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Far-field properties of aerated water jets in air

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ABSTRACT

This paper presents an experimental investigation on aerated water jets at a 45° angle into air. Different amount of air was injected into the water jets upstream of a circular nozzle. The focus was on the bulk trajectories of the aerated jets, as well as the intensity, size and velocity of the water drops in the far-field. It was found that, the injection of air into water jets will significantly accelerate water jet breakup in air, causing the water jet to spread much wider and more uniform. Meanwhile, water drop size became substantially smaller, but drop velocity only became slightly smaller. On the horizontal plane at the same elevation of the nozzle, intensity of falling water drops was noticed to have a Gaussian distribution in the transverse direction, while a left-skewed Gaussian distribution in the longitudinal direction. At the location of maximum intensity, drop size and velocity distributions also approximated Gaussian distributions, while the size distribution could be more complex in a pure water jet. Terminal water drop velocity was correlated with drop diameter, and its value was 20% smaller in an aerated jet than in a pure water jet for the drops with diameters of 2–10 mm. The energy dissipation of these jets was significant as these jets broke down to drops with relatively small terminal velocities.

Introduction

Liquid jets in air have been studied extensively as they have wide applications in hydraulic structures (Chanson, 2009; Pfister et al., 2014), sewer dropshafts (Zhang et al., 2014; Camino et al., 2015), fountains, irrigation, fire extinction, atmosphere cleaning, industrial painting or printing, chemical reactors, atomization and spray, among others (Lefebvre, 2000; Surma and Friedel, 2004; Dumouchel, 2008; Chanson, 2009; Gowing et al., 2010; Osta et al., 2012). Most of the studies concentrated on liquid–air multiphase flow properties near the injection nozzle (near-field) such as liquid jet breakup, instability analysis, drop or spray formation, and multiphase flow dynamics (e.g., Bogy, 1979; Hoyt et al., 1974; Faeth et al., 1995; Sallam et al., 2002; Birouk and Lekic, 2009; Portillo et al., 2011). Only limited studies examined the far-field behavior of liquid jets: Rajaratnam et al. (1994) and Rajaratnam and Albers (1998) studied high-speed (85–160 m/s) water jets in air up to 2500 times of the nozzle diameter but without details on water drop properties such as size and its distribution. Guha et al. (2010) numerically simulated these high-speed jets.

A water jet mixed with a certain amount of air at the injection point, called an aerated water jet in this study, is of particular interest. In dam spillways, high-speed water jets quickly become aerated by entraining the ambient air. After leaving spillways, the aerated jets eject into the air at certain angles and then impinge into the plunging pool (Vischer and Hager, 1995; Pfister et al., 2014). The breakup of the jets in air can directly impact on the level of total dissolved gases in the downstream rivers and fish-kill (Geldert et al., 1998; Orlins and Gulliver, 2000; Politano et al., 2009). Compared to pure liquid jets, aerated jets in air are expected to have different behavior.

Aerated liquid jets are usually produced using two types of artificial aeration in addition to the self-aeration as in dam spillways. The first type is to mix air and liquid in a mixing chamber/injector upstream of the injection nozzle (Surma and Friedel, 2004; Gowing et al., 2010; Wu et al., 2012). In Surma and Friedel (2004), aerated water jets were injected horizontally via a nozzle into a test chamber. Drop velocity was measured by using a phase Doppler anemometer within a distance of approximately 140 times of the nozzle diameter. Longitudinal and radial distributions of axial drop velocity were presented. However, their study was close to the nozzle, and no results were reported on drop sizes, drop concentration and water-phase/rain intensity. Gowing et al. (2010) and Wu et al. (2012) experimentally and numerically studied aerated water jets in air, but they focused on the bubbly flow inside the nozzles

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and on the augment of thrust due to air injection for marine propulsion devices.

The second type of artificial aeration is to mix air and liquid outside of the nozzle using coflowing (co-axial) two-phase jets. Coflowing two-phase jets are mostly related with twin-fluid atomization, in which a fast air jet is coflowing with a liquid jet and its kinetic energy is used to aid the breakup of liquid-phase. Extensive studies have been reported (Lin and Reitz, 1998; Lasheras and Hopfinger, 2000; Morozumi and Fukai, 2004; Sevilla et al., 2005; Matas and Cartellier, 2013). Recently Avulapati and Venkata (2013) reported a variant of coflowing two-phase jets, in which a gas flow was injected on to the impinging point of two liquid jets to assist atomization. Similarly, most of these studies were near the nozzle with a focus on the liquid breakup and drop properties.

Relevant to the studies of aerated jets in air, some studies on aerated jets in liquid have been reported: Lima Neto et al. (2008) in stagnant ambient water, and Zhang and Zhu (2013, 2014) in crossflowing water. They found that, compared to pure air injection, the introduction of liquid phase into the gas phase prior to the nozzle exit was found to significantly decrease bubble diameter. Lima Neto et al. (2008) and Zhang and Zhu (2013) also reported a criterion for producing small gas bubbles with relatively uniform sizes.

Based on the above studies, one would expect that, for water jets in air, adding air into the water jets upstream of the nozzle will be able to promote the breakup of water jets and produce smaller and more uniform water drops. This might be a useful alternative to the traditional way of liquid atomization using small orifices (Sharma and Fang, 2014), non-circular nozzles (Kasyap et al., 2009; Farvardin and Dolatabadi, 2013; Sharma and Fang, 2014) and other specially-designed nozzles (e.g., varying the injector length/diameter ratio in Osta et al., 2012).

This study reports an experimental study on aerated water jets at an angle into the air. The focus is on far-field drop properties in the horizontal plane at the same elevation of the nozzle, including longitudinal and transverse distributions of water/rain intensity, drop size and drop velocity. Effect of increasing initial gas volume fractions of aerated jets on these drop properties were examined in two groups of experiments: fixing the water flow rate in the first group, and fixing the water jet exit velocity in the second group.

Experimental setup and procedure

The experiments of aerated water jets in air were conducted in the T. Blench Hydraulics Laboratory at the University of Alberta (see Fig. 1 for the setup). All the ventilation openings in the laboratory were closed to avoid any wind effect on the jets. Air and water were pre-mixed using a Venturi injector (Model 2081-A, Mazzei Injector Corp.) before the mixture exited the nozzle. The air was supplied from a gas line in the laboratory and its gauge pressure was controlled at 5 atm using a pressure-regulating value. The air flow rate was controlled using an air rotameter with an accuracy of 3% (FL-2044, Omega Engineering Inc.). The water was supplied by using a pump controlled with a variable frequency drive. The water flow rate was measured using a magnetic flow meter. A brass nozzle was specially made as shown in the insert of Fig. 1. The nozzle's inner diameter contracted from 25.4 mm (same as the inner diameter of the PVC pipe that connected the nozzle and the Venturi injector) to d_0 = 6 mm (d_0 is the nozzle exit diameter). This gradual change prevented any significant disturbance to the jets by the nozzle itself.

Different ratios of air–water mixtures were injected at an angle of 45° into the air. Table 1 lists five experimental conditions, which can be divided into two groups. In the first group (Expt. #1–3), the water flow rate Q_w was kept constantly at 18 liters per minute (LPM), while the air flow rate Q_a was changed from 0 to 30 LPM. Therefore, the initial gas volume fraction of aerated jets $C_0 = Q_a/(Q_a + Q_w)$ was changed from 0% (pure water jet) to 63%. In the second group (Expt. #4–5), the liquid-phase (water) velocity at the nozzle exit $U_{w0} = 4Q_w/[(1 - C_0)\pi d_0^2]$ was maintained the same (16.5 m/s) as in Expt. #2, while C_0 was similarly changed from 0% to 63%. The liquid-phase velocity is an estimate of velocity of the liquid exiting the nozzle under the assumption that the area ratio occupied by the liquid-phase at the exit is the same as the liquid volume fraction ($1 - C_0$). The two groups of experiments were designed to examine the effect of changing C_0 on jet properties while keeping a constant value of Q_w and U_{w0}, respectively.

Rain of falling water drops was collected in the horizontal plane (*xy* plane in Fig. 1) at the same elevation of the nozzle exit and 2 m above the ground to avoid any backsplash of water from the ground. In each experiment, the study plane was divided into two or three regions based on rain intensity. And

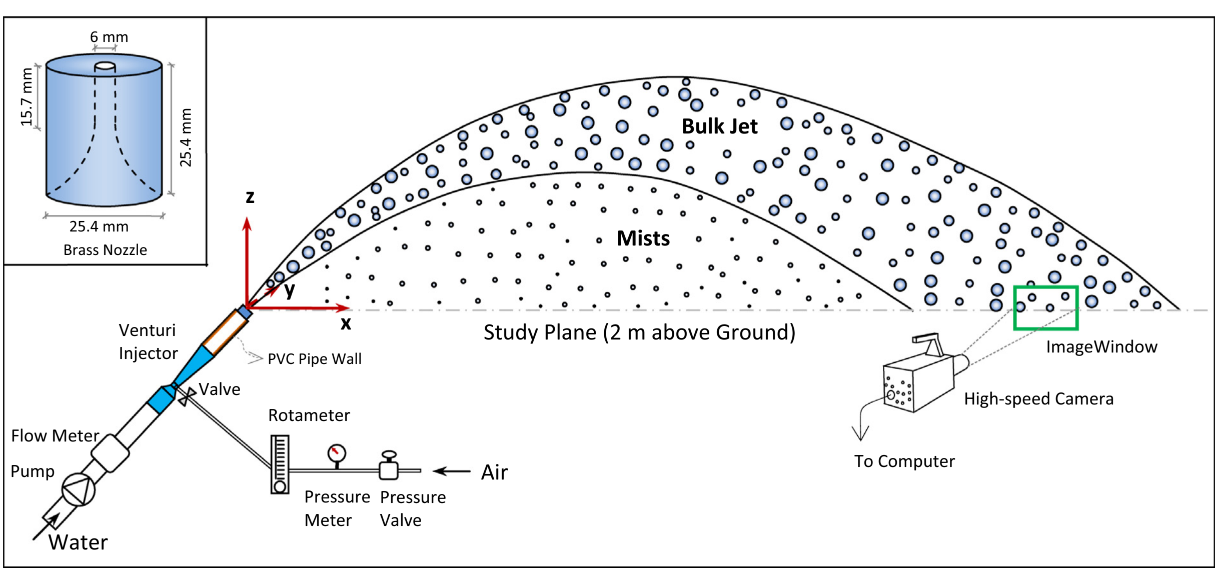

Fig. 1. Schematic of the experimental setup. Details of the nozzle are shown in the insert.