds number of $\mathrm{Re}_j = U_j d / \nu = 1200$.

The effect of the lateral confinement of the plane jet was determined following the method of Gaskin & Wood (2001). The effects of confinement are small in the region where the jet was observed and, in addition, the effects are the same for all the jets considered in the comparison study.

Five levels of background turbulence of increasing intensity were required. The control case of a coflow with zero turbulent intensity was produced by towing the plane jet at the coflow velocity through the flume filled with a still fluid to a depth of 25 mm. A background turbulent intensity of 5-8 % of the mean flow velocity was produced by the flume run in normal coflow mode (as measured with a single wire hotfilm anemometer at a depth of 15 mm). In order to increase the background turbulence in the coflow a number of possibilities were initially considered. A rectangular grid placed upstream of the jet nozzle and a beaded plexiglass sheet did not significantly increase the turbulent intensity without causing substantial changes to the mean flow. The method finally chosen was a series of submerged walls, 4 or 6 mm high, placed on the surface of the flume perpendicular to the flow direction, spanning the width of the flume. Turbulent intensities of 8-10%, 10-12% and 12-15% of the mean flow velocity, as measured at 15 mm from the flume bed, were generated using 4 mm walls at 450 mm spacing, 4 mm walls at 250 mm spacing and 6 mm walls at 250 mm spacing respectively (Figure 1). Before the jet experiments were run, the variation in the background turbulence with depth, and lateral and longitudinal position was determined along cross-sections of the flume at a depth of 15 mm and along vertical profiles at intervals along the centerline of the flume (Figure 2). Some variation in the mean velocity and turbulent intensity with downstream position were evident due to the "lumpiness" of the walls. A full description is given in McKernan (2000).

For flow visualization and concentration measurements, a method similar to the planar concentration analysis method described by Rummel et al. (2002) was used. A red dye (Triactive Red DF-6BF) was used as a conservative tracer in the jet flow. A CCD camera (Canon Optura) recorded the structure of the flow and the detailed concentration data at a rate of 30 frames per second. The initial dye concentration in the jet ensured observed dye concentrations were in the range of 1 to 50 ppm, where the camera response was linear (i.e. concentration to greyscale was linear). The camera images were calibrated to enable conversion from light intensity, recorded in the image pixels in RGB mode (green channel), to tracer concentration. To ensure repeatability, the experiments were done at night with the sole illumination coming from four spotlights, and the flume was lined with white plastic to get maximum image contrast. Local jet concentrations were calculated using data from 60 images, providing concentration data to $\pm 5\%$ error. A full description is given in Xue (2000).

The mean velocity and rms turbulent intensity in the streamwise direction were measured using a Dantec single wire hotfilm anemometer (model 55R11) run under Streamware software. For each data point, 16384 samples were collected at a frequency of 200 Hz. The error in the mean velocity was $\pm 5\%$ and the error in the turbulent intensity was $\pm 10-20\%$ due to the limitations of the hotwire resolution at the lower end of its velocity range. Data in a 0% turbulence coflow are not available. The data of Bradbury and Riley (1967) were used for comparison.

Transverse velocity and concentration profiles were measured at distances from the jet outlet of 100, 250, 350, 500, 600, 750 and 850 mm (i.e. $x/l_{j,wj}$ = 1.2, 3.1, 4.4, 6.2, 7.5, 9.4 and 10.6, where $l_{j,wj}$ = 80 mm). The data were analyzed to obtain profiles of the mean and fluctuating component of the velocity and concentration. From these profiles, centerline values, maximum values and a characteristic width defined by the location where the concentration or velocity was *1/e* of the maximum value (Figure 3) were obtained. The observed data are plotted to determine their variation with dimensionless downstream distance, $x/l_{j,wj}$. The lengthscale of the transition from the strong jet to the weak jet, $l_{j,wj} = M_{eo} / U_\infty^2$, (or momentum radius of the jet, Bradbury 1965, Nickels & Perry 1996, Gaskin & Wood 2001) collapses the data of coflowing jets onto a single curve (i.e. for a range of U_0/U_∞ values).

Results and Discussion

Observations from flow visualization of the plane jet in a shallow coflow

The general behavior of the plane jet released into shallow coflows with different levels of background turbulence can be observed from the flow visualization (Figure 4). For the case with no background turbulence, two regions of behavior can be identified. In the region close to the source up to a distance of approximately $x/l_{j,wj}$ = 5, the jet trajectory is linear and some integral scale eddies (scaling with the width of the jet), which are responsible for the near field entrainment, are visible. Beyond this distance the flow visualization shows that the integral scale structures develop as distinct alternating counter-rotating eddies and result in an apparently meandering flow trajectory. (In the lab the development of these large scale structures continue until the jet begins to feel the lateral confinement at a distance of 15-20 $l_{j,wj}$ downstream, resulting in suppression of the development of the eddy structures and a breakdown of the jet structure). The rate of jet width growth is constant over both regions.

In comparison, for the cases with background turbulence the flow behavior is markedly different. Closer to the source, the integral scale eddies are increasingly less distinct as the background turbulence levels increase. At distances greater than $x/l_{j,wj}$ = 5, the trajectory is linear instead of apparently meandering and the width growth is reduced. This clearly indicates a disrupted jet structure due to the suppression of the development of the integral scale eddies. The jet structure is disrupted by the smaller 3-D eddies of the background turbulence. The disrupted jet structure is seen in the advection of a slowly decaying but intermittent tracer concentration field (indicating remnants of the large eddy structures) underlain by a smeared tracer layer close to the bed. This will be discussed further below.

Observations of the velocity and concentration of the plane jet in a shallow coflow

The effect of increasing levels of background turbulence on the jet structure and entrainment can also be identified by quantitatively examining the following aspects: the change with distance of the jet centerline excess velocity and turbulent intensity, the jet centerline dilution (concentration) and centerline and maximum concentration fluctuations, and the jet width growth. All slopes and constants of proportionality have been determined using linear regression and have R^2 values greater than 0.95 where noted with *.

Transverse profiles of the mean and fluctuating components of excess velocity and concentration for the plane jet released horizontally into the shallow coflow were obtained (Figure 5). The mean velocity profiles are approximately Gaussian in shape and self similar when scaled with the mean centerline value and characteristic jet width (details in McKernan 2000). Note that maximum concentrations are higher in the more turbulent coflows. The turbulent intensity profiles of the velocity are less distinct due to limits in the sensitivity of the measurements with the hotfilm anemometer as mentioned above.

Previous theoretical and experimental work (e.g. Bradbury & Riley 1967, Dracos et al. 1992) has predicted and observed centerline excess velocity decay as $(U_\infty/U_m)^2 \propto x/l_{j,wj}$ and tracer concentration decay as $(C_o/C_m)^2 \propto x/l_{j,wj}$.

The data of Bradbury and Riley (1967), which were for a plane jet in a parallel air stream with very low levels of background turbulence, closely follow the theoretical relationship of $(U_\infty/U_m)^2 \propto x/l_{j,wj}$ with a constant of proportionality of 0.2 (Figure 6). In the present study, velocity measurements for the case with no background turbulence were not made due to limitations of the experimental setup. In the lowest level of background turbulence of 5-8%, the mean centerline excess velocity decays as $(U_\infty/U_m)^2 \propto x/l_{j,wj}$ with a constant of proportionality of 0.2 up to a distance of $x/l_{j,wj}$ =10. From this point jet excess velocity decay is more rapid. With increasing levels of background turbulence in the coflow, there is a clear trend of an increasing rate of velocity decay, which begins increasingly closer to the source, indicating destruction of jet structure by the background turbulence. Once the jet structure is destroyed, dilution will only occur due to turbulent diffusion by the background turbulence because the integral scale eddies of the jet have been broken up.

The centerline tracer dilution in the present study, increases with distance as $(C_o/C_m)^2 \propto x/l_{j,wj}$, with a constant of proportionality of 1.5 in the coflow with no background turbulence (Figure 6). The data show reduced dilution as the levels of background turbulence increase. The rate of dilution is reduced with the constant of proportionality reduced to 0.85 (0.90 for u'= 5-8%; 0.86 for u'= 8-10%; 0.81 for u'= 10-12%; 0.81 for u'= 12-15%). These results show that, as the integral scale eddies (and jet structure) are disrupted, the excess jet velocity is reduced. Since entrainment into a jet is proportional to a characteristic jet velocity (Morton et al. 1956), the reduced velocity results in reduced entrainment rates and hence the reduced dilution rates seen in these data.

The structure of the jet can be inferred from the graphs of the concentration fluctuations (Figure 7). Higher fluctuations in the concentration correspond to the presence of larger scale eddy structures, which also indicate the presence of the jet structure. Chen & Jirka, 1999 found concentrations in the center of the eddy structures four times higher than the collocated mean values in a plane jet in a shallow water layer. Considering first the ratio of the maximum root mean squared fluctuation to the time averaged centerline concentration, $\left(c'_{\max} / C_m\right)$, the maximum relative fluctuation increases with distance for the case with no background turbulence in the coflow. A similar trend was both observed and predicted by Bradbury & Riley (1967) and observed for the plane jet in a shallow water layer (no coflow) by Chen & Jirka (1999). The maximum fluctuations are found in the peaks of the double peaked profile (Figure 5). This suggests the presence of large scale eddies and implies an intact jet structure, as is also seen in the flow visualization (Figure 4). With background turbulence in the coflow, the maximum relative fluctuations are smaller and decrease with downstream distance. In addition the data clearly show a trend of decreasing magnitude of the fluctuations with increasing levels of background turbulence, indicating that the large-scale eddy structure is increasingly disrupted with increasing background turbulence levels and there is more mixing due to the smaller scale eddies of the background turbulence.

Considering the relative fluctuations at the centerline, $\left(c'_{cl}/C_m\right)$, similar trends are observed for the jet in all levels of background turbulence (Figure 7). The relative centerline fluctuation increases up to a distance of $x/l_{j,wj} = 5$ as the eddy structure is developing. Beyond $x/l_{j,wj} = 5$, the relative centerline fluctuation decreases. For the case with no background turbulence this indicates the increasing size of the integral scale eddies and the increasingly meandering trajectory as clear ambient fluid is entrained into the centerline of the jet. The double peaked structure of the concentration fluctuation profile becomes more pronounced with downstream distance. Whereas, with the presence of background turbulence, the double peaked structure gradually decays, with a similar rate of the concentration fluctuation decay seen for the centerline fluctuations as for the peak fluctuations. The magnitude of the concentration fluctuations decreases with increasing background turbulence levels. Some evidence of the eddies, as regions of increased tracer concentration advected with the flow, remains but the lateral movement of the eddies is suppressed. This is explained by the disruption and decay of the jet structure resulting in the advection of an intermittent tracer concentration field that is slowly decaying subject to turbulent diffusion by the background turbulence.

The width of the jet is defined by the points on the profile where the mean local velocity or concentration is *1/e* of the mean centerline value. The rate of width growth of the jet (Figure 8) is affected by the background turbulence. Considering first the width defined by the velocity profile, the rate of width growth increases as background turbulence levels increase. For comparison, the data of Bradbury & Riley (1967), with very low turbulence levels, have been plotted. The changes to the width growth supports the hypothesis that with increased background turbulence levels the jet structure is destroyed, the jet velocity decays rapidly and the velocity profile has a lower maximum value and greater width. Considering the width growth from the concentration data, the width growth occurs at a rate of 0.08 $x/l_{j,wj}$ for the case with no background turbulence. With a level of background turbulence of 5-8%, the width growth is similar to the case with no background turbulence up to $x/l_{j,wj} = 5$, beyond this point the width growth decreases to a rate of 0.03 $x/l_{j,wj}$. This indicates, that at this level of background turbulence, the jet structure has been disrupted, the lateral movement of the eddies has been suppressed and width growth due to turbulent diffusion is lower than had the jet structure still been intact. As the background turbulence levels increase above 5-8%, the rate of width growth then increases due to the higher turbulent diffusion with the higher background turbulence levels. In these experiments, the width growth has increased back up to that of the case with no background turbulence at a background turbulence level of 12-15 %, although the dilution and the excess jet velocity are lower.

b'_c is the width defined by the distance between concentration fluctuation peaks. It shows the same trends in width growth (Figure 9) as does the width growth defined by the mean concentration described above. The concentration fluctuation peaks are indications of the large eddy structures. The suppression of the large eddy structures, due to the presence of the background turbulence, results in the reduction of the rate of separation of the peaks (and of the relative magnitude of the peaks).

Further indications of the disruption of the jet structure, suppression of the integral scale eddies and more small scale mixing are found in the growth of the width of the intermittency profile, b_I. Intermittency is defined as a measure of the temporal variation of the fluctuations of concentration (or velocity) in a flow at a fixed point. The intermittency factor is defined as

$$I(T) = \frac{1}{T} \lim_{T\to\infty} \int_0^T I(t)dt \tag{5}$$

where $I(t) = 1$ when $c \geq c_t$ and $I(t) = 0$ when $c < c_t$, and c_t is a threshold value equal to $0.15C_m$, above which the jet is deemed present. The change in the intermittency of the jet due to different levels of background turbulence is shown (Figure 10). The variation with distance of b_I/b, which is the ratio of the width of the intermittency profile where $I(t) = 1$ to the concentration half width. This ratio decreases slightly for the jet released into the non-turbulent coflow. However in the coflows with background turbulence, b_I/b is approximately constant up to $x/l_{j,wj} = 5$ then increases at a constant rate (slope of 0.25). The increasing relative width of b_I indicates an increasing absence of large scale entrainment, due to the lack of ambient fluid engulfed and entrained by the large scale eddies, which would be indicated by an $I(t) < 1$. In the region where $I(t) = 1$, there is more complete mixing in the jet by the smaller scale eddies, so there is no unmixed ambient fluid within the jet region. These observations indicate the disruption of the jet structure in the presence of background turbulence.

The conclusion of the present work is that, in the near field, background turbulence, at the levels investigated, at some point disrupts the jet structure. This results in a decreased dilution, because the turbulent diffusion suppresses and is less than the jet induced entrainment and dilution. In previous work it has also been concluded that at some point the jet structure is broken down by the background turbulence. However, it was concluded that this results in an increase in dilution (Gaskin & Wood 1993, Wright 1994, Ching et al. 1995, Guo et al. 1999, Law et al. 2001). Some of these experiments only observed velocities, which show an increased velocity decay and increased velocity width growth, but cannot show the decreased tracer dilution. Other studies only used dye and observed increased width growth. The present study shows that increased width growth is found at the higher background turbulence levels investigated, but that even with increased width growth lower dilutions are found due to the excess velocity decay. In addition, for the experiments made in a tank with oscillating grid turbulence, the jet or plume flows towards the grid and hence into an increasing turbulent intensity. This will result in rapid break up of the jet or plume as the jet's turbulent intensity is decreasing while that of the background turbulence is increasing. This will tend to hide behavior that occurs over the narrow range of background turbulence to jet turbulence ratios over which the transitional behavior occurs.

Conclusions

The entrainment and dilution of an effluent changes from jet induced entrainment in the near field region to turbulent diffusion in the far field. It is clear that the level of background turbulence determines the rate of turbulent diffusion in the far field, however in the near field the effect of background turbulence on dilution rates is less straightforward. In the present experimental study, the effect of the level of background turbulence on the entrainment into a plane jet in a shallow coflow was investigated by observing the changes to the jet structure and to the mean and fluctuating components of the jet concentration and velocity. The level of background turbulence in the coflow was varied from a turbulent intensity of 0% to 12-15%.

The observations indicate that once the background turbulence is great enough to disrupt the integral scale eddies of the jet structure, entrainment changes from large scale engulfment by these large scale eddies to turbulent diffusion by the smaller eddies of the background turbulence. The effect of the background turbulence is significant at distances of $x/l_{j,wj} > 5$. Increased levels of background turbulence cause increased rates of velocity decay. The rate of dilution of the disrupted jet structure due to the turbulent diffusion by the background turbulence (at levels of background turbulence large enough to disrupt the jet structure) is less than dilution due to jet induced entrainment. Width growth is reduced at lower levels of background turbulence. With higher levels of background turbulence, width growth can reach the rate of width growth due to jet induced entrainment, however the dilution rates are lower due to the reduced excess jet velocity resulting from the disruption of the jet structure.

These results indicate, that in the near field, background turbulence, at the levels investigated, decreases dilution, because the turbulent diffusion suppresses and is less than the jet induced entrainment. Therefore superposition of dilution due to jet entrainment and dilution due to turbulent diffusion in models is not justified. Further work must be done to see if similar results are found for an axisymmetric jet, to investigate in detail how the jet structure is disrupted, how the entrained turbulence interacts with the jet turbulence and affects jet entrainment, and to determine the relative level of background turbulence to jet turbulence at which the changes occur.

Acknowledgments

The authors would like to acknowledge the support of the National Science and Engineering Research Council of Canada.

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Notation

b	half width of jet, defined as half the jet width where the local mean velocity or concentration is $1/e$ of the mean centerline value
b'_c	the distance between concentration fluctuation peaks
b_I	width of the intermittency profile where $I(t) = 1$
b_t	length of the interface between the buoyant jet and the ambient fluid
C_o	initial jet tracer concentration
C_m	mean jet tracer concentration on the jet centerline
c'_{cl}	centerline value of the root mean squared concentration fluctuation
c'_{max}	maximum value of the root mean squared concentration fluctuation
c_t	threshold value of concentration used to define intermittency
d	width of jet outlet
h	depth of shallow co-flow
$I(t)$	intermittency, $I(t) = 1$ when $c \geq c_t$ and $I(t) = 0$ when $c < c_t$
$l_{j,wj}$	length scale giving the transition for a plane jet between the strong jet and weak jet region equal to the ratio of the initial excess momentum to the coflow velocity squared = M_{eo}/U_∞^2
l	turbulent eddy size
M	jet momentum
M_{eo}	initial excess jet momentum
q_α	entrainment flow
r	radius of jet flow
Re_j	Reynolds number of the plane jet = $U_o d/\nu$
Re_∞	Reynolds number of co-flow = $U_\infty h/\nu$
T_a	advection timescale of eddy
T_0	overturning timescale of eddy
U	mean absolute jet velocity = $U_\infty + U_{eg}$
U_{eg}	local mean excess jet velocity
U_o	initial excess jet velocity on the jet centerline
U_m	mean excess jet velocity on the jet centerline
U_∞	co-flow velocity
u_α	entrainment velocity
u	local excess jet velocity
u_{eddy}	characteristic velocity of the eddy
u'	turbulent intensity of the jet = $rms\ (u - U_{eg})$
u'_∞	background turbulent intensity
v', w'	turbulent intensity in y and z direction
x	horizontal distance downstream from jet outlet
y	horizontal distance from jet centerline
ν	kinematic viscosity of water

LIST OF FIGURES

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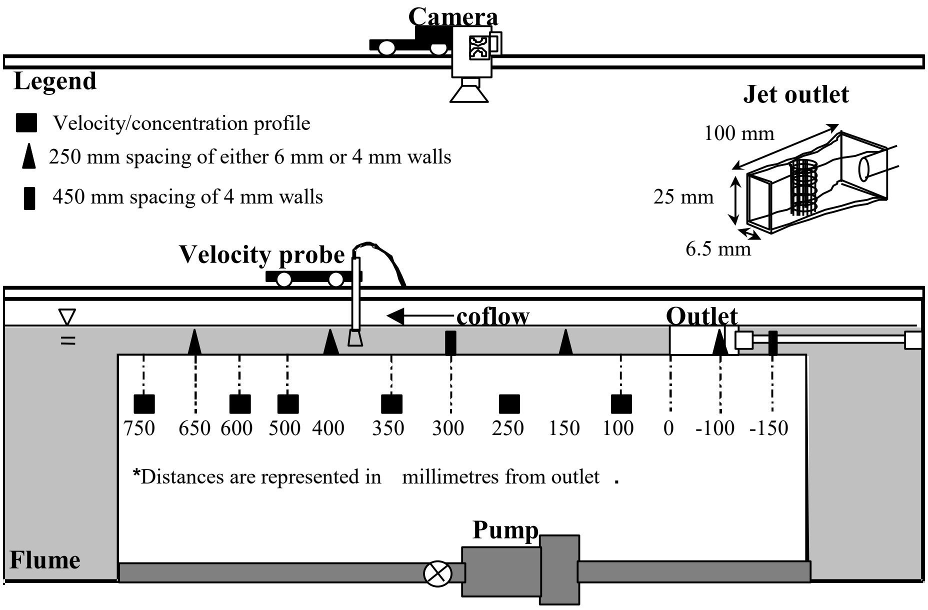

Figure 1. Experimental setup including the location of turbulence walls and data profiles.

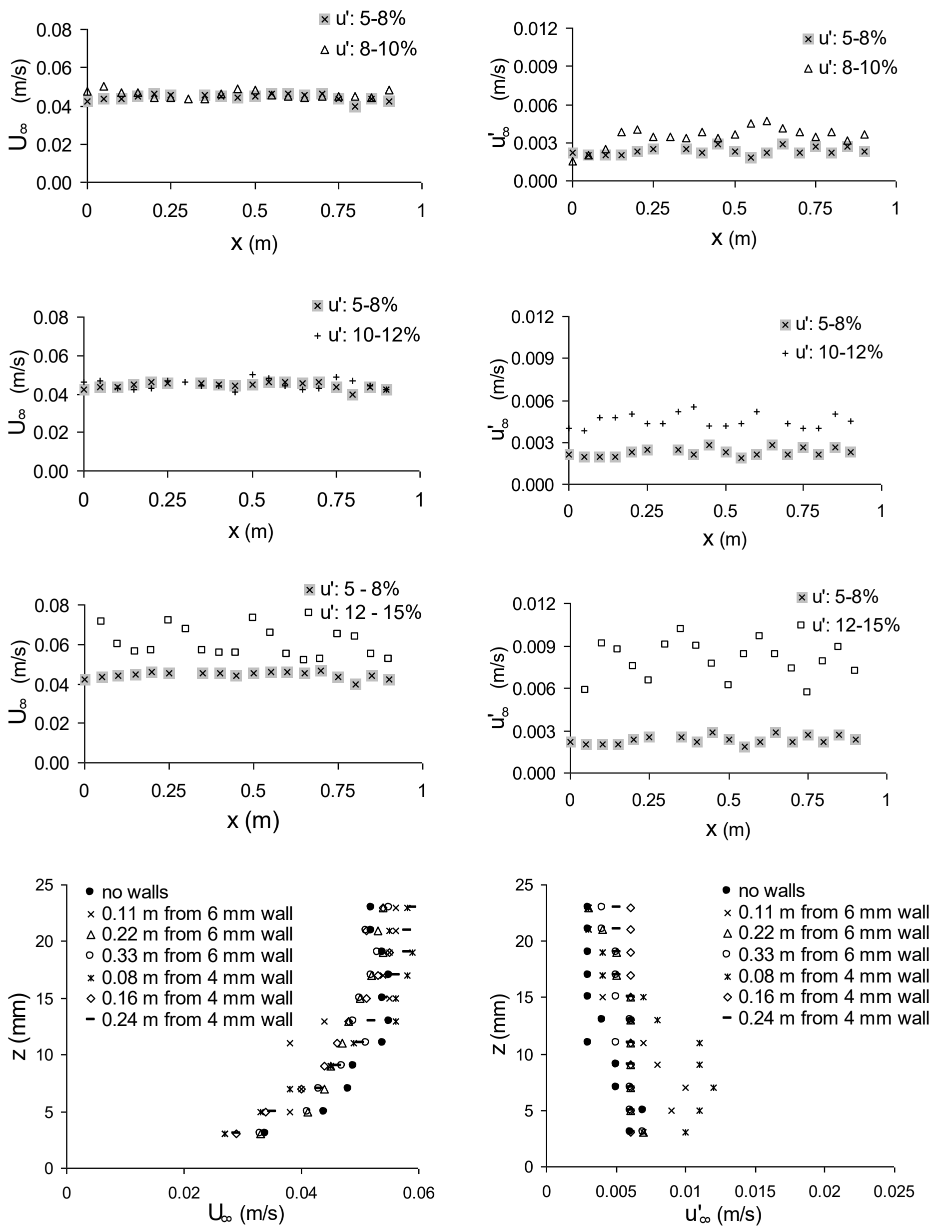

Figure 2. Co-flow characteristics: mean velocity and turbulent intensity resulting from the placement of 4 mm and 6 mm high walls compared to the 'no wall' open channel turbulence where u′ = 5-8%.

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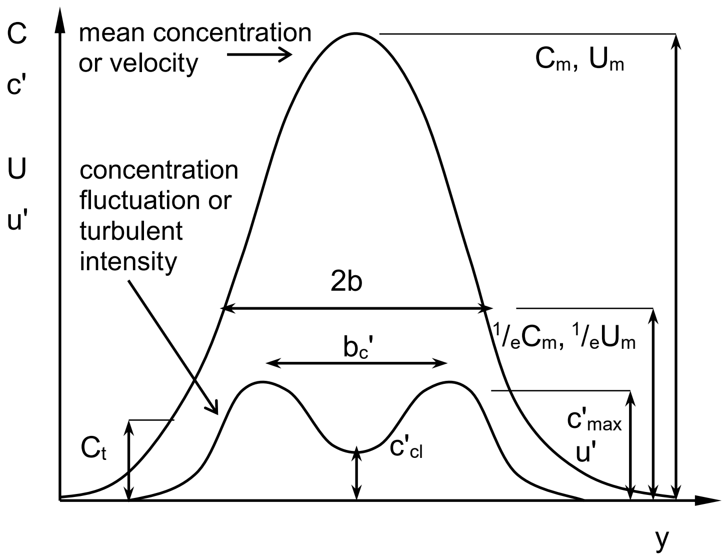

Figure 3. Definition of jet variables.

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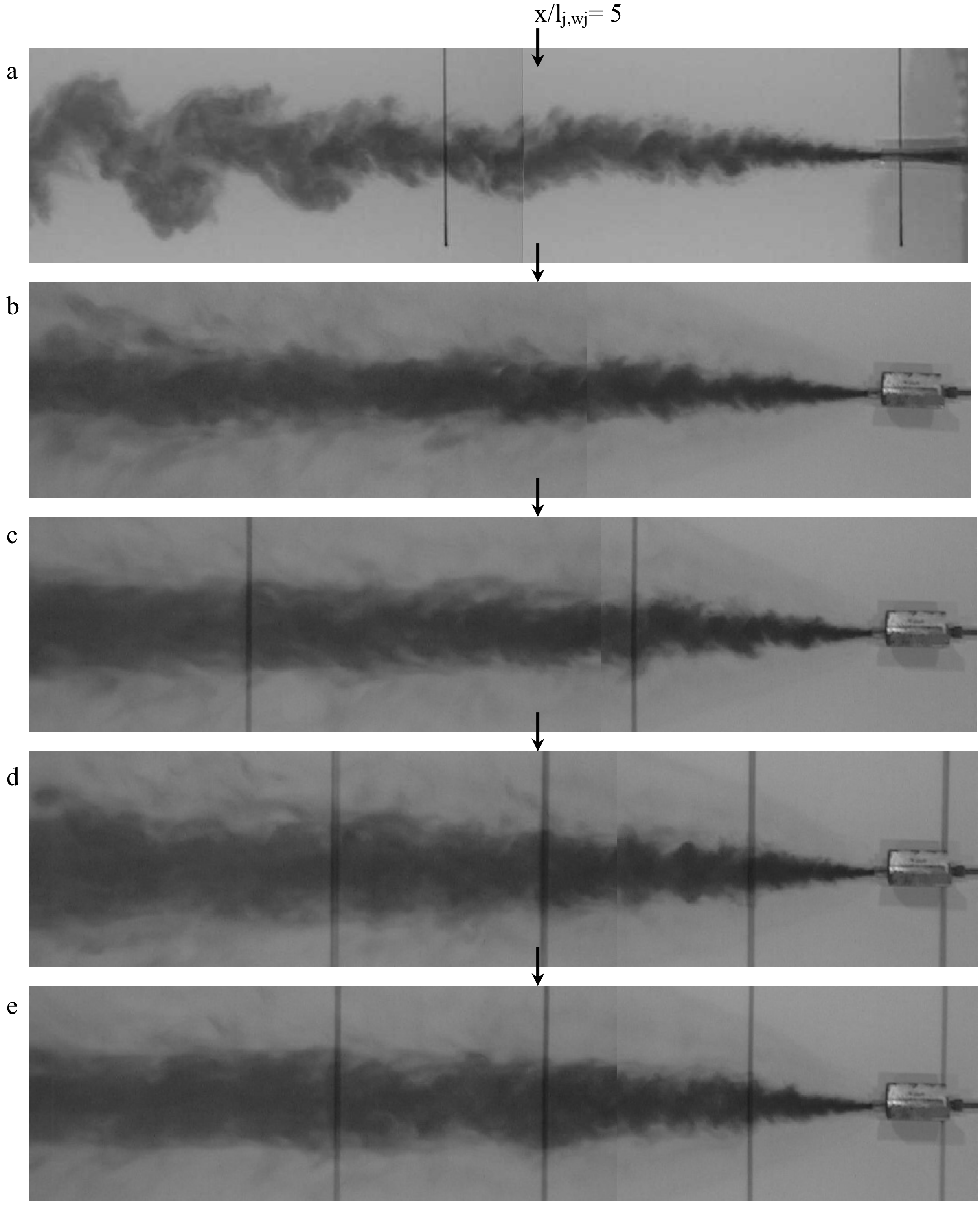
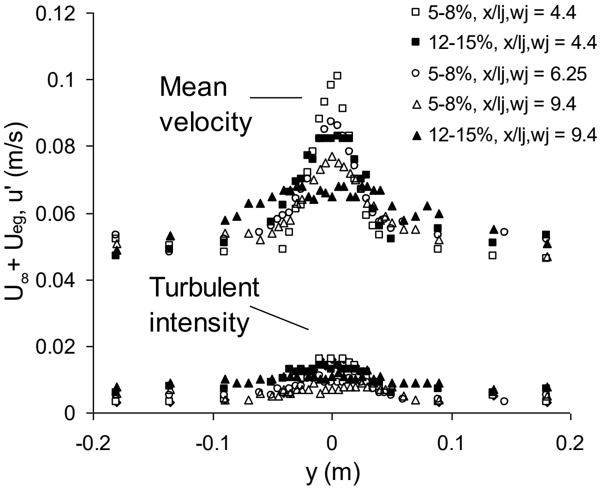


Figure 4. The plane jet released into a co-flow with a turbulence intensity of a) 0% (towed jet), b) 5 – 8%, c) 8 – 10 %, d) 10 – 12 % and e) 12 – 15%.



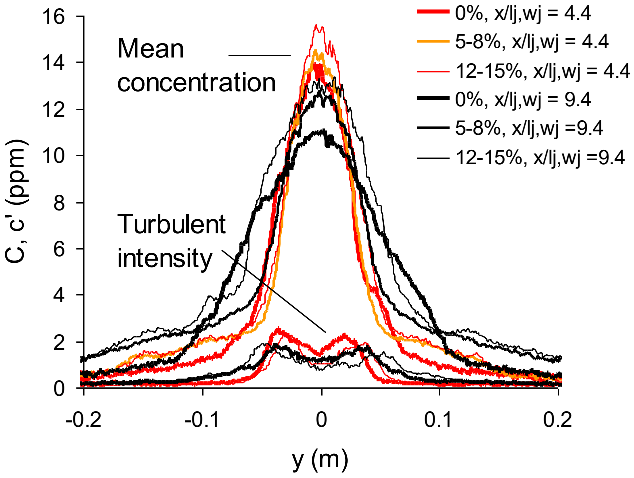
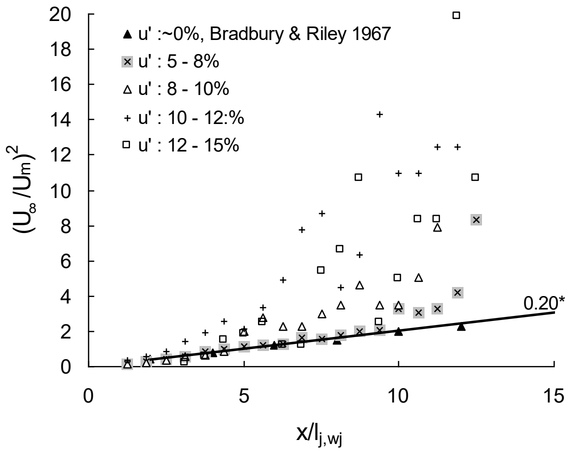


Figure 5. Profiles of the mean and fluctuating components of the velocity and concentration of the plane jet in a shallow coflow.



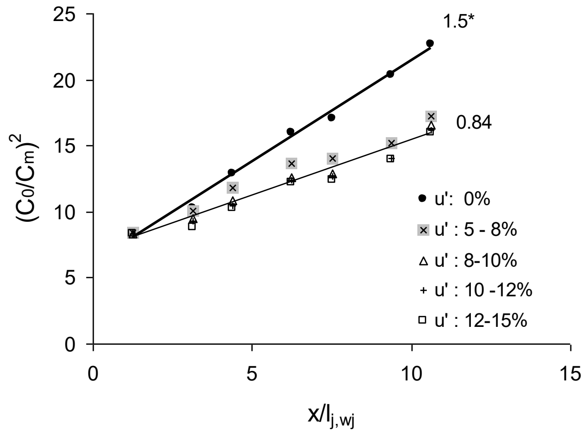


Figure 6. Mean centerline velocity and concentration decay of the plane jet in a shallow coflow.

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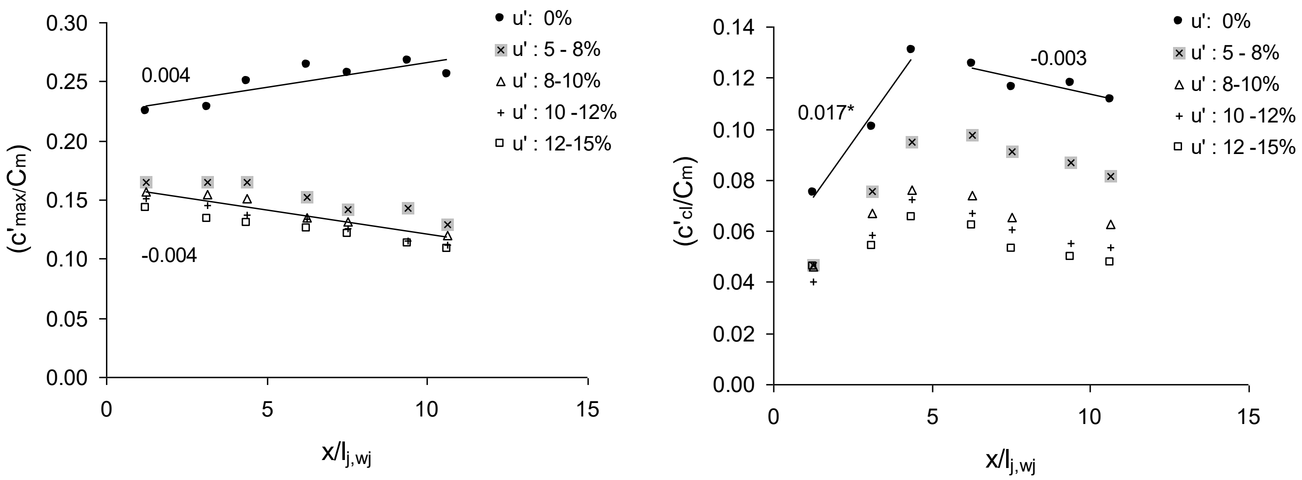

Figure 7. Fluctuations in the concentration, maximum and centerline values, of the plane jet in a shallow coflow.

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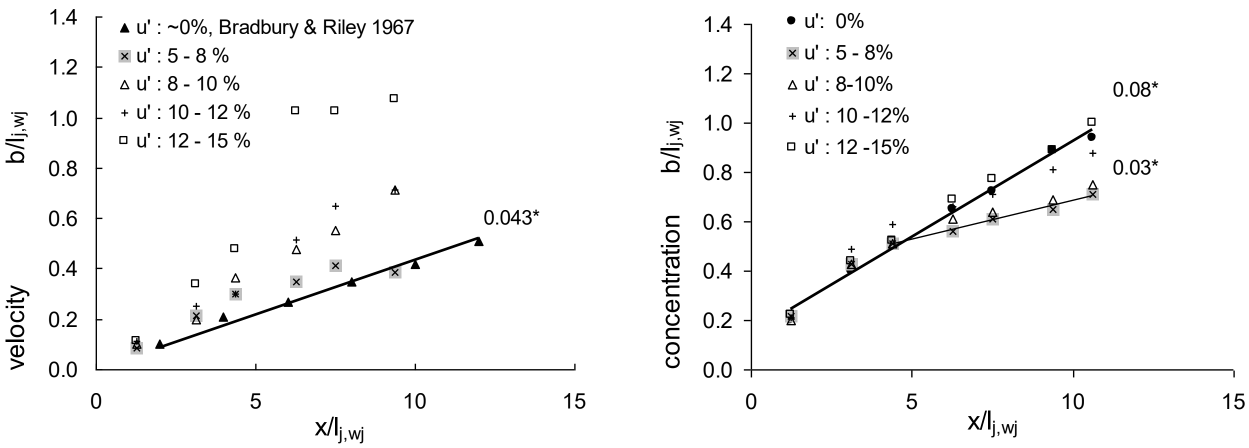

Figure 8. Velocity and concentration width growth of the plane jet in a shallow coflow.

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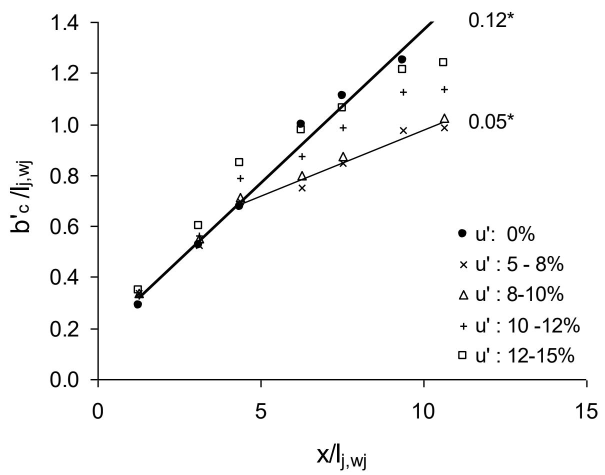

Figure 9. Width, b'_c, defined by the distance between concentration fluctuation peaks of the plane jet in a shallow coflow.

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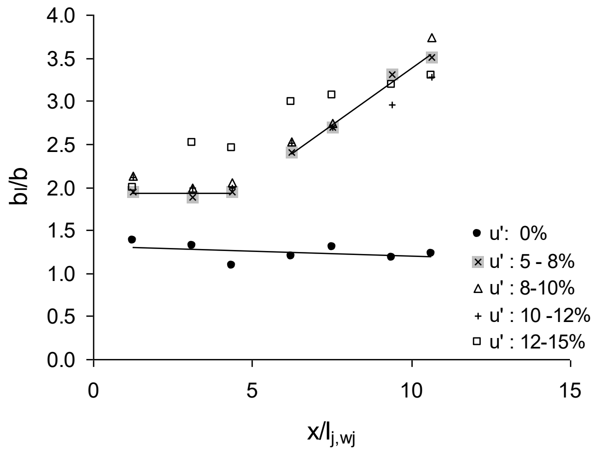

Figure 10. *b_I/b*, ratio of the intermittency width to the concentration half width of the plane jet in a shallow coflow.