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Intrusive measurements of air-water flow properties in highly turbulent supported plunging jets and effects of inflow jet conditions

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HIGHLIGHTS

- Air-water flow measurements in supported plunging jets using large-size facility.
- Effects of jet length and impact velocity on air entrainment in plunging pool.
- Effects of jet disturbance levels on turbulent and air-water flow properties.
- Quantification of bubbly flow turbulence intensity using a total pressure sensor.

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ABSTRACT

A plunging jet is an efficient device to entrain gas into liquid flow. In many practical occasions, the gas entrainment needs to be carefully controlled, and the interaction between the shear flow turbulence and entrained bubbles has to be better understood. This paper presents a physical study of vertical supported two-dimensional plunging jets using a relatively large-size facility. The air-water flow and turbulence properties were measured with an intrusive phase-detection probe and a total pressure sensor simultaneously. The inflow pre-aeration and turbulence level of the falling jet were carefully characterised, and the effects of jet impact velocity and jet length on air entrainment in plunging pool were investigated. The experimental results were systematically compared to relevant studies. A discussion was developed on the quantification of turbulence intensity in highly-aerated flow based on total pressure measurement. The flow turbulence properties were derived respectively from the interfacial phase-detection signals and total pressure signals. The results highlighted difference in terms of the turbulence intensities between interfacial motions and water-phase turbulence. The present work showed that the jet impact velocity, jet length, inflow disturbance and pre-entrainment of air had considerable effects on air entrainment capacity and subsurface air-water flow properties in plunging jets hence should be carefully characterised in relevant studies.

1. Introduction

A plunging jet is the impingement of a rapid jet into a slower body of fluid. The occurrence of a plunging liquid jet is often accompanied by the entrainment of environmental gas at the intersection between the jet and the receiving bath, namely, along the impingement perimeter (Ervine et al., 1980). The flow in the downstream vicinity of the impingement point is a two-phase mixing flow with development of a turbulent shear layer (Thomas et al., 1983; Chanson, 1997). The intense turbulence and its interaction with the entrained gas bubbles enhance the mixing of fast and slow liquid fluids, as well as the mass and heat transfer between the gas and liquid phases (Chanson, 2009).

While a natural plunging jet flow such as a waterfall or a plunging wave is mostly an uncontrolled hydraulic phenomenon, an artificial plunging jet can be generated easily in a relatively stable manner and used as a device to facilitate fluid mixing in industrial processes, like in chemical reactors and water treatment plants (Bin, 1993; Kiger and Duncan, 2012). There are numerous occasions where the flow aeration associated with the jet impingement is beneficial (e.g. wastewater re-oxygenation, fish farming industry) or, contrarily, undesirable hence must be minimised (e.g. bottle filling, steel industry, nuclear reactor cooling system) (Kirchner,

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1974; Van de Donk, 1981; Qu et al., 2011). Understanding the gas entrainment mechanisms, bubble diffusion processes and bubble-turbulence interplay is of fundamental importance for a safe and economical design/operation in these applications.

The most common plunging jets are water jets with free-surface open to air. Physical modelling and theoretical analysis demonstrated the critical role of the jet impact velocity on the onset of air entrainment and the air-water flow patterns underneath the impingement point (Sene, 1988; Bin, 1993). The jet disturbance is another key parameter, often linked with the jet length, local velocity turbulence and flow instabilities (Qu et al., 2011; Kiger and Duncan, 2012). While the air entrainment regimes were successfully investigated with high-speed flow visualisation (Chirichella et al., 2002), detailed characterisation of air-water flow properties in the plunging pool relied more upon intrusive phase-detection techniques (Serizawa et al., 1975; Brattberg and Chanson, 1998). Basic air-water flow properties that are of direct concern to engineering applications include void fraction, air entrainment rate, bubble size and penetration depth. These characteristics were well documented in literature for various types (circular/planar, laminar/turbulent) of jets (Lin and Donnelly, 1966; McKeogh and Ervine, 1981; Clanet and Lasheras, 1997; Cummings and Chanson, 1997a, 1997b; Chanson and Manasseh, 2003; Soh et al., 2005). The development in data processing and analysis in the past decade enabled further insight into the multiphase turbulence in terms of interfacial turbulence intensity, bubble clustering and integral turbulent length/time scales (Chanson and Carosi, 2007; Wang et al., 2014). Such measure of turbulence level in highly-aerated flow is difficult because of the presence of air bubbles, which not only limits the deployment of traditional monophase-flow measurement techniques, but also challenges the numerical modelling when the simulation results required verification against quantified bubble-turbulence interactions like bubble grouping and turbulence modification (Mudde, 2005). For plunging jet flows, there is lack of experimental study providing benchmark data on such detailed levels, and the current understanding on this highly-aerated, highly-turbulent flow is still vague.

To date, a number of studies demonstrated the impact of inflow turbulence on the inception conditions of air bubble entrainment (Ervine et al., 1980; Cummings and Chanson, 1999). Yet no study recorded quantitatively the impact of inflow turbulence levels on the two-phase flow properties for jet velocities substantially larger than the onset velocity. Herein the present study aimed to investigate the air-water flow properties in two-dimensional plunging jets and the processes of bubble advection and diffusion under the impact of intense turbulence. Physical experiments were performed using relatively large facilities and latest data analysis techniques. Systematic comparison was developed with particular focus on the effects of different inflow turbulence conditions of the jets upon the air entrainment and two-phase flow characteristics in the plunging pool. The effects of impact velocity and jet length were also tested for a range of flow conditions. The experimental results are presented in the order of jet pre-aeration and turbulence level, air-water flow properties in the plunging pool, two-phase turbulence properties in the plunging pool, and air entrainment rate.

2. Experimental setup and data processing

2.1. Experimental facility

The experimental setup was a two-dimensional vertical supported planar water jet. The apparatus consisted of a rectangular jet nozzle, a receiving water tank and the water supply system. Fig. 1 illustrates the experimental facility (Fig. 1a) and a detailed side-view sketch of the nozzle and the jet (Fig. 1b), where x, y, z are respectively the longitudinal, normal and transverse coordinates. Water was fed into the nozzle from a constant-head tank for discharges no greater than 0.0137 m^3/s and from a high-head pump for larger flow rates up to 0.038 m^3/s. The flow rates were measured respectively using an orifice meter and a Venturi meter in the feeding pipelines, with expected accuracy within ±2%, and the conservation of mass was checked for all experimental results. The rectangular nozzle was 0.269 m wide with a 0.012 m opening, discharging a quasi-two-dimensional planar jet into a large receiving tank. The free-falling jet was supported by a full-width PVC sheet extending from the nozzle edge into the receiving pool. The jet support was 0.35 m long, equipped with transparent sidewall windows to facilitate visual observation. The nozzle and the jet support were set at 88.5° from the horizontal to prevent jet detachment. The receiving tank was 2.5 m long, 1 m wide and 1.5 deep, built with a sharp-crest weir that allowed for a constant water level in the tank during the experiment (Fig. 1a). The large pool setup ensured that the air entrainment and diffusion processes in upper part of the pool were free of stagnation pressure or boundary friction effects of the tank walls.

The same jet nozzle was used in the previous work of Cummings and Chanson (1997a, 1997b, 1999), Brattberg and Chanson (1998) and Bertola et al. (2017). Table 1 summarises the respective flow conditions, along with remarks on the respective instrumentation, scanning rate and duration. Compared to the work in 1990s, the pipeline system and receiving tank were newly constructed, and the instruments had different sensor sizes. The sampling duration was substantially increased from less than 3 s to 90 s according to a sensitivity study. New data collection and processing techniques developed over the past two decades were adopted (Chanson and Carosi, 2007; Wang et al., 2014). The recent work of Bertola et al. (2017) was conducted using the same facility and instrumentation, except for a modified inflow condition in the present experiments linked to the installation of flow redistributors at upstream of the jet nozzle (Fig. 1b). The flow redistributors were a series of mesh rollers fitting in the pipe T-junction. They were introduced to reduce the three-dimensional flow instabilities noted by Bertola et al. (2017). The effects of the mesh rollers on jet turbulence modification and the consequential plunging jet air entrainment are discussed specifically in this paper.

2.2. Experimental instrumentation

The air-water flow properties were measured locally with an intrusive dual-tip phase-detection probe. The probe was equipped with two parallel needle sensors. Each needle sensor had a core electrode ($\varnothing = 0.25$ mm) isolated from an outer electrode ($\varnothing = 0.8$ mm). Bubbles were advected in the flow, and the air-water interfaces were detected by the sensor tip based on the change in electro-resistance between the core and outer electrodes when the sensor tip was in air or water phases (Crowe et al., 1998). The two sensors were aligned vertically against the jet flow direction, with a transverse separation $\Delta z = 2$ mm and a longitudinal distance $\Delta x = 7.1$ mm between the leading and trailing tips. Both sensors were sampled simultaneously at 20 kHz for 90 s at each measurement location. While the basic air-water flow properties such as the void fraction and bubble count rate were derived from the time series of the phase-detection probe signal, a correlation analysis of the signals of two sensors provided further turbulence properties including air-water interfacial velocity and turbulent length/time scales (Chanson and Carosi, 2007).

A miniature total pressure sensor was attached next to the phase-detection probe to measure the local instantaneous total pressure of the air-water flow. The pressure sensor had a 5 mm