CHAPTER 335

Enhanced Mixing Through Perforated Discs on Round Buoyant Jet

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Abstract

Jets have been widely used in submarine outfall diffuser systems for discharging the sewage effluents into large bodies of sea water to facilitate rapid mixing of the effluent with the ambient water. The primary goal of an outfall diffuser system is to accomplish rapid mixing of the effluent with the ambient water. In an effort to enhance the near field mixing, various obstruction devices may be placed exterior to the diffuser nozzle. This experimental study focuses on the enhanced mixing mechanisms of the jets obstructed with perforated discs.

Experiments are conducted in a deep water tank with glass walls on four sides of the tank. The tank has the dimension of 3.35 m in depth with a square cross-section of 1.15 m. The water particle velocities of the resulting flow field are measured by using a portable four-beam, two-component, fiber-optic Laser-Doppler Velocimeter system (LDV). The concentration of the entrained fluid is measured by using a Laser-Induced Fluorescence system (LIF). The data acquisition system used for obtaining data on the concentration profiles is processed by Labview's programmable virtual instruments software.

The experimental data consist of the axial (vertical) and radial (horizontal) velocities, turbulent intensities, Reynolds stresses and concentrations. It is found that velocity fluctuations in both the axial and radial velocities help to generate vorticity and to induce mixings over a larger area in the neighboring flow region. Moreover, the velocity gradient is significantly increased over the region based on the experimental data involving the perforated discs. The results also show that a large reduction in the concentration of the entrained fluid can be achieved due to the

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obstructing disc. The results demonstrate quite convincingly the ability of the perforated disc to enhance the mixing and entrainment of the discharging fluid with the ambient fluid.

1.0 Introduction

For the removal of municipal sewage, treated or untreated waste water must be disposed of in such a way that will generate minimal effects to the environment. An ocean discharging system is commonly used to discharge sewage effluents into coastal water and to induce mixing of the effluent with the sea water. The systems are generally comprised of embedded pipes, the main outfall, which delivers the waste water to a diffuser system. The length of the main outfall pipes normally range from 1 km to 9 km, depending upon the sea bed topography, ocean currents and environmental requirements.

There are three major factors that affect the mixing of effluent (Fischer et al. 1979). They are: jet parameters, environmental parameters and geometrical factors of the discharging jet. Both the jet parameters and the environmental parameters have been studied extensively in the last four decades. Geometrical factor is an interesting field for the scientists and engineers to study because better geometrical arrangements may result in greater dilution. Increasing dilution in an ocean discharging system would produce significant saving in the construction costs by reducing needed mixing height of the rising plume.

The present experimental investigation includes measurements of axial and radial velocity, turbulent intensity, turbulent shear stress and concentration profiles. The purpose of the measurements is to accurately measure various flow parameters in the flow field of the jets obstructed with perforated disc to provide an answer to the important question posed for the study.

2.0 Experiments

Experiments were performed in a deep water tank system with vertical glass face. The water tank has the dimensions of 335 cm high, 115 cm wide and 115 cm deep. The facilities also included a mixing tank, a constant-head tank, air bubbling hose and a manometer (flow meter). The mixing tank provides a space for adding dye or salt into effluent fluid. The constant-head tank is used for maintaining a steady flow for the effluent fluid, while the air bubbles provide enhance mixing in both the mixing tank and the glass water tank before conducting experiments. Fluid velocity and Rhodamine 6 G dye concentration can be measured by a Laser Doppler Velocimeter (LDV) and a Laser-Induced Fluorescence system (LIF), respectively. For measuring purposes, this glass walled tank is equipped with an instrument carriage supporting a Laser Doppler Velocimeter or a Laser-Induced Fluorescence device. The carriage is able to move both vertically and horizontally with respect to the tank, thus velocities and concentrations could be measured at various axial and radial locations. The jet nozzle is located on the top of the tank and pointing down. The density of the exit fluid from the jet nozzle is greater (heavier) than that of ambient fluid. Sodium Chloride (salt) is added into the exit fluid to obtain the desired initial density difference between exit fluid and ambient fluid.

A portable four-beam, two component, fiber optic Laser Doppler Velocimeter (LDV) manufactured by TSI, Inc. was used for measuring the water particle velocities. The software of data acquisition for controlling the LDV system, *Flow Information Display (FIND) Data Analysis Package* from TSI, Inc. was used. The concentration is measured by a laser-induced fluorescence system (LIF) at various cross sections downstream from the jet nozzle. This system includes a 2W Argon-Ion laser (Spectra Physics Model 265), a CCD camera (EG&G Reticon LC300A), an analog input/output data acquisition board (National Instrument, AT-MIO-16X) and data acquisition program (Labview). The laser beam is oriented in the direction perpendicular to the centerline of the flow, and it is shot into the water tank across the entire flow field from one side of the tank. A line fluorescence light source is then detected by an array of light-sensitive photo diodes inside the EG&G Reticon LC300A camera. The data acquisition system receives signals from the camera and converts the analog signals to digital data. The data for the concentration profile is processed by Labview's virtual instruments software.

3.0 Results and Discussion

3.1 Velocity Profile and Width of Simple Jets

The results of the velocity measurement conducted for the present work are in agreement with those of Fischer et al (1979) and Papanicolaou and List (1988). This agreement ensures that the instrumentation system used for the present study can yield reliable results. Thus, comparisons can be made between the results conducted for simple jets and for jets obstructed with perforated disc.

Figure 1 shows the normalized diagram by combining all of the velocity profiles of the simple jets into one figure. Data distribution in Figure 1 is a Gaussian distribution. The jet has U_{mean}/U_c value in the range of $| r/z | < 0.2$, beyond this range the U_{mean}/U_c values tend to zero. The normalized diagrams for representing the results of jet obstructed with each perforated disc are presented in Figures 2. Most values of U_{mean}/U_c of each obstructed case are located in between $| r/z | < 0.4$. After comparing the results of velocity profiles for the case of simple jets and the cases of jets obstructed with perforated discs, conclusions can be drawn as follows: (1) For the jets obstructed with different perforated discs compared with the simple jet (Figures 3), the axial (longitudinal) velocity distributions of the jets with perforated disc have more fluctuations exhibited in each profile. (2) The cases of the jets obstructed with perforated disc have larger plume width on each cross section. (3) For jets obstructed with various perforated disc, the axial velocity distributions are more uniform and broader when compared with the case of simple jets. (4) The centerline velocities of the jets obstructed with perforated disc have relatively smaller value with compared with simple jets.

3.2 Turbulence Properties

The axial (vertical) and radial (horizontal) turbulent intensities have been measured simultaneously by LDV for both simple jets and jets obstructed with perforated discs. After comparing the results on the turbulent intensity (both axial and radial) for both simple jets and jets obstructed with perforated discs, general conclusions can be made as follows: (1) Simple jets have larger fluctuations of the axial velocity around the boundary of jet. In the outer region of the cross section (beyond the boundary of the plume width), the percentages of axial turbulent fluctuation of jets with each perforated disc are much greater than those of the simple jets. This shows that jets obstructed with perforated discs can produce more turbulent fluctuation of axial velocity than the simple jets in the outer region of the cross section. (2) The distributions of turbulent fluctuations in the axial and radial component for the jets obstructed with perforated discs are much more uniform and much broader than those of simple jets. (3) The jet obstructed with the 2x8 perforated disc has an overall higher U'_{rms}/U_c value than those for other disc arrangements. (4) The percentages of radial turbulent fluctuation of jet obstructed with perforated disc have higher values than those of simple jets at all of the cross sections within the region of the jet width. Moreover, the overall percentages of radial turbulent fluctuation of jets obstructed with perforated discs are higher than those of simple jets in the region beyond the boundary of the jet for each cross section. This shows that the jets obstructed with perforated discs have higher radial (horizontal) turbulent fluctuation than simple jets beyond the boundary region.

The results from the measurement of turbulent intensity indicate that the jets obstructed with perforated discs will enlarge the region of turbulent fluctuation and resulting in more interaction between ambient and effluent fluid. This also supports the experimental hypothesis that using the perforated discs to obstruct the jets will result in larger areas of axial and radial fluctuations in the flow field.

3.3 Reynolds Stress

The shear layer between the effluent fluid and the ambient fluid was proved by Fischer et al (1979) as an important factor to entrain the ambient fluid into effluent fluid and to induce mixing of both fluids. The Reynolds stress ($\overline{U'V'}$ or turbulent shear stress) measurements were conducted for both simple jets and jets obstructed with perforated discs. Experimental results have been presented in Figure 4 for the simple jets and in Figure 5 for the jets obstructed with perforated discs. Comparisons between the results of simple jets and jets obstructed, can lead to the following conclusions: (1) Fluctuations can be observed on the $\overline{U'V'}$ profiles of the jets obstructed with perforated discs. This is because the effluent fluid flows through the perforated disc (or holes on the disc) and generates many small vortices inside the boundary of the jets. Thus, it creates a larger area of shear layer and induces more entrainments for the entire flow field. (2) Results show that the jets obstructed with perforated discs have higher value of $\overline{U'V'}$ at the region outside of the jets' boundary, and this is the advantage of using the obstructed perforated discs to broaden the extents of the velocity field and the velocity fluctuation. A broader mixing area is created by the obstructing perforated discs, Thus, mixing is enhanced by a broader region possessing certain value of turbulent shear stress.

3.4 Concentrations and Dilutions

The concentration measurements were conducted and included in the present study. The simple jets' maximum concentrations obtained for the present work are in agreement with the previous studies such as Fischer et al. (1979) and Papanicolaou (1984). The widths of concentration profiles of the simple jets measured in the present study are also in agreement with those of Papanicolaou and List (1988).

After comparing the results of concentration measurements for both simple jets and jets obstructed with perforated discs, conclusions can be made as follows: (1) the results of the simple jets are similar to that reported by Fischer et al. (1979) and Papanicolaou and List (1988), (2) the maximum concentration for the cases of the jets obstructed with perforated discs are quite smaller than those of the simple jets, and (3) the concentration widths (b_c) for the jets obstructed with perforated discs are broader than those of the simple jets.

The calculations for the mean dilution achieved for the simple jets and for jets with perforated discs also were performed. The results indicate that (1) the C_{max}/C_{ave} ratios of the simple jets are in the range of 1.315~1.592, this result is in agreement with that summarized by Fischer et al. (1979) which is 1.4 $\pm$ 0.1, (2) for the jets obstructed with perforated discs, the mean dilution is higher than that of the simple jets, (3) the values of mean dilution reflect that both $\frac{\mu}{Q_O}$ (from velocity measurements) and C_{max} (observed from concentration measurement) are in consistant trends, (4) the C_{max}/C_{ave} ratios of the jets obstructed with perforated discs are in the range of 1.052 to 1.369, (5) the μ/Q (mean dilution) versus z/l_Q (normalized distance) of the simple jets and the jets obstructed with perforated discs have been plotted in Figures 6. They show that the jets obstructed with perforated discs have a higher mean dilution than that of the simple jets for a given z/l_Q. Another measure of the effectiveness of enhanced mixing is to compare the maximum dilution for both the case of simple jet and that for jet obstructed with perforated disc. This is shown in Figures 7. It is found that there is a significant increase of the maximum dilution with perforated disc.

4.0 Conclusions

The results of the present work proved that the jets obstructed with perforated discs have wider profiles of velocity, turbulent intensity, turbulent shear stress and concentration than the simple jets. The normalized diagrams from the experimental results also indicate that the data distributions of the jets obstructed with perforated discs are flatter and broader than those of simple jets in the fields of velocity, turbulent intensity, turbulent shear stress and concentration. All of this provides evidence that jets obstructed by perforated discs have larger areas for mixing than those of the simple jets.

It is clear from the concentration measurements that for the jets obstructed with perforated discs, the concentration of the entrained fluid is greatly reduced and that the region for mixing is significantly enlarged. The results from the calculation of mean dilution and maximum dilution also indicate that the jets with perforated discs can produce significantly increased dilutions when compared with simple jets. The overall experimental results demonstrate quite convincingly the ability of the perforated disc to enhance the mixing and entrainment of the discharging fluid with the ambient fluid.

Acknowledgment

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References

1. Chen, C. J. and Rodi, W. (1978), Vertical Turbulent Buoyant Jets - A review of Experimental Data. *HMT Vol. 4, Pergamon Press*, 83 pp.

2. Fan, L. N. (1967), Turbulent Buoyant Jets into Stratified or Flowing Ambient Fluids, *Report No. KH-R-15, W.M. Keck Laboratory of Hydraulics and Water Resources*, California Institute of Technology.

3. Fan, L. N.; Brooks, N. H. (1969), Numerical Solution of Turbulent Buoyant Jet Problems, *Report No. KH-R-18, W.M. Keck Laboratory of Hydraulics and Water Resources*, California Institute of Technology.

4. Fischer, H. B.; List, E. J.; Koh, R.C.Y.; Imberger, J.; and Brooks, N. H. (1979), Mixing in Inland and Coastal Waters, *Academic Press*, New York, N. Y., 483 pp.

5. Hannoum, I. A. and List, E. J. (1988) Turbulent mixing at a shear free density interface. *J. Fluid Mechanics*, 189, 211-34.

6. Koh, R. C. Y. and Brooks, N. H. (1975), Fluid mechanics of wastewater disposal in the ocean. *Ann. Rev. Fluid Mech.*, 7, 187-22.

7. Noutsopoulos, G. C. and Demetriou, J. (1980), The round vertical turbulent buoyant jet impinging on a concentric disc, *Progress Water Technology*, 13, 305-314.

8. Noutsopoulos, G. C. and Yannopoulos, P. C. (1989), Axial dilution in obstructed round buoyant jet. *J. of Hydraulic Engineering*, Vol. 115, No. 1, Jan., 1989. 71-81.

9. Papanicolaou, P. N. and List, E. J. (1987), Statistical and spectral properties of tracer concentration in round buoyant jets. *Int. J. Heat Mass Transfer*, Vol. 30, No. 10, 2059-2071.

10. Papanicolaou, P. N. and List, E. J. (1988), Investigations of round vertical turbulent buoyant jets. *J. Fluid Mech.*, Vol. 195, 341-391.

11. Wallace, R. B. and Wright, S. J. (1984), Spreading layer of two-dimensional buoyant jet, *J. Hydraulic Engineering*, Vol. 110, No. 6, June 1984. 813-828.

12. Wu, Lilun (1996), Enhanced mixing through perforated disc on round bouyant jet, Ph.D Thesis University of Southern California, Los Angeles, CA

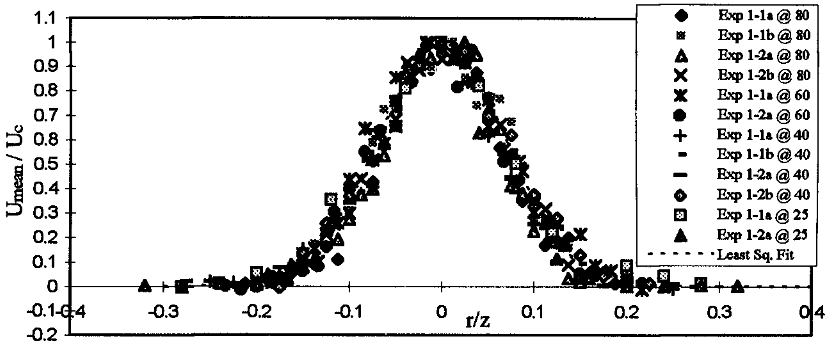

Figure 1 Non-dimensional Mean Axial Velocity Profile for Jets Plotted Against Non-dimensional Distance from Jet Axis, z/D $\geq$ 50

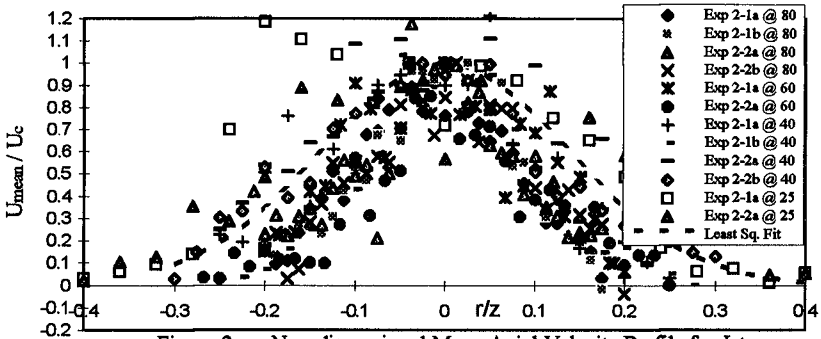

Figure 2a Non-dimensional Mean Axial Velocity Profile for Jet Obstructed with Perforated Disc (2x2) Plotted Against Non-dimensional Distance from Jet Axis, z/D > 50

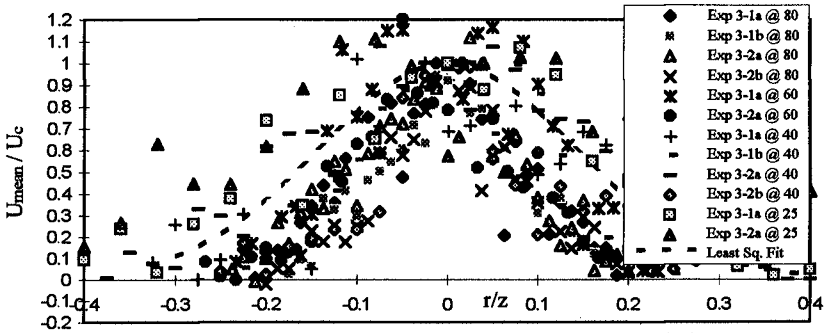

Figure 2b Non-dimensional Mean Axial Velocity Profile for Jet Obstructed with Perforated Disc (2x8) Plotted Against Non-dimensional Distance from Jet Axis, z/D > 50

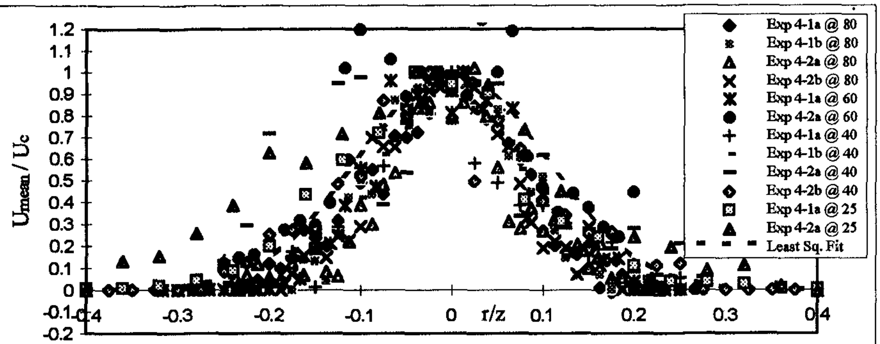

Figure 2c Non-dimensional Mean Axial Velocity Profile for Jet Obstructed with Perforated Disc (B2x8) Plotted Against Non-dimensional Distance from Jet Axis, z/D > 50

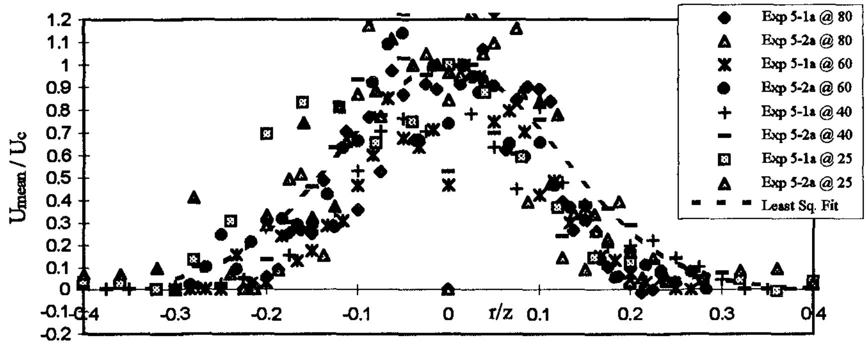

Figure 2d Non-dimensional Mean Axial Velocity Profile for Jet Obstructed with Perforated Disc (323) Plotted Against Non-dimensional Distance from Jet Axis, z/D > 50

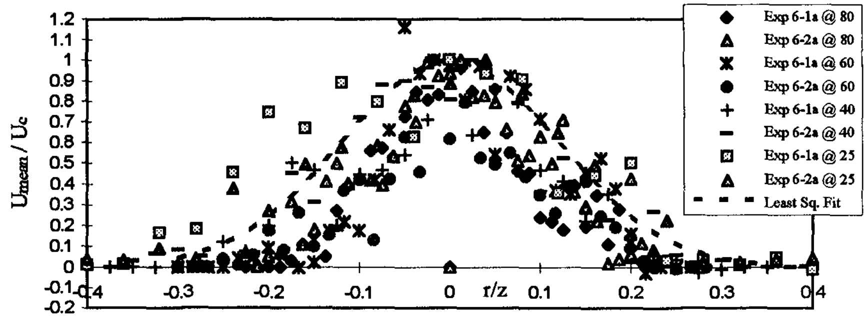

Figure 2e Non-dimensional Mean Axial Velocity Profile for Jet Obstructed with Perforated Disc (4+1) Plotted Against Non-dimensional Distance from Jet Axis, z/D > 50

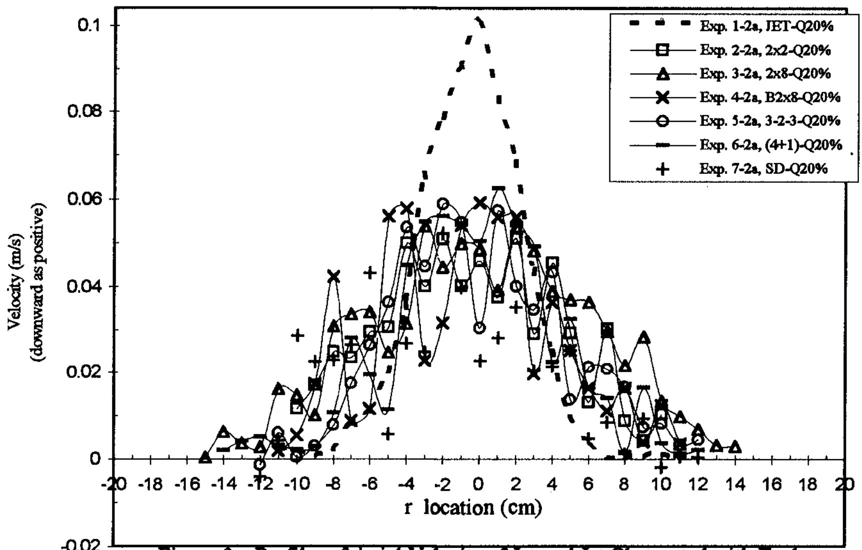

Figure 3a Profiles of Axial Velocity of Jet and Jet Obstructed with Each Perforated Disc at z=40 cm for Q=24.72 cm^3/s

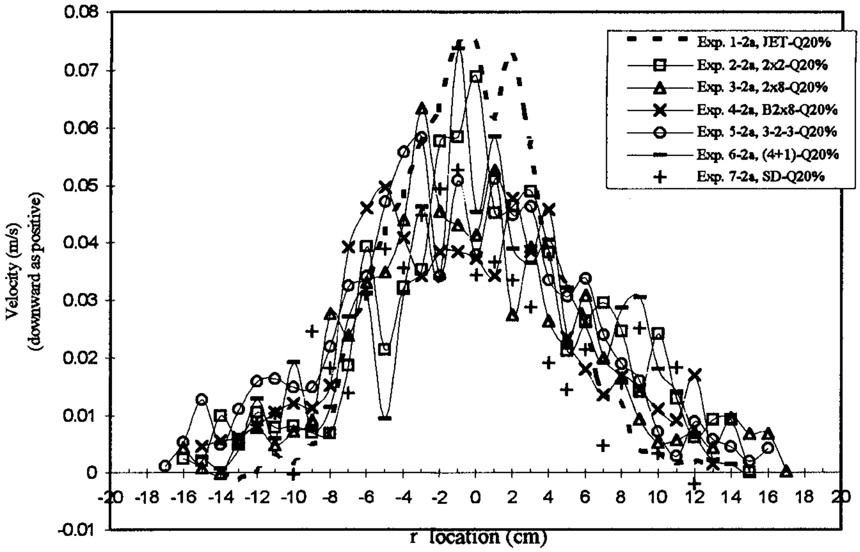

Figure 3b Profiles of Axial Velocity of Jet and Jet Obstructed with Each Perforated Disc at z=60 cm for Q=24.72 cm^3/s

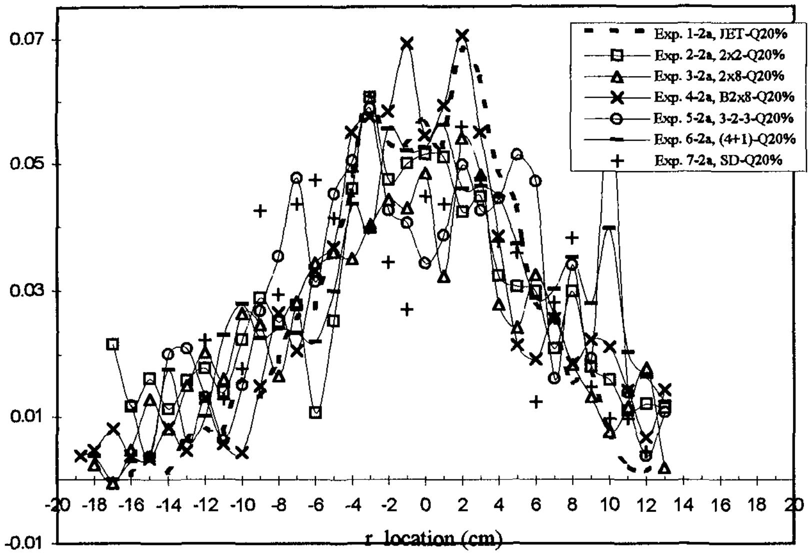

Figure 3c Profiles of Axial Velocity of Jet and Jet Obstructed with Each Perforated Disc at z=80 cm for Q=24.72 cm^3/s

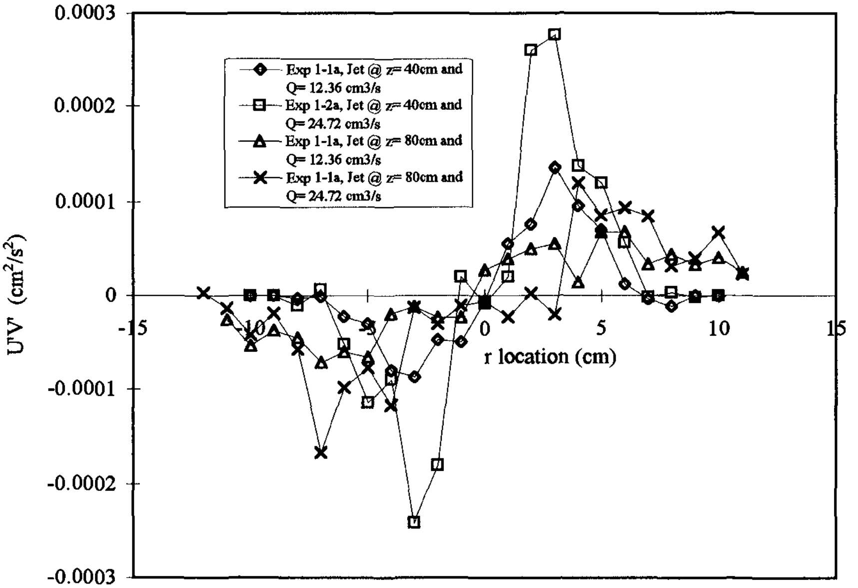

Figure 4 Profiles of Reynolds Stresses (Turbulent Shear Stress) of the Simple Jet

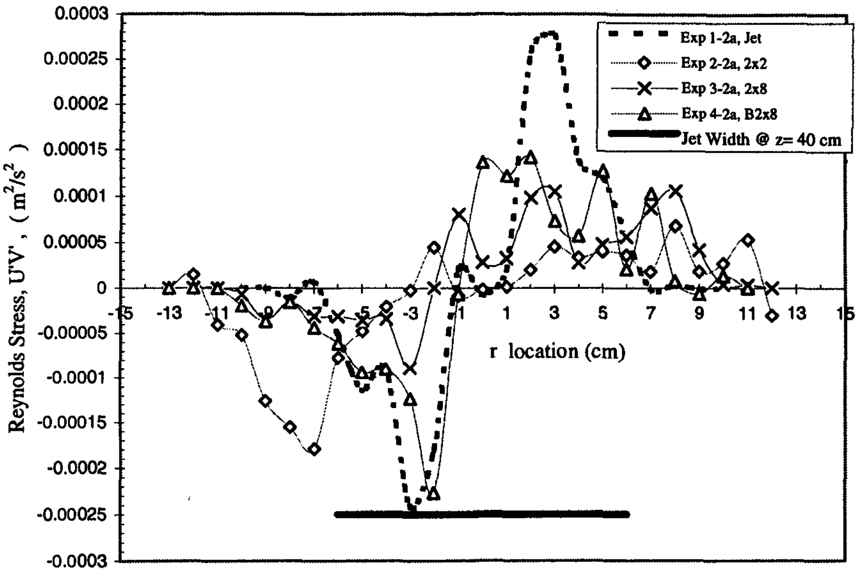

Figure 5a Profiles of Reynolds Stresses (Turbulent Shear Stress) at z=40 cm for Q=24.72 cm^3/s

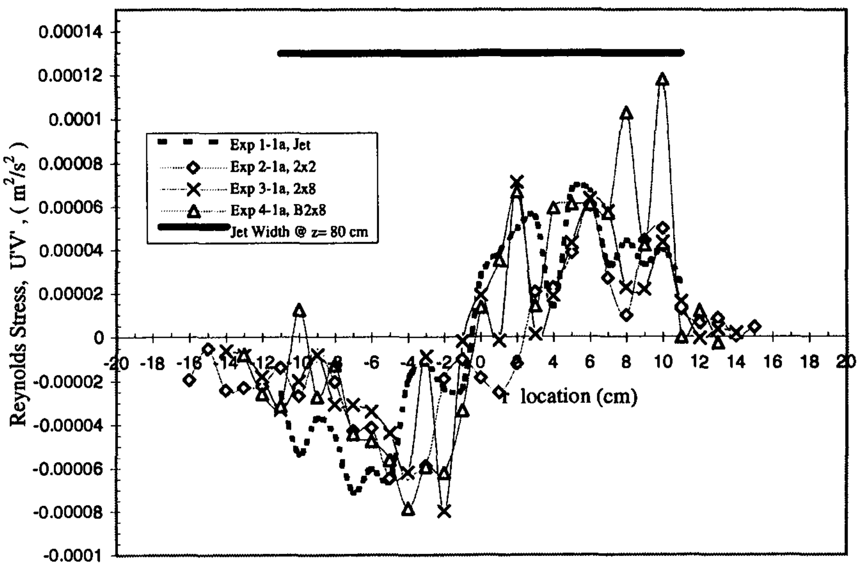

Figure 5b Profiles of Reynolds Stresses (Turbulent Shear Stress) at z=80 cm for O=24.72 cm^3/s

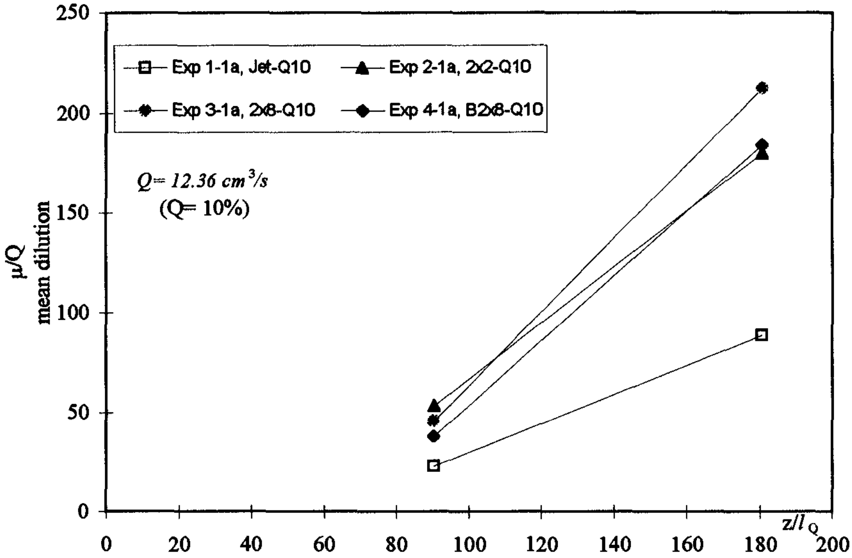

Figure 6a Mean Dilution as a Function of Distance along the axis for Q=12.36 cm^3/s

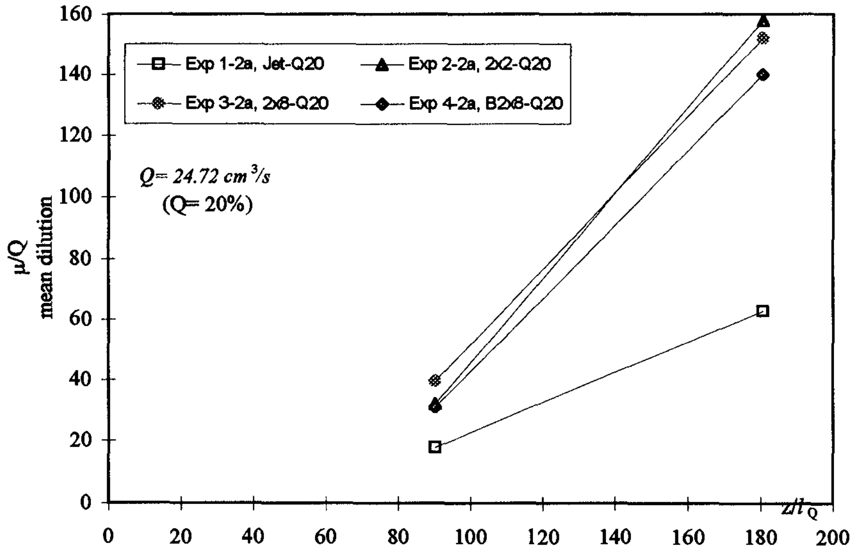

Figure 6b Mean Dilution as a Function of Distance along the axis for Q=24.72 cm^3/s

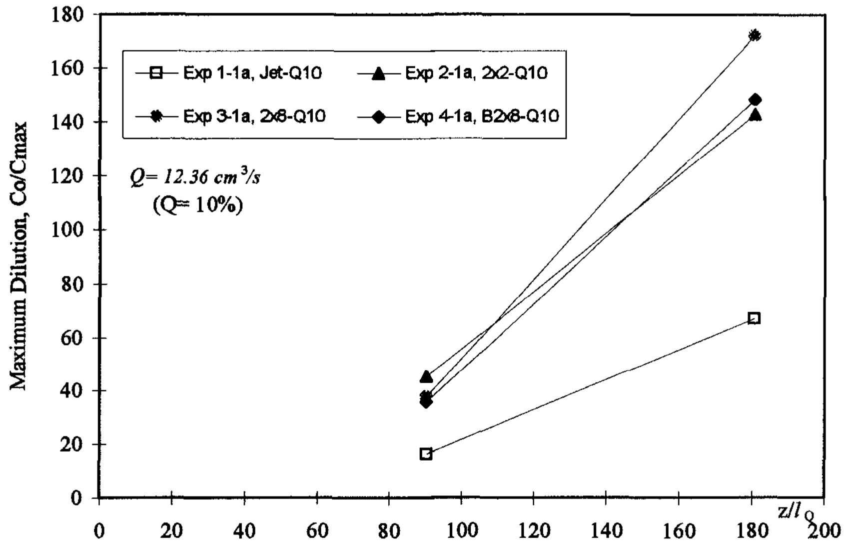

Figure 7a Maximum Dilution as a Function of Distance along the axis for Q=12.36 cm^3/s

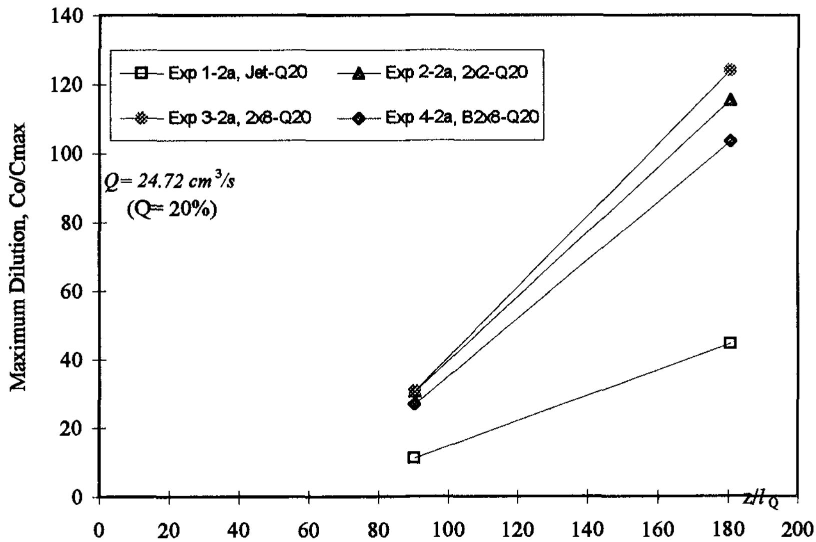

Figure 7b Maximum Dilution as a Function of Distance along the axis for Q=24.72 cm^3/s