Mixing with multiple circular turbulent jets

Mélange de plusieurs jets circulaires turbulents

AHMED K. MOAWAD, *Research Associate, Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada, T6G 2G7*

N. RAJARATNAM, *Professor, Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada, T6G 2G7*

S. J. STANLEY, *Associate Professor, Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada, T6G 2G7*

ABSTRACT

This paper presents the results of a laboratory study investigating chemical mixing in an open channel with multiple circular turbulent jets. The experiments were carried out for α, which is the ratio of the velocity of the jets to that of the crossflow, varying from 8 to 16, with a combination of coflowing and crossflowing jets and only crossflowing jets. The number of ports for the jets was varied for 20 to 36 and the spacing between the ports was varied from 12d to 24d where d is the diameter of the ports. Concentration measurements covered the relative distance x/d=2000, where x is the longitudinal distance from the diffuser. The dimensionless mixing distance $\alpha xm/d$ at which the standard deviation of the concentration field reached a value of 5% was equal to 25000 where x_m is the mixing distance. The results indicate that a diffuser with turbulent crossflowing jets could be an alternative to mechanical methods for achieving mixing of chemicals in open channels in water treatment plants.

RÉSUMÉ

Cet article présente les résultats d'une étude en laboratoire sur le mélange chimique de plusieurs jets circulaires turbulents dans un canal à surface libre. Les expériences ont été réalisées pour á (rapport de la vitesse des jets à celle de l'écoulement transverse) variant entre 8 et 16, avec une combinaison de jets co-courants et transverses, et de jets uniquement transverses. Le nombre d'orifices pour les jets variait de 20 à 36 et l'espace entre les orifices était de 12d à 24d, d étant le diamètre des orifices. Les mesures de concentration couvraient une distance relative x/d = 2000, x étant la distance longitudinale à partir du diffuseur. La distance adimensionnelle de mélange áx_m/d à laquelle l'écart type du champ de concentration atteint une valeur de 5% était égale à 25000, x_m étant la distance de mélange. Les résultats montrent qu'un diffuseur composé de jets turbulents transversaux pourrait être une alternative aux méthodes mécaniques pour le mélange des produits chimiques dans les canaux à surface libre des usines de traitement des eaux.

Introduction

In most water and wastewater treatment plants, mixing is a part of chemical or biological water treatment process. The mixing system should provide a complete homogenization of the added chemicals with the plant influent stream. This type of mixing is required in the disinfection (chlorination) processes, addition of fluoride as well as other processes which require addition of chemicals. Without adequate mixing, localized regions of high concentrations of the added chemical might exist which is generally undesirable. Mixing of liquids can be accomplished using conventional methods which include chambers equipped with rotary mixing devices such as impellers, fixed blades in pipe lines, hydraulic jumps and others. In water treatment plants, open channels are commonly used for conveyance. In this paper, turbulent jet mixing in an open channel is suggested as an alternative to mechanical mixing. Mixing was accomplished by installing a diffuser discharging an array of jets perpendicular to the flow (crossflowing jets) along with coflowing jets. Jets in crossflow have been used previously to provide mixing in pipes (Ger and Holley 1976; Chao and Stone 1979; Fitzgerald and Holley 1981). Benzina et al. (1974) have reported that the use of counterjet injection, combined with the effects of hydraulic blockage, could produce thorough mixing in open channels. The optimum mixing distance was defined as the distance to a section where the variation of the concentration over the cross-section was within some specified value.

This study investigates the viability of using turbulent jets in achieving rapid mixing. Several jets with different α values were studied where α is the ratio of the velocity of the jets to that of the crossflow in the channel. The effect of spacing and the number of jets on the optimum mixing distance and on the minimum dilution was investigated. The results from this preliminary study are believed to be useful in the design of an efficient mixing system which can be implemented by water treatment plants as an alternative to mechanical mixing.

Background: Jets in crossflows

Turbulent jets in crossflows have been investigated extensively (See Rajaratnam 1976 and Wright 1977 for a list of references). Wright divided the flow in the deflected jet into two main regions, referred to as the momentum dominated near field (MDNF) and the momentum dominated far field (MDFF). The MDFF is followed by a passive plume region (PPR) where the mixing and the resulting dilution is due to the turbulence in the ambient flow. The transition from the MDFF to the PPR was assumed (Rajaratnam and Langat 1995) to occur where the excess velocity in the jet above that of the crossflow velocity U falls to about 1% of (U_o-U) where U_o is the velocity of the jet at the nozzle.

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The dilution produced by a circular jet in crossflows in the mixing region, defined as the region in which significant dilution occurs because of jet mixing, was investigated by Hodgson and Rajaratnam (1992). In this mixing region, using the concept of the MDNF and MDFF and experimental observations, $\alpha x/d$ was found to be a characteristic dimensionless distance (Hodgson and Rajaratnam 1992) and the minimum dilution defined as C_0 / C_m was given by the equation :

$$\frac{C_0}{C_m} = 1.09[\frac{\alpha x}{d}]^{0.56} \tag{1}$$

where C_o is the concentration at the nozzle, C_m is the maximum concentration at any downstream section and x is the downstream distance along the crossflow from the nozzle producing the jet of diameter d. For a diffuser with multiple jets in crossflow, it is possible that the minimum dilution would increase rapidly with the downstream distance. Mixing would be affected by the momentum fluxes and the interaction between the different jets and with the ambient current. It is very likely that all the three regions (MDNF, MDFF and PPR) would exist.

General considerations

When multiple jets are discharged into confined crossflows as in an open channel, the maximum value for the minimum dilution C_o/C_m attained would not exceed the value of the ratio of C_o to C_i where C_i represents the concentration at a fully mixed section. In the presence of a background concentration (C_b) in the crossflow and since the values of C_0/C_m are always referred to this concentration, the maximum dilution value attained would not exceed the value of C_o / C_i' where $C_i'=C_i-C_b$. The value of C_i can be determined from the mass balance equation:

$$C_i = \frac{C_0Q_0 + C_bQa}{Q_0 + Q_a} \tag{2}$$

where Q_o is the total discharge from the nozzles and Q_a is the ambient crossflow discharge. From Eq. 2, it can seen that for a fully mixed section with $Q_o<<Q_a$ and $C_b<<C_o$ the value of C_o/ C_i' depends mainly on the values of the ambient and the jet discharges so that

$$\frac{C_0}{C_i'} = \frac{Q_a}{Q_0} \tag{3}$$

Hence at a fully mixed section

$$\frac{C_0}{C_m}Q_r = 1 \tag{4}$$

where $Q_r = Q_0 / Q_a$

Experimental Arrangement

The experiments were performed in a rectangular flume 1.20 m wide, 0.60 m deep and 18.5 m long. Wooden boards were used to reduce the width of this channel to 0.60 m in the test section and a plan view of the experimental arrangement is shown in Fig. 1(a). Water was supplied to the flume from the laboratory sump and the discharge was measured using an inline magnetic flowmeter. A tailgate was used to control the depth of flow. The mean velocity of the crossflow was obtained from the measured discharge and the cross-sectional area of the flow.

The injection or diffuser system was placed at a distance of 10 m from the entrance to the flume. The diffuser consisted of three vertical pipes which housed the jet nozzles which were flushed with the pipe walls. The system was originally designed to accommodate 70 nozzles (see Fig. 1(b)). The nozzles were arranged in such a way that the jets can either be in the direction of flow in the channel (coflowing jets) or perpendicular to the flow (crossflowing jets). The middle pipe had three lines of jets, two lines producing crossflowing jets while the third line produced coflowing jets. Each of the two side pipes had two lines of jets, one set crossflowing jets and the other set producing coflowing jets. The nozzles were 3.2 mm in diameter and the vertical distance between the nozzles was 12 d. The first nozzle from the bottom was placed at a distance of 12 d. A 250 W Jacuzzi pump raised the water from a 900 L tank placed outside the flume to a constant head tank. This tank, placed about 3.5m above the flume, provided the flow to the jet nozzles. The flow to the jet nozzle was measured using a (volumetrically calibrated) Fischer rotameter. The jet velocity was calculated from the measured flow rate

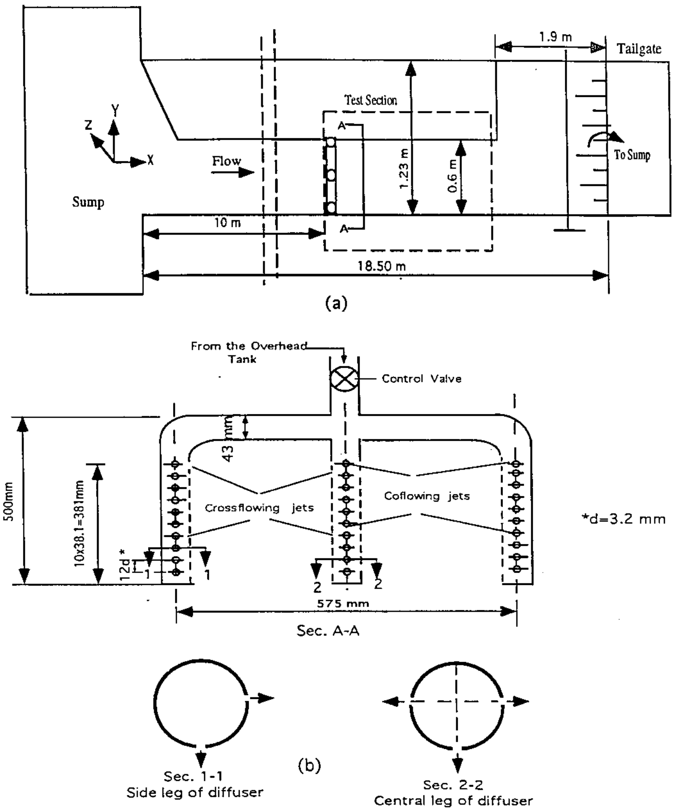

Fig. 1. (a) Plan View of the Flume (b) Details of the Diffuser

and the cross-sectional area of the nozzles. During all the experiments, the jets were kept submerged so as to maintain a constant piezometric head at the nozzles. The number of the nozzles under operation was varied by closing some of them using cork stoppers. Rhodamine WT with market concentration of 20% by weight and specific gravity of 1.19 was used as the tracer in this study. This dye was mixed thoroughly in a 900L tank with water pumped from the same sump which provided the crossflow.

The sampling technique used was the same as that described in Moawad and Rajaratnam (1998). A horizontal rake was used to sample the fluid at different elevations. The rake was set to withdraw samples at the same level in the y direction, starting from the bottom of the channel and moving vertically upward in the z direction. The concentration of the Rhodamine dye in the jet fluid was measured by a Turner model 10-AU digital fluorometer. The fluorometer was calibrated to diluted standards over a range of 0.05 to 120 ppb. The background concentration of the water was continuously monitored and was not allowed to exceed 1/1000 of the initial concentration C_o at the nozzles.

Experiments and Experimental Results

The primary details of the experiments conducted are shown in Table 1. The diameter of all the nozzles was 3.2 mm. In experiments CC1 to CC3, both the coflowing and crossflowing jets were used. A total of 35 jets were used, of which 20 were crossflowing jets and the remaining 15 were coflowing jets with a constant spacing of 24 d. In experiments CC4 and CC5, the coflowing jets issuing from the vertical pipes adjacent to the side walls of the flume were closed and there were 20 crossflowing jets and 5 coflowing jets issuing from the central vertical pipe, with a constant spacing of 24 d. In the experiments CF1- CF7, all the coflowing jets were closed and only crossflowing jets were used, with spacings of 24 d in experiments CF1 to CF3 and 12 d in experiments CF4 to CF7.

The velocity ratio α was varied from 8 to 16. The spacing between the ports was given two values of 12d and 24d. The number of ports n was varied from 20 to 36. The depth of flow D in the channel was equal to 388 mm for experiments CC1-CC5 and CF1-CF3 and CF7 whereas for the remaining experiments, D was equal to 227 mm. The jet velocity was varied from about 0.7 m/s to 1.6 m/s with the ambient flow velocity varying from 0.06 m/s to about 0.2 m/s. The jet Reynolds number, defined as $U_0 d/\nu$, where ν is the kinematic viscosity, was varied from about 2300 to 5000 and in this range of Reynolds number, the effect of viscosity on the behavior of the jets is believed to be negligible. The Reynolds number of the ambient flow ranged from 20000 to 40000.

Concentration Profiles

Concentration field downstream of the jets was measured in the transverse direction y and in the vertical direction z at different longitudinal sections. A total of about 4000 concentration measurements were made. The concentration measurements covered a distance of x/d= 2000. In terms of the transformed distance $\alpha x/d$, the measurements covered a range from 630 to 32050. The concentration at any point C was normalized by the concentration C_i at the section at which the dye becomes uniformly mixed. This concentration C_i for any experiment was calculated from Eq. 2.

As mentioned earlier, the flow field of single jet and multiple jets in a crossflow can be divided into three different regions, referred to as the MDNF, MDFF and PPR respectively. The same notions may also be used for the present study. Near the diffuser, it was found that the distance at which the jets merged was dependent on α. As α increases, merging between the jets occurs at shorter distances. In this study, since the main objective was to produce uniform mixing, more attention was given to the mixing occurring in the far field and the passive plume regions. Hence, most of the observations were made in those regions. The concentration distributions in the transverse direction (y-z plane) were investigated at different locations downstream of the nozzles. Figs. 2(a-c) show typical concentration profiles at three sections for experiment CF7. These and other profiles (not shown herein) showed as to how the concentration field eventually became almost uniform.

A study of the concentration profiles for experiments CC1 to CC3, with 20 crossflowing and 15 coflowing jets, showed locations of smaller dilution downstream of the nozzles producing coflowing jets, for distances up to about 3.5 m, especially near the side walls. For experiments CC4 and CC5, the coflowing jets on the side pipes were closed. A study of the concentration data for all the experiments in the CC series showed that the coflowing jets were not effective in achieving rapid mixing. Hence, further

Table 1 Details of experiments

Expt. No	Number of ports **n**	Spacing **S**	Depth of Flow **D** (mm)	Jets Discharge Q_o (L/min)	Crossflow Discharge **Q** (L/s)	Jet Velocity U_o(m/s)	Velocity of crossflow **U** (m/s)	$\alpha=U_o/U$	Jet Reynolds No.
CC1	35	24d	388	12.5	20.62	0.722	0.09	8	2293
CC2	35	24d	388	15	17.51	0.902	0.075	12	2865
CC3	35	24d	388	20	17.51	1.203	0.075	16	3821
CC4	25	24d	388	12	19.61	1.010	0.084	12	3209
CC5	25	24d	388	15	18.38	1.26	0.079	16	4012
CF1	20	24d	388	8	24.5	0.84	0.105	8	2674
CF2	20	24d	388	12	24.5	1.26	0.105	12	4012
CF3	20	24d	388	15	22.9	1.58	0.098	16	5015
CF4	20	12d	227	8	14.34	0.842	0.105	8	2674
	20	12d	227	15	26.89	1.57	0.197	8	5015
CF5	20	12d	227	12	14.34	1.26	0.105	12	4012
CF6	20	12d	227	15	13.36	1.57	0.098	16	5015
CF7	36	12d	388	17	14.27	0.99	0.062	16	3158

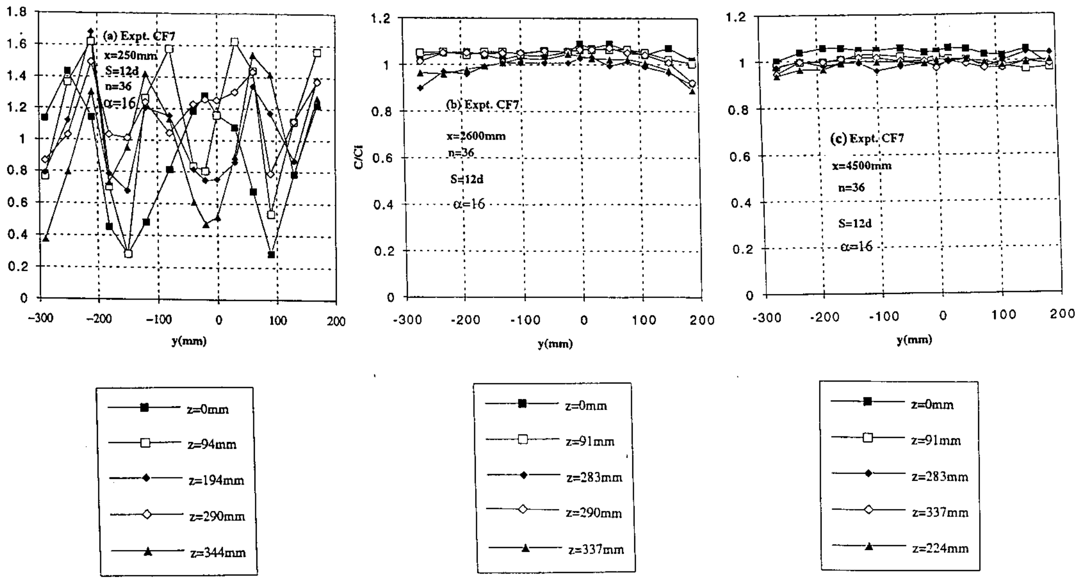

Fig. 2(a-c) Typical transverse concentration profiles at different levels at different sections for experiment CF7

experiments were performed with only the crossflowing jets (CF Series). For experiment CF7, the concentration field became almost uniform for x greater than about 2.6 m. For some practical applications, it is useful to determine the section beyond which the concentration attains 50% of the fully mixed concentration. From the concentration measurements for the CF series, the maximum transformed distance αx/d at which the value C/C_i reached 0.5, was estimated to be about 5000.

Analysis of Experimental Results Mixing Distance

The degree of mixing at any section was defined using a normalized form of the standard deviation of C/C_i given as

$$\sigma = \sqrt{\frac{\Sigma[\frac{c}{c_i} - \frac{\bar{c}}{c_i}]^2}{(N-1)}} \tag{5}$$

where N is the number of observations and $\bar{c}$ is the average concentration at that section. A value of zero for the normalized standard deviation σ would indicate complete mixing. It would be expected that σ would approach zero asymptotically. For practical purposes, adequate mixing may be assumed to occur when this standard deviation reaches a specified value. In this study, this limit value was set equal to 5%. The distance required for this mixing to occur is termed as the mixing distance x_m. The standard deviation was calculated for all the measured sections for all the experiments and Fig. 3 shows the variation of σ with the normalized longitudinal distance αx/d. The experimental results are described by the equation

$$\sigma = 108(\alpha x / d)^{-0.76} \tag{6}$$

with a correlation coefficient of 0.93. From Fig. 3 it can be seen that the standard deviation σ was about 0.9 near the diffuser where the concentration distribution was highly non-uniform. As the distance from the nozzles increases, the concentration profiles become progressively more uniform and the standard deviation decreases to 0.05 at αx/d equal to approximately 25000. Hence the mixing distance x_m is given by the expression

$$x_m = 25000(d/\alpha) \tag{7}$$

It appears that the mixing distance x_m is approximately the same for all the experiments, independent of the configuration of jets, the spacing between the ports or on the number of ports, within the limits of the present experimental work.

Minimum Dilution

The minimum dilution at any section is defined as the ratio of the concentration at the ports C_o in terms of the maximum concentration C_m at that section. Since the maximum concentration C_m at any section is with respect to the background concentration C_b, if the maximum value at the section is C_{max} then C_m is equal to

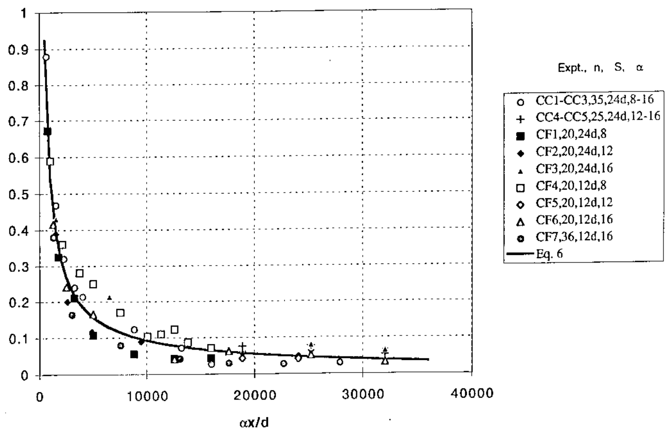

Fig. 3. Variation of the standard deviation with the dimensionless distance αx/d for all the runs

C_{max}-C_b. Following the work of Hodgson and Rajaratnam (1992) for single jets in crossflows, the variation of the minimum dilution C_o/C_m with the dimensionless distance $\alpha x/d$ was studied. Fig. 4 (a) shows the variation of C_o/C_m with $\alpha x/d$ for the experiment CC1, near the side wall, center of the channel as well as the sectional average. Fig. 4 (b-d) show the variation of C_o/C_m with $\alpha x/d$ for the experiment CF1-CF3, CF4 and CF6 and CF7 respectively. In Fig. 4(a-d), it may be observed that after a certain value of $\alpha x/d$ the experimental results fall on the C_o/C_i' line, which is also defined by experimental points because the background concentration was not necessarily the same for all sections.

At the fully mixed section, Eq. 4 indicates that $(C_o/C_m)\ Q_r$ is equal to 1.0. The experimental observations are shown in Fig. 5 with $(C_o/C_m)\ Q_r$ plotted against $\alpha x/d$. It is interesting to see in Fig. 5 that all the experimental results almost come together and they approach the fully mixed line thereby indicating that the fully mixed state was not realized in the experiments.

Using the results presented in this paper for this diffuser, one could make some preliminary calculations. For example, with a mixing channel and diffuser, similar to that studied herein, if the diameter of the ports is 5 mm, then the mixing distance would be 10 m. If the mixing channel is narrower than the width used in this study, the mixing length is likely to be shorter. If it is much larger, the standard deviation of the concentration field at x=10 m is likely to be larger. For the idea of the diffuser presented in this work to be of wider use, more work would have to be performed to generalize the dimensions of the mixing channel.

Conclusions

In this study, laboratory experiments were carried out to investigate the effectiveness of multiple jets for chemical mixing in an open channel . The experiments were carried out with the velocity ratio α varying from 8 to 16. Two jet arrangements were considered. The first was a combination of coflowing and crossflowing jets and the second one used only crossflowing jets, discharged into the ambient flow. Although both the configurations were studied, main experiments were carried out for the jets in crossflow. The number of ports for the crossflowing system was varied for 20 to 36 and the spacing between ports varied from 12d to 24d. The concentration measurements were carried out for distance x/d up to 2000.

The approximate distance at which the concentration at any section is above the 50% of that of the fully mixed section, is estimated in terms of the dimensionless distance $\alpha x/d$ to be equal to 5000. The standard deviation of the concentration distribution was used as a measure of the degree of mixing at each section. The dimensionless mixing distance $\alpha x_m/d$ at which the standard deviation reached a value of 5% was equal to 25000. For a fully mixed section, the dilution attained by the system was dependent on the ratio between the jet discharge and the ambient discharge. The results indicated that the results of the standard deviation and the dilution are independent of the spacing and the number of ports. Finally, the results of this study show that turbulent jets could be a successful alternative to mechanical methods for achieving chemical mixing. For the idea of the diffuser presented

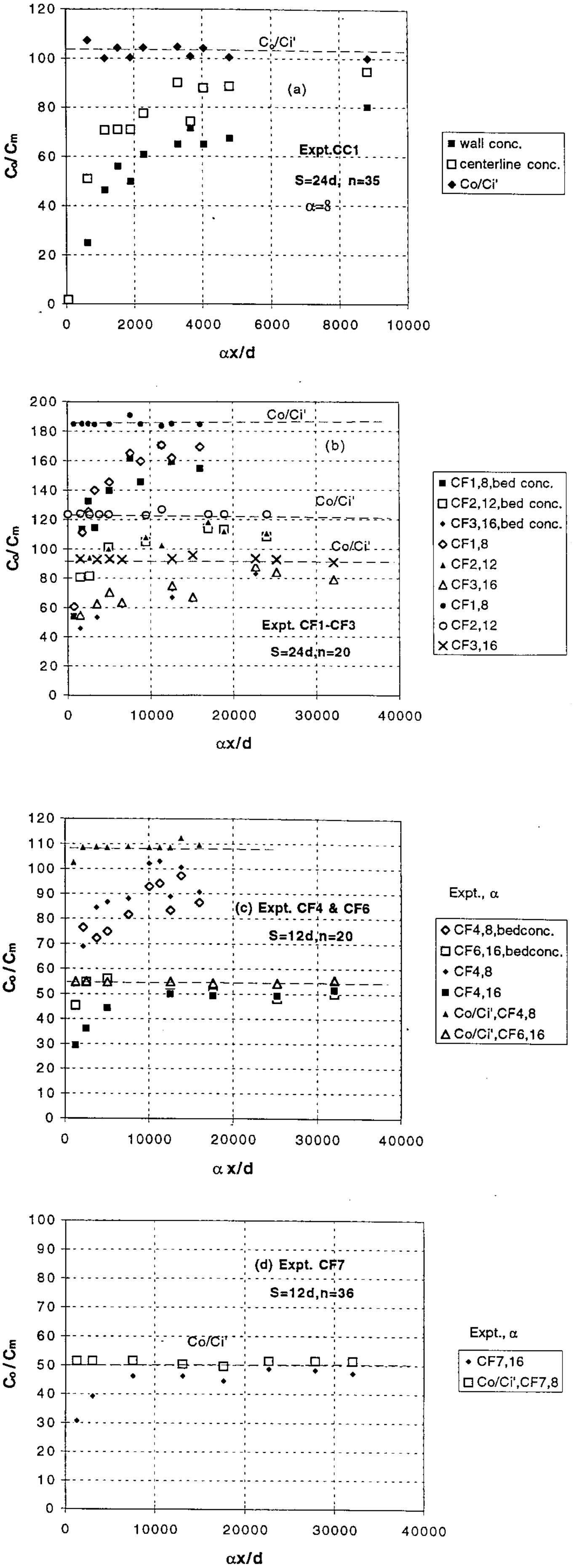

Fig. 4(a-d) Variant of the minimum dilution (C_0/C_m) with $\alpha x/d$ for different experiments: (a) CC1 (b) CF1-3 (c) CF4-6 and (d) CF7

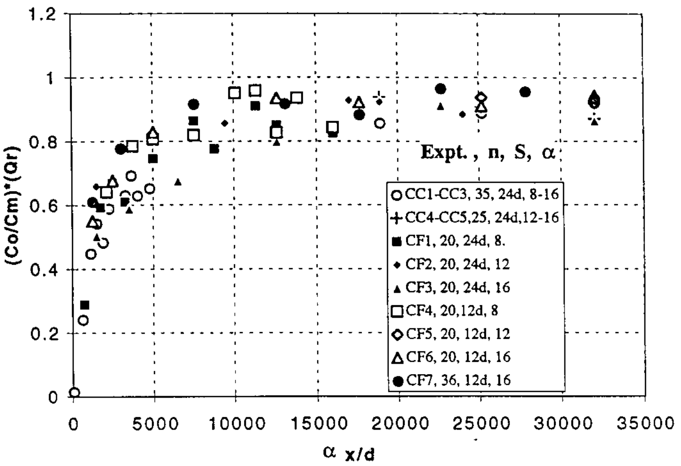

Fig. 5. Variation of $[(C_0/C_m)Q_r]$ with $\alpha x/d$

in this work to be of wider use, more experimental work would have to be performed to generalize the dimensions of the mixing channel.

Acknowledgment

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Appendix II. Notation

The following symbols are used in this paper:

C = concentration at any point in the jet;
C_i = concentration at a fully mixed section;
C_m = maximum concentration at section;
C_o = initial concentration at nozzle;
D = depth of flow;
d = jet diameter;
n = number of ports;
R = Reynolds number of the jet;
S = spacing between ports;
U = crossflow velocity;
U_o = velocity of the jet at nozzle;
x = longitudinal distance downstream from diffuser;
x_m = mixing distance
y = distance measured in the transverse direction;
z = vertical distance measured from the bed;
α = ratio of jet velocity to crossflow velocity (U_o / U);
ν = kinematic viscosity of fluid;
ρ = density of water;
σ =standard deviation;