13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

LABORATORY MODELLING OF A ROUND JET IN AN UNSTEADY CROSSFLOW

K.M. LAM and L.P. XIA

Department of Civil Engineering
The University of Hong Kong, Pokfulam Road, Hong Kong, CHINA

ABSTRACT

We describe an experimental technique to investigate the effect of an oscillating crossflow on the dispersion of a turbulent round jet. A vertical jet-pipe-nozzle assembly is made to oscillate horizontally in the steady flow stream in a laboratory flume. To an observer moving with the assembly, the jet is issuing into a crossflow which consists of a mean current and a sinusoidally oscillating component. We use computer-aided flow visualisations to study the dispersion pattern and compare it with the pattern obtained by discharging a vertical jet into a horizontal flow with progressive shallow-water waves, a situation bearing a close similarity to a genuine oscillating flow with a non-zero mean velocity.

INTRODUCTION

The mixing and dispersion of turbulent jets issuing into an oscillating cross-flow are crucial to the discharge of pollutants into the atmosphere or receiving water bodies. Unsteadiness in the crossflow can be caused by tidal intrusion or wave propagation into rivers. Periodical velocity oscillations can be introduced into wind flow due to vortex shedding from upstream obstacles such as hills and tall buildings. Previous studies of jet dispersion in non-steady crossflows are reviewed by Koole and Swan (1994), which is concerned with a horizontal jet in a wave environment. A vertical jet in an oscillating crossflow is studied by Brocard (1985). In both situations, the oscillating ambient flow stream has a zero mean velocity and enhanced mixing and dispersion of the jet is observed. There have been very few studies on jet dispersion in an unsteady crossflow with a non-zero mean velocity. With this scarcity of research data, we embarked on a parametric study of how the unsteadiness in a non-zero mean velocity crossflow affects the mixing and dispersion of a vertical jet (Lam and Xia 1994). In this paper, we present our experimental technique to simulate an unsteady crossflow in the laboratory. We also show how the mixing and dispersion of the vertical jet can be dramatically affected.

SIMULATION OF OSCILLATING CROSSFLOW

As an analogy to our flow problem, the cylinder wake in an oscillating flow stream of non-zero mean velocity has received much attention. A recent review can be found in Griffin and Hall (1991). Due to the difficulties in producing controllable flow perturbations in the main flow stream in a wind tunnel or a water channel, the common experimental technique is to oscillate the cylinder in a steady flow stream (e.g. Tanida et al. 1973). Armstrong et al. (1986) actually produced an oscillating flow stream in a wind tunnel by rotating a set of shutters equipped at the downstream end of the working section. This piece of work suggested that the two flow situations are completely equivalent when the acoustic wavelength is large compared with the diameter of the cylinder.

In reference to these studies in unsteady wake flows, we look at the possibility of simulating jet dispersion in an unsteady crossflow by oscillating a vertical jet in the steady flow stream of a laboratory flume. The flow is then viewed by an observer who is moving with the jet. A complication arises here as compared to the oscillating wake situation in that oscillating the jet has to be accomplished practically by shaking the jet nozzle. This induces an oscillating pressure gradient field across traverse sections of the jet-pipe-nozzle assembly. As a result, the fluid in the jet-pipe-nozzle assembly is given continuous lateral accelerations and the issuing jet is not strictly vertical at most of the time. For a jet-pipe-nozzle assembly under a sinusoidal movement $A\sin(2\pi ft)$ in the lateral direction, the peak velocity of the assembly is $u_p=2\pi fA$ and the peak acceleration is $2\pi fu_p$. The peak pressure gradient induced across a traverse section of the jet nozzle with diameter D is related to this peak acceleration, $2\pi fu_p$. When the jet exit velocity is V_j, the inertia force in the vertical direction is related to V_j^2/D. Hence the secondary effect of lateral flow overshooting can be characterised by the ratio between these two inertia forces or the non-dimensional parameter fu_pD/V_j^2, which we shall show later to be of small values over our range of interest.

To verify the validity of our modelling technique of oscillating the jet in a steady crossflow, it is necessary to perform reference experiments under the actual situation of a stationary vertical jet in an oscillating crossflow. In a laboratory flume, it is difficult to produce an oscillating flow with non-zero mean velocity. The best we can achieve in our laboratory flume is a situation where progressive surface waves are imposed on a mean horizontal flow. Under the shallow-water wave condition, the velocity at a particular location is made up of a mean component plus a sinusoidal component. The velocity oscillations are grossly independent of height but they are progressive in nature. However, if we limit our observation over a portion of the wavelength, the oscillations can be taken to be spatially coherent.

EXPERIMENTAL SET UP

The experiments were carried out in a 10m long × 0.3m wide × 0.3m deep laboratory flume. A vertical jet was produced by discharging water through a circular nozzle of D=7.5mm exit diameter at the end of a vertical pipe. For convenience sake, the discharge was vertically downwards with the nozzle exit about 5D below the water surface. Jet discharge was fed from a constant head tank with the jet exit velocity V_j adjusted and metered with a calibrated rotameter. Fig. 1 shows a schematic diagram of the experimental set-up.

For the oscillating jet simulation method, a steady current U_a was maintained in the flume by a recirculating flow while the jet-pipe-nozzle assembly was mounted on a trolley and imposed a sinusoidal horizontal motion by means of a crank-yoke mechanism. The crank was driven by a stepper motor so that the frequency of oscillation f could be precisely adjusted. The stroke of oscillation A could also be adjusted and together with f, determined the magnitude of the peak velocity oscillations in the crossflow $u_p=2\pi fA$. The phase of oscillation was derived from the stepper motor driving signal and displayed on a phase angle indicator in steps of 1/20 cycle.

To an observer moving with the jet nozzle, the ambient crossflow is thus described by $U(t)= U_a + u_p \sin(2\pi ft)$. Simple dimensional analysis suggests that the flow problem is governed by the following parameters: jet-to-current velocity ratio V_j/U_a; unsteadiness parameter of the crossflow u_p/U_a; and non-dimensional frequency or Strouhal number $St = fD/U_a$. The secondary effect parameter fu_pD/V_j^2 can be derived from these three parameters.

For the reference experiments using progressive waves, the vertical jet was held stationary. Surface waves were generated in the flume by a flat, bottom hinged paddle located at the end of the flume (Fig. 1b). The paddle was driven by a motor through a crank-yoke mechanism with adjustable frequency and stroke so that a wide range of waves could be generated. The paddle was equipped with an opening with adjustable size so that it also acted as a weir over which water flowed to maintain a mean current U_a in the flume. A wave height monitor was installed at a location downstream of the jet to derive the phase of oscillation of the crossflow. The velocity signal at a point in the crossflow was measured by a laser-Doppler anemometer. The mean flow component U_a and the amplitude u_p of the oscillating component were derived from the measured signal.

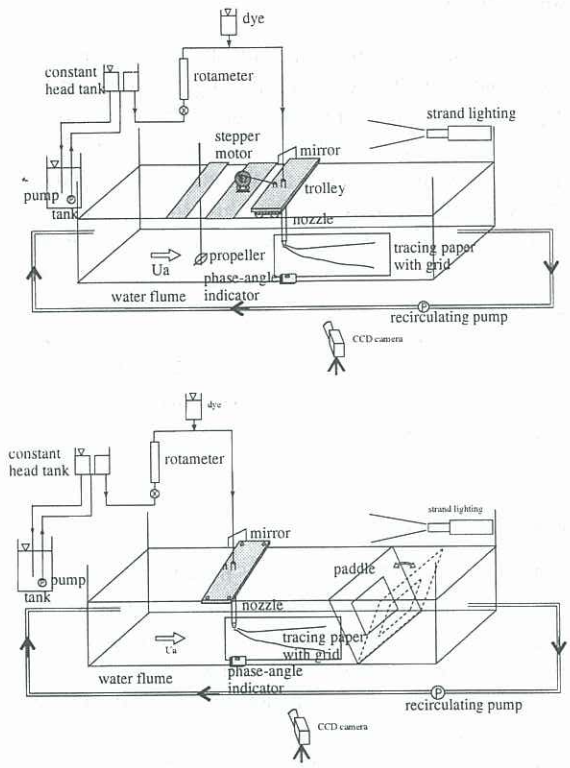

Figure 1 : Schematic diagram of experimental set-up. Oscillating jet method (above) and progressive shallow water waves method (below).

COMPUTER-AIDED FLOW VISUALISATIONS

Spreading of the jet was analysed with a computer-aided flow visualisation technique using image processing. With a dye added into the jet discharge, the jet dispersion pattern was projected onto tracing paper mounted along a side of the flume with a parallel light beam provided from the other side by a 2500 watt strand lighting. The shadowgraphs together with the display of the phase-angle indicator were recorded with a CCD camera. The video images were then grabbed into digital data with a Data Translation DT3852 frame grabber and a computer. Each image frame was represented by a 640×480 pixel matrix of 8-bit grey level elements. We then carried out phase-locked eduction of the coherent jet dispersion pattern as follows: all the grabbed images underwent a contrast enhancement with the standard histogram sliding and stretching technique (Lam and Chan 1995). The grabbed image frames were sorted into groups of the same phase angle, with an ensemble size of 10 frames for each phase. The averaged flow image at the particular phase was obtained by ensemble averaging of the brightness matrices of all frames. This phase-locked averaging technique removed the small-scale incoherent flow fluctuations and retained the coherent flow patterns.

With a set of fixed instrumentation setting, the averaged grey levels should bear a well-defined relationship to the averaged dye concentration in the flow field., from which the dilution of jet fluids could be quantified.

RESULTS AND DISCUSSION

We have carried out investigations over a wide combination of different values of the three flow parameters. In this paper, we present in detail the results at $u_p/U_a = 0.65$, $St = 0.14$ and $V_j/U_a = 8$. The steady current in the flume was $U_a = 6$ cm/s and the frequency of oscillation was 1.1 Hz. The secondary effect parameter fu_pD/V_j^2 thus has a very small value at 0.0014.

Fig. 2 shows the phase averaged dispersion patterns of the jet at four selected phases of an oscillation cycle obtained with the two simulation methods. At phase number 0, the crossflow is at its mean velocity but is accelerating while at phase number 10, it undergoes deceleration. The phase number indicates the phase in the oscillation cycle in multiples of 1/20 cycle starting from $t = 0$ in the oscillating crossflow $U(t)=U_a+u_p\sin(2\pi ft)$. Phase numbers 6 and 16 roughly correspond to the instants when the crossflow velocity is at its maximum and minimum values respectively.

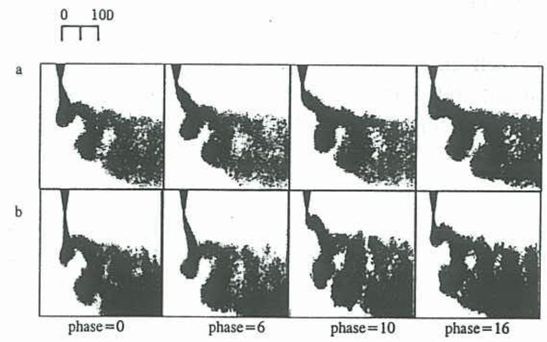

Figure 2 : Dispersion patterns of the jet at four phrases. (a) Oscillating jet method; (b) Progressive water waves method. Phases indicated at 1/20 cycle from t=0 (see text).

It is evident in Fig. 2 that the two simulation methods result in almost identical dispersion patterns. Successive acceleration and deceleration in the crossflow organise the jet discharging fluid into successive large-scale patches which are spatially separated on the outer side of the bent-over cross-flowing jet. These patches of concentration of jet fluids are separated by narrow intrusions of ambient flow fluid in the outer side of the jet. In the inner side of the jet, the patches remain connected. The secondary effect of lateral jet overshooting in the oscillating jet simulation method is negligible and does not lead to any observable difference in the subsequent dispersion patterns.

The time-averaged mean dispersion patterns of the jet could be obtained from an average of the phase-locked patterns over all phases of a cycle. Fig. 3 shows the mean dispersion patterns obtained with the two simulation methods. The dispersion pattern of a jet in a steady crossflow at the same velocity ratio V_j/U_a=8 is also shown in the Figure. It is obvious that sinusoidal oscillations in the crossflow and the subsequent formation of jet fluid patches result in a remarkable increase in the jet width in the bent-over region. It is also evident that the mean dispersion patterns obtained with the two unsteady crossflow situations are very similar to each other.

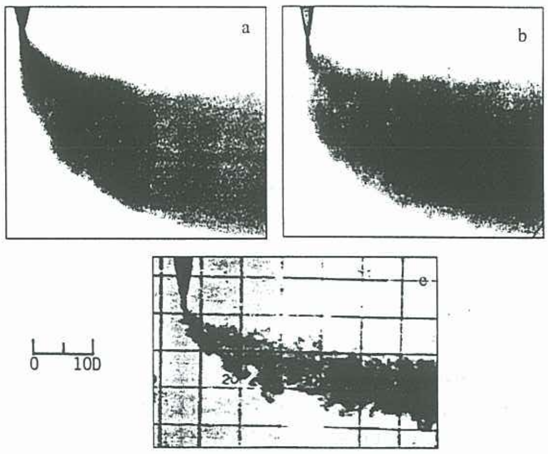

Figure 3 : Time-averaged dispersion pattern for:
(a) Oscillating jet method;
(b) Progressive water waves method;
(c) In steady crossflow.

Quantitative information on the concentration of dye-carrying jet fluids can be obtained from the grey level matrices in Fig. 3. The normalised dye concentrations across the jet width at a downstream station of x/D=30 are shown in Fig. 4 for the two simulated unsteady crossflows. The concentration distributions in the two situations agree well with each other, thus supporting the similarity of the two flow patterns both qualitatively and quantitatively. The slightly wider dispersion of jet fluids under the progressive water waves may be due to the existence of additional flow oscillations in the vertical direction as a result of the shallow wave motions.

In applications to waste disposal, the following remark is worth noting. After long-time averaging, the mean jet dispersion can be said to be enhanced by the unsteadiness in the crossflow since the jet is made to wander over a larger width. However, high concentration of jet fluids remains in individual patches, which can lead to very high instantaneous concentration levels. Moreover in full scale hydraulic situations, the time span of the patches can be in terms of hours during which nutrients in the wastewater discharge can undergo significant biological and chemical processes.

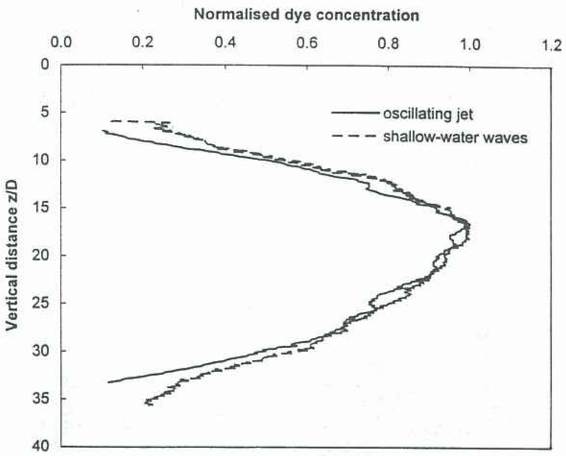

Figure 4 : Lateral distribution of normalised dye concentration across the jet at $x/D = 30$.

We have also carried out a computational fluid dynamics (CFD) study to compute the flow field of a vertical jet in a crossflow which consists of a mean flow current and a sinusoidally oscillating component (Xia and Lam 1997). The numerical results showed very similar patterns as the present experimental observations both in the simulated crossflow and in the progressive wave situation. The validity of our experimental technique to provide an unsteady crossflow is further supported.

CONCLUSION

This paper reports our laboratory technique to model the situation of a vertical jet issuing into a crossflow consisting of a mean flow current and a sinusoidally oscillating component. The jet-pipe-nozzle assembly is oscillated in a steady crossflow in the laboratory flume and the flow is viewed from an observer moving with the jet. A reference experiment is performed in which an approximately genuine unsteady crossflow with a non-zero mean velocity is obtained in a horizontal free surface flow with progressive shallow-water waves. Very similar flow patterns are obtained with computer-aided flow visualisations in the two simulated crossflows. The results are encouraging and we are confident that the oscillating jet method is a valid technique to model jet dispersion in an unsteady crossflow within our interested range of flow parameters.

REFERENCES

ARMSTRONG, B.J., BARNES, F.H. and GRANT, I., "The Effect of a Perturbation on the Flow over a Bluff Cylinder", *Physics of Fluids*, **29(7)**, 2095-2102, 1986.

BROCARD, D.N, "Surface Buoyant Jets in Steady and Reversing Crossflow", *J. Hydr. Engrg, ASCE*, **111**, 793-809, 1985.

GRIFFIN, O.M. and HALL, M.S., "Review - Vortex Shedding Lock-on and Flow Control in Bluff Body Wakes", *ASME J. Fluids Eng.*, **113**, 526-537, 1991.

KOOLE, R. and SWAN, C., "Measurements of a 2-D Non-buoyant Jet in a Wave Environment", *Coastal Engineering*, **24**, 151-169, 1994.

LAM, K.M. and CHAN, H.C., "Investigation of Turbulent Jets into a Counter-flowing Stream Using Digital Image Processing", *Exp. Fluids*, **18**, 210-212, 1995.

LAM, K.M. and XIA, L.P., "Interaction of a Round Jet With an Unsteady Crossflow", *Proc. 1st Int. Conf. on Flow Interaction*, Hong Kong, September 1994, 512-515, 1994.

TANIDA, Y., OKAJIMA, A. and WATANABE, Y., "Stability of a Circular Cylinder Oscillating in Uniform Flow or in a Wake", *J. Fluid Mech.*, **61**, 769-784, 1973.

XIA, L.P. and LAM, K.M., "A vertical jet issung into an unsteady crossflow consisting of a mean current and a sinusoidally fluctuating component", *J. Wind Eng. Ind. Aero.*, **67/68**, 843-857, 1997.