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Spray characteristics of free air-on-water impinging jets

Y. Xia[a], M. Alshehhi[a], Y. Hardalupas[b], L. Khezzar[a,*]

[a] Mechanical Engineering Department, Khalifa University of Science and Technology, Petroleum Institute, Abu Dhabi, United Arab Emirates
[b] Mechanical Engineering Department, Imperial College London, London, UK

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A B S T R A C T

Characteristics of a water-on-air free impinging jets atomizer is investigated in this study by means of flow visualization using high speed photography with Phase Doppler Anemometry (PDA) to measure the droplet size and velocity. Spray structures and breakup process are illustrated with the aid of images captured for the water and air jets impinging at 45°. The breakup length of the water jet decreases with the increase of the air to liquid jet momentum flux ratio (*ALMFR*) and remains constant for values of *ALMFR* larger than 1. Divergence and deflection spray angles increase rapidly with the air to liquid momentum ratio (*ALMR*) and then remain constant for values of *ALMR* larger than 4. A larger impinging angle leads to a smaller breakup length and larger spray angles. PDA results indicate that the planar distribution of droplet size is symmetrical around the Y-axis, but not around the X-axis. Smaller droplets are located near the spray center, but their location varies for different experimental conditions, with the minimum value of $D_{32} = 50\,\mu m$ and increasing to around $120\,\mu m$ at the outer region of the spray for conditions $Q_L = 100$ mL/min, $\dot{m}_g = 13.5$ g/min and $\theta = 45°$. The spatially-averaged Sauter mean diameter (SMD), representing the average size of droplets over a cross section plane of a spray, is defined and it remains the same at any cross section of the spray operating with the same experimental conditions. Spatially-averaged SMD is found to decrease with the increase of *ALMR*. Droplet mean velocity is the largest at the position downstream of the air jet exit (14 m/s at a plane of z = 75 mm in the spray with $Q_L = 100$ mL/min, $\dot{m}_g = 13.5$ g/min and $\theta = 45°$) and decreases gradually with increasing distance from the point where droplets with the maximum velocity are located. The study makes up for the spray visualization of the study of a single water jet impinging on a single air jet externally, and provides more information on the spray characteristics of this injector, which will contribute to the evaluation of improved computational models and improved injector design.

1. Introduction

Liquid jet atomization is encountered in various applications, such as gas turbines, rocket engines and industrial furnaces. In such systems, it is recognized that higher volumetric heat release rates, easier ignition, a wider burning range and less exhaust pollutant emissions can be achieved by reducing the generated mean drop size in most combustion cases (Lefebvre, 1985; Rink and Lefebvre, 1986). Therefore, understanding of factors affecting the mean drop size and its control is crucial for the design and proper operation of such systems.

The need for improved combustion control has motivated the development of different atomizer configurations to acquire better atomization with high rates of mixing and surface area of liquid fuels, among which twin-fluid atomizers have attracted particular attention since they can lead to satisfactory atomization with relative slow moving liquid (Lefebvre, 1988). Numerous studies on various designs of twin-fluid atomizers have been conducted in an effort to derive better understanding of the atomizers' performance and resulting spray characteristics, such as effervescent atomizer (Sovani et al., 2001; Jedelsky et al., 2009; Gomez et al., 2011), air-blast atomizer (Chigier and Farago, 1992; Engelbert et al., 1995; Lasheras and Hopfinger, 2000; Strasser and Battaglia, 2017), air-assist atomizer (Avulapati and Venkata, 2013; Inoue et al., 2013; Avulapati and Ravikrishna, 2015; Xia et al., 2017), flow blurring atomizer (Gañán-Calvo, 2005; Simmons and Agrawal, 2010; Jiang et al., 2014; Niguse and Agrawal, 2016;), liquid jet in cross flow (Lubarsky et al., 2012; Kourmatzis and Masri, 2015; Jadidi et al., 2016).

Impinging jets atomizers with one gas and two-liquid jets have also been considered by Avulapati and Venkata (2013), Avulapati and Ravikrishna (2015), and Xia et al. (2017). In Xia et al. (2017), the spray characteristics have been quantified. In contrast to this configuration, performance characteristics of another variant of impinging jets atomizers consisting of one liquid

* Corresponding author.
E-mail address: lkhezzar@pi.ac.ae (L. Khezzar).

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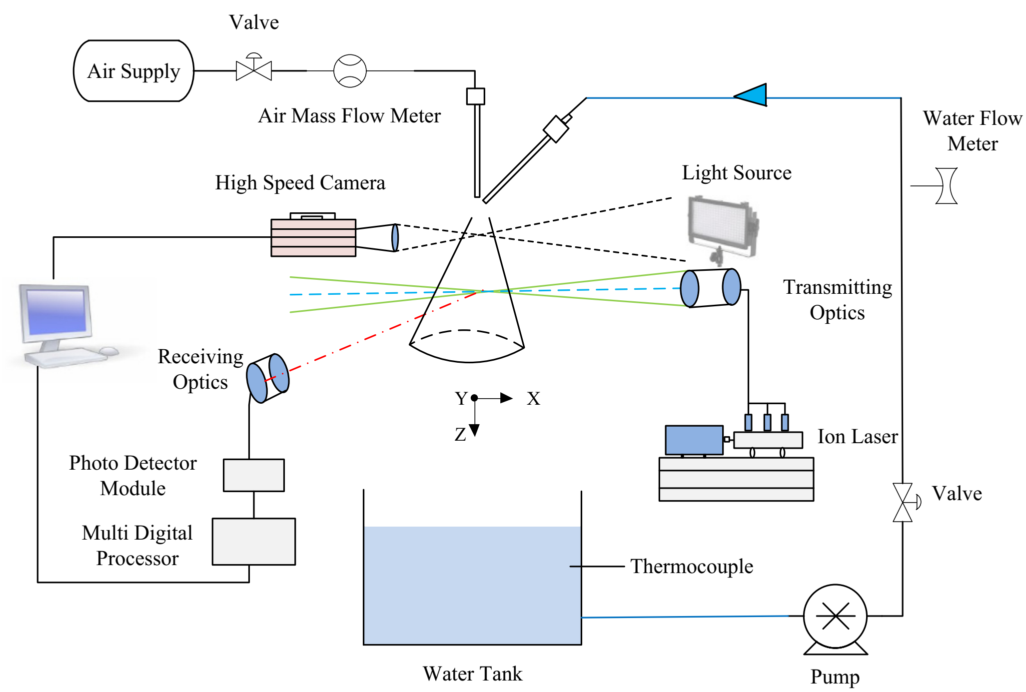

Fig. 1. Schematic of the experimental setup.

jet impinging onto another gas jet have not received equal attention as the other atomizers. So far, according to the authors' knowledge, this configuration of atomizer has only been mentioned by Boden et al. (1999) and Prabhakaran and Basavanahalli (2013). Boden et al. (1999) carried out an experimental study of such an air-water impinging jets atomizer using phase Doppler anemometry (PDA) to investigate the effects of air to liquid momentum ratio, impinging angle and initial jet diameter on the atomization efficiency. Increase of liquid flow rate is found to worsen the atomization, while the impinging angle of the two jets did not affect the atomization efficiency. However, the spray structure is not presented due to the absence of visualization of the liquid breakup process. Prabhakaran and Basavanahalli (2013) recently re-examined characteristics of the spray from such a configuration of gas-liquid impinging injector trying to figure out a unifying parameter that can combine several influencing factors based on results obtained from photography and Malvern particle analyzer. Their results, which contained droplet size information only, indicate that the impinging angle of the jets affects the Sauter mean diameter (D_{32}) of the spray droplets in contrast to previous findings.

In order to shed more light on this configuration of liquid-gas impinging atomizer, a vertical air jet impinging on an inclined liquid jet is considered. The study consists of flow visualization using high speed camera and simultaneous droplet size and velocity measurements with phase Doppler anemometry (PDA). In addition, liquid jet breakup length and spray angles are quantified based on spray images captured by the high speed camera.

The resulting spray from this water-air impinging atomizer is not axisymmetric, and in order to evaluate the atomization efficiency at different conditions independently of the rate of spread of the droplets, which varies with droplet size, it is not enough to solely consider the centerline values of D_{32}, since the droplet sizes away from the centerline can be also varying and are not taken into account when evaluating atomization efficiency. Therefore, a weighted spatially averaged Sauter mean diameter (SMD), integrated over a cross section plane of the spray, is used to quantify the atomization efficiency. This is defined as:

$$\overline{D_{32}} = \frac{\int D_{32}(x,y)G(x,y)dxdy}{\int G(x,y)dxdy} \tag{1}$$

where D_{32}(x,y) is the local value of the measured SMD at the point (x,y) of the spray, G(x,y) is the local volume flux of the droplets, measured by the PDA, and *dxdy* is the elemental area of the local measurement point inside the spray. The rest of this manuscript contains a description of the experimental setup and measurement techniques, followed by the presentation of the results and conclusions.

2. Experimental set up and measurement techniques

The experiment was conducted at an ambient room temperature of 20 °C and atmospheric pressure. High speed photography and PDA are separately used to conduct spray visualization and simultaneous droplet size and velocity measurements, respectively.

The schematic of the test rig is shown in Fig. 1, of which the main components include a water-air impinging jets atomizer, the high speed camera and PDA systems.

The air jet is vertical and impinges on an inclined water jet. Water and air flowrates were supplied and controlled independently. A magnetically coupled centrifugal pump, together with a needle valve and a calibrated Omega water flow meter of 1% accuracy, is employed to transport the water from a tank to the water jet nozzle. Compressed air from the centralized compressor system is supplied to the air jet nozzle and the air flow rate is metered using an Alicat mass flow meter with an accuracy of ±0.3% reading +0.2% F.S. The spray is collected by the water tank after ejection.

The water-air impinging jets atomizer, as shown in Fig. 2, is made of two stainless steel pipes, of which the water pipe diameter is 0.686 mm, while the air pipe diameter is 1 mm. The water and air pipes are 152.4 and 304.8 mm in length, so the length to diameter ratios *L/d* for water and air jets are 222.2 and 304.8 respectively, ensuring fully developed conditions at the exit of both air and liquid nozzles. The two pipes are fixed onto a manufactured well aligned frame and the distance between the nozzle exit and the geometrical impingement point *O* is 10 mm for both air and water pipes. The impinging angle between the