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ScienceDirect
Journal of Hydro-environment Research 3 (2009) 21–34
Journal of Hydro-environment Research
www.elsevier.com/locate/jher

Velocity and concentration measurements in initial region of submerged round jets in stagnant environment and in coflow

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Received 20 February 2008; revised 17 March 2009; accepted 17 March 2009

Abstract

Velocity and concentration fields are measured in submerged round jets in a stagnant environment and in coflow using laser Doppler anemometry and laser-induced fluorescence. Measurements are made in the initial region within distances of 40 jet exit diameter at jet Reynolds number between 1000 and 5000 and coflow-to-jet velocity ratio from 0 to 0.43. Different behaviors of jet spreading and dilution are found in jets at three different ranges of Reynolds number in which the jets are classified as initially laminar, transitional or turbulent. In the zone of established flow, the jet centerline velocity and concentration decay with downstream distance at different rates in the three groups of jets. For jets in coflow, axial development of normalized forms of centerline mean excess velocity and mean concentration at different velocity ratios can be reasonably well collapsed onto universal trends through the use of momentum length scale. Turbulence properties inside a jet are increased by the presence of a strong coflow. Inside the zone of flow establishment, some strange features are observed on jet turbulence properties. The length of zone of flow establishment increases from the turbulent jets, to the transition jets and to the laminar jets. The zone lengths for concentration are shorter than those for velocity by one to two jet exit diameters. Both lengths are shortened further in the presence of a coflow. For jets a stagnant environment and in the strong jet flow region of jets in coflow, jet widths increase linearly with downstream distance in transitional and turbulent jets. Self-similarity of radial profiles of mean velocity or excess velocity, mean concentration, turbulence intensities and concentration fluctuation level is explored in the zone of established flow.

Keywords: Jets; Dilution; Reynolds number; Flow characteristics

1. Introduction

Mixing and dilution capabilities of a submerged round jet are important in many engineering and hydraulic applications involving discharge of jet effluent into an ambient fluid. Extensive measurement data of mean velocity and statistical turbulence properties have been reported in the literature (e.g., Rajaratnam, 1976; Fischer et al., 1979; Wood et al., 1993; for review). The decay rate of mean jet centerline velocity and the growth rate of jet width are usually analyzed to indicate the efficiency of jet spreading and mixing. Changes of these jet properties occur in the zone of established flow (ZEF) where self-similarity is being achieved for many flow quantities, in particular the radial velocity profiles. Relatively fewer measurements have been made on the zone of flow establishment (ZFE), also known as the potential core, of the jet.

In addition to flow velocities, measurement of concentration field of jet effluent is equally important in determining the spreading and dilution of a jet. Early experimental studies employed probe-based single point measurements by change in conductivity, temperature or light absorption by dye. The amount of data was far less extensive than velocity data and limited mostly to discharge of buoyant jet effluent. Introduction of laser-induced fluorescence (LIF) technique has resulted in increasing numbers of jet experiments with concentration measurements and data (e.g., Papantoniou and List, 1989; Davidson and Pun, 1999). It is found that along the jet centerline, the mean concentration starts to drop earlier than

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1570-6443/$ - see front matter
doi:10.1016/j.jher.2009.03.002

flow velocity and that the concentration jet width is larger and grows faster than the velocity jet width.

Initial jet exit conditions and jet Reynolds number have been found to affect development of a round jet (Xu and Antonia, 2002; Kwon and Seo, 2005). At low Reynolds numbers (Re), roughly lower than 1000, the jet is laminar and Kwon and Seo (2005) found a number of flow behaviors different from a turbulent jet at high Re. For instance, the ZFE has a length longer than the turbulent jet value of 6.2 jet exit diameters and the rate of drop of centerline velocity does not follow that $-1/x$ relationship as a turbulent jet (x being the downstream distance from the jet exit).

Spreading and mixing of a round jet is affected by the presence of a main flow in the ambient fluid. Among all possible relative directions of jet exit to the moving ambient, the coflow and crossflow situations have been studied most. A coflowing jet is found to have two asymptotic regions; a strong jet region near to the jet exit and a downstream weak jet region where magnitudes of local velocities in the jet become comparable to the ambient flow velocity (Antonia and Bilger, 1973; Davidson and Wang, 2002).

This paper reports results of our experiments on a number of round jets at different Reynolds numbers in stagnant ambient and in coflow of different ambient flow velocities. Non-intrusive laser-based measurement techniques are adopted: laser Doppler anemometry (LDA) for velocity measurement and LIF for concentration measurement. The main purpose is to provide data of jet spreading and mixing in ZFE of simple jets (that is jet in a stagnant environment) and jets in coflow under a wide range of Re and coflow strengths. Our emphasis is on relatively low Re in the order of thousands. Past experimental works were mostly related to industrial applications and were performed at high Re above 10,000. However, low Re jets are relevant to a wide range of flows in environmental and biological applications and have received more frequent attention in recent years (Zarruk and Cowen, 2008). We attempt to test the similarity behavior of the jet at the different ranges of Re and coflow strengths. Our measurements are made in the initial region of the jet within an axial distance of 20–40 jet exit diameters. This initial near-field region and the ZFE have received less attention in previous studies and few measurement data are available on the transition to self-similarity which occurs here.

2. Experimental setup

The experiments were carried out in Croucher Laboratory of Environmental Hydraulics at The University of Hong Kong. The main flow apparatus was a laboratory flume with a 10 m long and 0.3 m wide flow section. To produce a coflow, horizontal flow of speed U_o up to about 0.2 m/s was maintained in the flow section by recirculating water. Variations and fluctuations of flow speeds in the flume had been measured with LDA. The variation of axial flow velocities within the central part of the flow section was less than 3% while the turbulence intensity at mid-depth was about 5%. In the simple jet experiments, water was kept stagnant in the flume by installing gates at two ends of the flume. Water depth was kept at about 0.35 m in all experiments. A submerged round jet was formed by discharging water into the flume from a circular nozzle fed from a constant overhead tank. The nozzle had an exit diameter $D = 3$ mm and was placed at mid-depth of the flume. To ensure clean initial exit conditions, the nozzle was preceding by a 4:1 contraction section and there was a parallel flow section of length $2D$ before jet exit. The jet exit velocity U_j was set with a flow valve at value between 0.3 m/s and 1.5 m/s.

The mean jet flow field was axisymmetric. Axial and radial flow velocities were measured with a two-component fiber-optic LDA along the jet centerline and at a number of jet sections. Measurements along jet centerline covered a distance from 0 to $40D$ with resolution ranging between $0.5D$ and $1.5D$. Measurements across jet sections were made within radial distances from $-4D$ to $4D$ and spatial resolution ranged between $0.3D$ and $0.5D$. At each measurement point, velocities were measured for 1 min to obtain the mean velocities and statistical turbulence quantities such as turbulence intensities and Reynolds stresses.

In LIF measurements, fluorescent dye Rhodamine 6G was added to jet effluent in the overhead tank at a constant concentration. The laser beam from a 4-W Argon-ion laser was turned into a laser sheet with a triangular lens. The laser sheet cut through the central vertical plane of the jet. A high-speed CCD camera of resolution 1028 pixel × 672 pixel recorded LIF images at 50 images/s. For each test flow condition, 500 LIF images were recorded. The initial time scale of the jet was estimated by D/U_j to be of the order of ms and as the jet spread downstream, the time scale would become longer. The sampling period of 10 s was considered sufficiently long to capture the mean jet behaviors. Calibration of the LIF system had been carried out with known concentrations of Rhodamine 6G from 0.005 to 0.065 mg/L. Thereafter, concentration field of fluorescence dye in the jet flow could be determined from the gray values in the LIF images.

Some LIF experiments on jet in coflow were carried out in a water basin with the equivalent situation of towing the jet nozzle in otherwise stagnant water (Davidson and Wang, 2002). In the present study, the towed jet experiments were carried out in a basin of length 12 m and width 5 m. It was filled with water to about 0.8 m and the jet nozzle was towed with a computer-controlled table along the length of basin. Flow images were taken with the CCD camera which was towed together with the jet nozzle.

3. Experimental conditions

The different flow conditions tested are listed in Table 1 for LDA and Table 2 for LIF measurements. The main flow parameters being varied were the jet Reynolds number $Re = U_jD/\nu$, and the relative strength of coflow as measured by the coflow-to-jet velocity ratio, $R = U_o/U_j$. Reynolds numbers of jets covered a range between $Re = 1000$ and 5000 roughly. Although it is commonly accepted that most jet flows will be turbulent if Re exceeds 2000, the value of Re at which a laminar jet becomes turbulent depends on many factors including initial jet conditions and the transition is gradual. As shown in Tables 1 and 2, we have classified our jets into three