NEAR AND INTERMEDIATE FIELD MIXING OF A ROSETTE JET GROUP

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Abstract. The mixing characteristics in the near and intermediate fields of a rosette buoyant jet group in a crossflow are investigated through a series of experiments. The results are interpreted using a Lagrangian near field jet model (VISJET) and a recently developed near-far field coupling methodology - the Distributed Entrainment Sink Approach (DESA). It is found that the the prediction of near field mixing using the composite dilution concept is in excellent agreement with observations. The effect of number of jet nozzles on initial dilution is well-predicted. The DESA prediction of surface dilution, buoyant spread and surface layer thicknesses in the intermediate field are also in good agreement with observations.

1. Introduction

In many coastal cities, partially treated wastewater is often discharged into the receiving water through submarine outfall diffusers. In densely populated Asian cities, outfalls are often located in shallow water not far away from sensitive areas such as beaches or fishfarms. For impact assessment it is of paramount importance to develop models for accurate prediction of pollutant concentration in both the near and intermediate field. And yet, current models cater mainly for either the near field or the far field.

In modern outfall designs, the wastewater is typically discharged from an outfall riser in the form of rosette jet groups. A rosette jet group discharging into an ambient current is a complex flow involving mixing, merging and interaction of coflowing, crossflowing, and counter-flowing jets (Fig. 1). Previous attempts to predict initial dilution of rosette jet groups are mainly based on the "line plume" approximation, e.g. Isaacson et al. [2] and Roberts and Snyder [4]. These models tend to give conservative dilution predictions and cannot predict effects of changes in diffuser configuration (e.g. number of jets) on initial dilution (Roberts and Snyder [4]). In addition, the intermediate field mixing characteristics of such rosette jet groups has hitherto not been reported. We report herein recent experiments and numerical modelling of a rosette jet group in a crossflow.

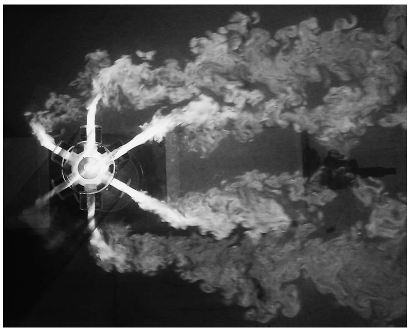


Figure 1: Top view of a rosette jet group in crossflow

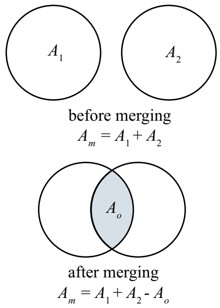


Figure 2: Illustration of the composite dilution concept

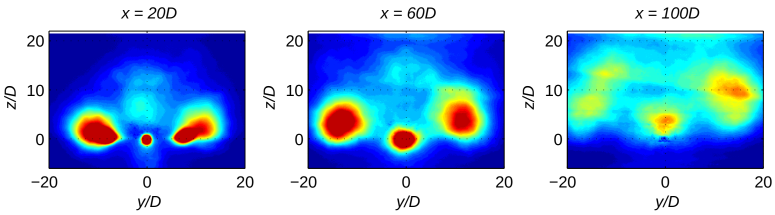
2. Composite dilution concept and DESA

The individual jets in a rosette jet group discharge at different angles relative to the ambient current (e.g. as jets in coflow, crossflow, and counterflow). Previous experiments have shown that: (i) in the bent-over phase of the jet, the jet velocity is approximately the same as the crossflow velocity, $u \approx U_a$; (ii) for many practical diffuser design and crossflow situations, the effect of jet merging can be treated based purely on kinematic considerations. The cross-sectional average concentration of the jet group is then given as

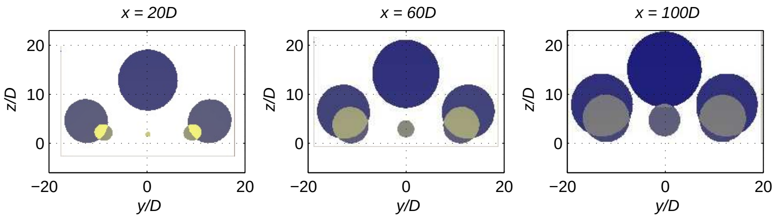
$$C_m = \sum_{i=1}^{N} A_i C_i u_i / A_m U_a = \sum_{i=1}^{N} A_i C_i / A_m \tag{1}$$

where A_m, C_m are the cross-sectional area and cross-section averaged concentration of the merged jets respectively, and A_i, C_i are the cross-sectional area and averaged concentration of an individual jet; u_i, U_a = velocity of jet and crossflow, and N = number of individual jets (Lai et al. [3]). The reciprocal of this average concentration gives the corresponding composite dilution of the jet group.

The mixing characteristics of the rosette jet group beyond the near field are predicted by a dynamic coupling of the near field VISJET model and a 3D shallow water circulation model using a recently developed Distributed Entrainment Sinks Approach (DESA) (Choi and Lee[1]). In DESA, the VISJET prediction of rosette jet characteristics is embedded within the 3D circulation model; the action of the buoyant jet on the surrounding flow is modelled by a distribution of sinks along the jet trajectory and an equivalent diluted source flow at the predicted terminal height of rise. In this way, a true two-way dynamic link can be established at grid cell level between the near and far field models. DESA has been validated for a variety of complex 3D near-far field interaction problems (Choi and Lee[1]).



(a) LIF images of the cross-section of a rosette jet group



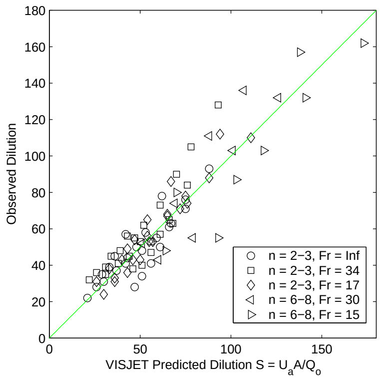
(b) VISJET simulated cross-sectional view of a rosette jet group

Figure 3: Cross-sectional concentration profile of rosette jet group

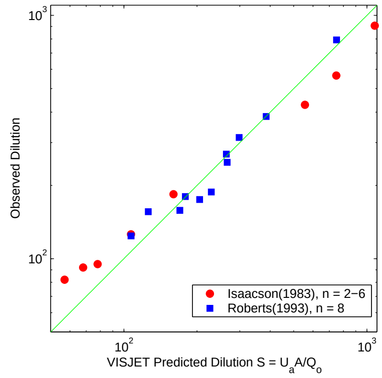
3. Experiments

Experiments are carried out in a 12 m by 5 m wide shallow water basin; the water depth is set at 0.3 m. Six- and eight-nozzle risers are considered. The diffuser discharge flow is measured by a calibrated rotameter. Buoyancy of the source fluid is obtained by addition of ethanol to water. Densities of the source fluid and the ambient are measured using a precision density meter. Crossflow velocity is measured by an Acoustic Doppler Velocimetry (ADV) placed approximately 1 m upstream of the diffuser. The range of the hydraulic parameters are: jet densimetric Froude number, $Fr = U_o/\sqrt{g(\Delta\rho/\rho_o)D} \approx 15-30$ (where U_o = jet velocity, $\Delta\rho$ = density difference of jet and ambient, ρ_o = jet density and g = gravitational acceleration); jet-to-crossflow velocity ratio, $K = U_o/U_a \approx 16-40$.

Two series of experiments are carried out to study both the near and intermediate field mixing characteristics of a rosette jet group. In series 1, the near field cross-sectional concentration field of a rosette jet group is measured. Four hundred cross-sectional LIF images (576×768 pixels) at $20D-100D$ downstream of the diffuser are captured with 0.1 second interval by an underwater CCD camera. Based on in-situ calibration, the tracer concentration field can be obtained from the time-averaged LIF images. In series 2, the surface buoyant spread of a rosette jet group is visualized. Dye is injected into the source fluid while discharging and the resulting surface buoyant spread is captured using an overhead CCD camera. For each case, 400 images are captured and time-averaged. The images covers the area of approximately 1 m ($\sim 400D$) × 1.8 m ($\sim 720D$).



(a) Dilution data of present study



(b) Dilution data of Isaacson et al.(1983) and Roberts and Snyder (1993)

Figure 4: Comparison of measured and VISJET predicted cross-sectional averaged dilutions

4. Results and Analysis

4.1. *Near field mixing characteristics*

Fig. 3 (a) and (b) show the cross-sectional time-averaged LIF image and predictions of a 6-jet rosette jet group at 20 - 100*D*. It can be seen the individual jets merge and interact in a complicated manner. The behavior of the coflow jet (lower centre), crossflow jet (each side), and counter flow jets (top centre), and the jet merging can be clearly seen. The strong mixing of the counterflow jet can also be noted. The complex merging is well-simulated by VISJET which assumes only kinematic merging.

The cross-sectional average dilution of the rosette jet group at downstream sections are calculated by averaging the mass contained within a jet cross-section defined by a boundary of $0.25C_{max}$, and the result is compared with the VISJET prediction (Fig. 4(a)). It can be seen the predicted average dilution agrees well with the observed dilution. Earlier experimental results of non-buoyant jets (Lai et al.[4]) are also included for comparison. In addition, the VISJET prediction is also compared with experiments of Isaacson et al.[2] and Roberts and Snyder[4] on rosette jet groups in a highly non-linear stratified condition (note that a factor of $\sqrt{2}$ is used to convert their data into flux-averaged dilution) (Fig. 4(b)); the good agreement further supports the applicability of the composite dilution concept that takes into account any reduction in dilution due to overlapping of plumes.

An important application of the composite dilution formula is to determine the optimum number of jets nozzles (*N*) for a rosette jet group. The effect of jet nozzle number on dilution in a crossflow is studied (Fig. 5). Two sets of experimental data are used for the validation of the VISJET prediction. In the simulations, the total discharge, total nozzle cross-sectional area, ambient water depth

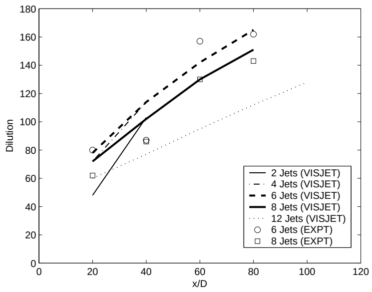


Figure 5: Effect of nozzle number on the dilution

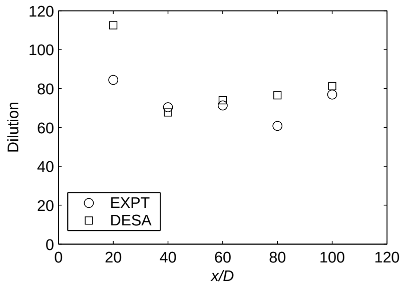


Figure 6: Minimum dilution of a Rosette Jet Group ($N = 6$; $U_a = 2$ cm/s; Fr = 15)

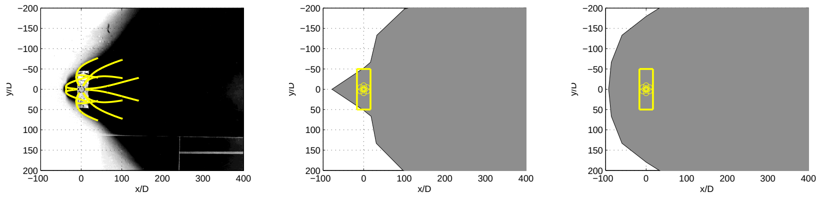
and crossflow velocity are kept the same for all the cases, while the number of jet nozzles is varied, $N = 2-12$. The experimental parameters are $Fr = 13-22$, $K \approx$ 17, and $h/D = 60$ – 150, where $h =$ water depth. The cross-sectional averaged dilutions at the downstream reach of 20 – 100 D are compared before the buoyant jet reaches the water surface. In agreement with data, the 6-nozzle riser configuration is predicted to give the highest dilution. The 12-nozzle riser case shows poor mixing performance over the whole range – the severe overlapping leads to a decrease in the merged area A_m in Eq. (1). The poor dilution performance of a 12-nozzle riser is also noted in the experiments of Roberts and Snyder[4].

4.2. *Intermediate field mixing characteristics*

The surface spreading in the intermediate field is measured and compared with the DESA prediction. The time-averaged captured images of the surface spreading of a rosette jet group of 6-nozzles with $Fr = 15.2$, $K = 25$, and $h/D = 100$ is shown in Fig. 7(a). The VISJET predicted jet trajectories are superimposed onto the images.

The DESA prediction of surface spreading (dilution = 1000) is shown in Fig. 7(b). A computational domain of 19 $\times$ 20 $\times$ 20 grid cells are used that corresponds the physical dimension of 3.8 m $\times$ 6 m $\times$ 0.3 m. A uniform horizontal grid is adopted, with grid size 0.2 m $\times$ 0.3 m, and time step $\Delta t = 0.0025s - 0.005$ s, with a Courant number $\approx$ 0.01 – 0.05.

It is clearly shown in Fig. 7 that the DESA-predicted surface spreading is reasonably close to the observation especially in near-intermediate region where the effect of rosette jet configuration is still dominant. On the other hand, the prediction using an actual source (AS) approach (with the volume and pollutant mass sources introduced at the point of discharge) results in significant over-prediction of upstream buoyant spread (Fig. 7(c)). Similar results are found with experiments of different conditions. The cross-sectional view along the downstream direction and the surface dilution comparison between the measured data and the DESA prediction are also carried out. The spreading layer thickness and dilution profiles



(a) Observed (b) DESA predicted (c) AS predicted

Figure 7: Surface buoyant spreading layer of a rosette jet group; Fr = 15; U_a = 3 cm/s

(Fig. 6) of the measurement and prediction are in good agreement.

5. Concluding Remarks

The near and intermediate field mixing characteristics of a rosette jet group is studied. It is found that the near field dilution of a rosette jet group can be well predicted by the composite dilution formulation. Several applications in relation to outfall designs is demonstrated. For the intermediate field mixing characteristics, a recently developed near-far field coupling approach, DESA, results in good prediction of the measured data including the surface buoyant spread, surface layer thickness and the surface dilution.

Acknowledgement

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