International Journal of Multiphase Flow 77 (2015) 19–31

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmultiphaseflow

Twin-fluid atomization of viscous liquids: The effect of atomizer construction on breakup process, spray stability and droplet size

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ARTICLE INFO

Article history:
Received 28 January 2015
Revised 9 June 2015
Accepted 30 June 2015
Available online 7 July 2015

Keywords:
Twin-fluid atomizer
Two-phase flow
Atomization
Liquid breakup
Spray imagining
Spray stability
Comparison of atomizers

ABSTRACT

This study focuses on the low-pressure spraying of viscous liquids (μ = 60, 147 and 308 mPa s) using four types of internal-mixing twin-fluid atomizers. We compare two well-known designs, namely the Y-jet and "outside in gas" (OIG) effervescent atomizers, with our new design (CFT) and an "outside in liquid" (OIL) configuration for the effervescent atomizer. The atomizers were operated by two gas inlet pressures (0.14 and 0.28 MPa) and various gas-to-liquid ratios (GLR = 2.5%, 5%, 10% and 20%). The comparison focused on internal liquid–gas flow, spray stability, primary breakup, and droplet size.

The primary breakup was investigated using a high-speed camera. A near-nozzle spray pattern was related to the ratio of forces, which affects liquid deformation, by dimensionless numbers. The breakup was driven mainly by air resistance in the OIG, OIL, and CFT atomizers and by surface tension in the Y-jet atomizer.

The OIL and Y-jet atomizers provided the most stable spray, regardless of the working regime or atomized liquid. The OIL atomizer produced the smallest droplets at low GLRs, while the droplet sizes for the Y-jet atomizer increased significantly at low GLRs. For the OIG atomizer, spray stability was influenced by the GLR, with the best stability being achieved at a GLR of 10% and 20%. The presence of large droplets at a low GLR caused an increase in droplet size. Switching the inlet ports of the effervescent atomizer (OIG–OIL) affected the internal flow, which differed under the same working regimes for these two configurations. The internal flow pattern of the OIL atomizer was estimated to be annular for all regimes, while for the OIG atomizer, it changed from a plug to slug flow with an increase in the GLR.

Introduction

Internal-mixing twin-fluid atomizers have been used in countless commercial applications over the recent decades, such as in gas turbine engines (Lefebvre, 1988), internal combustion engines (Wade et al., 1999), scramjet engines (Gadgil and Raghunandan, 2011), spray drying (Mujumdar et al., 2010), spray coating (Esfarjani and Dolatabadi, 2009; Qian et al., 2011), process industries (Loebker and Empie, 1997) and fire suppression (Huang et al., 2011; Lal et al., 2010). Y-jet nozzles in particular have been widely used in oil boilers, industrial furnaces, agricultural sprays, spray dryers and paint sprays (Zhou et al., 2010).

Atomizers with internal mixing are favored for their good atomization quality at low pressure (Sovani et al., 2001) and their low sensitivity to a liquid's rheological properties when compared with high-pressure atomizers. Twin-fluid atomizers provide easy and independent control of the individual spray parameters (Karnawat and Kushari, 2006). The consumption of atomizing gas is lower than with their externally mixed counterparts.

The capability to process highly viscous liquids is advantageous in several areas, especially in the combustion of heavy fuels, liquid wastes (Buckner et al., 1990; Ferreira et al., 2009; Jedelsky et al., 2009; Kermes et al., 2008; Loebker et al., 1998), coal–water (Chawla, 1985; Daviault et al., 2012; Jagannathan et al., 2011), and coke sludge slurries. It also helps in the spray drying of food (with suspensions of water and gelatinized native corn starch or native waxy corn starch, Schröder et al., 2011) and pharmaceutical and consumer products (PEO solutions (Broniarz-Press et al., 2010) such as water–oil emulsions (Broniarz-Press et al., 2009; Schröder et al., 2012), black liquor (Risberg and Marklund, 2009), and liquids for fluid catalytic cracking (Jolodar et al., 2005).

Published designs for internal-mixing twin-fluid atomizers appear in a variety of internal configurations, as indicated above

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2015.06.010
0301-9322/

and in several reviews (Jedelsky et al., 2009; Sovani et al., 2001). The internal design of an atomizer certainly affects its performance and predetermines its possible uses. In some applications—such as combustion, surface coating, and powder generation—a temporally unsteady spray has a negative effect. For example, it leads to increased combustion noise and it puts extra load on the combustion chamber. On the other hand, some engineering applications can profit from such an unsteady spray. For example, it can enhance the air entrainment rate in consumer products (Liu et al., 2011; Panao and Moreira, 2005). The generation of a fine spray, or the ability to control spray size, is a traditionally common requirement for most applications.

The internal flow is a process that greatly influences the work of twin-fluid atomizers (Buckner and Sojka, 1991; Lorcher et al., 2003; Stähle et al., 2014). This can be estimated using theoretical flow regime maps (Barnea, 1987) or experimental ones (Baker, 1954; Hewitt and Roberts, 1969; Golan and Stenning, 1969). Theoretical maps have the advantage of not being limited by experimental parameters. Experimental maps, meanwhile, can only be applied with the specific range of experimental parameters (e.g. pipe size, working fluids, GLR) specified by the researcher. This disadvantage was partially solved by Schicht (1969) and Weisman and Kang (1981) when they attempted to find generalized dimensionless parameters to cover a wide range of working parameters. Another approach to identify the internal flow, which is especially useful for Y-jet atomizers, was introduced by Song and Lee (1996). He used the liquid-to-gas momentum ratio $\Phi = m_l^2 \cdot d_l^2 \cdot \rho_g \cdot \sin\Theta / (m_g^2 \cdot d_g^2 \cdot \rho_l)$ and related it to the observed internal flow regime. Here, the mass flux per surface unit is denoted as "m", density as "ρ", port diameter as "d" and the intersecting angle as "Θ". The indexes "l" and "g" denote the liquid or gas.

A number of studies deal with twin-fluid atomizers (Ochowiak, 2013), Xiuyuan et al., 2013; Pougatch et al., 2014; Barroso et al., 2014; Hong et al., 2014), but these are very rarely compared. Chung et al. (2000), Lincheta et al. (2002), Ferreira et al. (2009) or Gottlieb and Schwartzbach (2004) compare their designs with commercial atomizers, but this does not extend over several types of these devices. In this paper, we therefore decided to provide a systematic comparison of four selected twin-fluid atomizers that differ widely in their mixing principles under the same working conditions. According to the available literature, each type was evaluated in several variations of its internal dimensions, with the best being chosen for this study. Our aim was to investigate differences in the breakup process, spray stability and droplet size while spraying liquids of different viscosity. We judged their performance and evaluated their potential for various applications. The Y-jet and OIG atomizers are well-known atomizing devices that are widely used in many industrial applications (Mullinger and Chigier, 1974; Lefebvre, 1988; Chung et al., 2000; Sovani et al., 2001). The OIL atomizer is a variant of the effervescent atomizer, where the liquid and gas ports are switched, thus influencing the mixing mechanism of the flow components. The CFT atomizer is a new design that was recently developed at the Brno University of Technology. It was inspired by atomizers invented by Chin (1995), Ferreira e al. (2001), and Tamaki et al. (2004), and its name represents the initials of these authors.

Experiment

The near-nozzle spray was observed using a high-speed camera (OLYMPUS i-speed2) with a framerate of 10,000 fps and an exposition time of 5 μs. The measuring volume was illuminated by a continual LED light with a light diffuser being used to provide a uniform image background (Fig. 1). The focusing optics comprised a PENTAX TV lens (50 mm, f1:1.4) with extension rings for a total length of 25 mm in order to achieve image magnification. Droplet sizes were measured 100 mm downstream of the discharge orifice using a Malvern Spraytec laser diffraction system.

The atomizers were operated under a wide range of working parameters defined by the inlet air pressure ($\Delta p = 0.14$ and 0.28 MPa) and gas-to-liquid ratio of the mass (GLR = 2.5%, 5%, 10% and 20%). Three liquids of different viscosity were sprayed (Table 1). The temperature of the air and liquid was kept within 18–20 °C.

The air inlet pressure was kept constant for varying GLRs. The liquid injection pressure was changed as GLR changed to compensate for the pressure loss between the liquid inlet port and the mixing chamber of the atomizer. This value was measured for safety reasons, namely for the load on the hydraulic system, but it was not recorded.

Experimental rig

A simplified schematic of the test rig is shown in Fig. 2. An eccentric screw pump (2NL 20A, Erich Netzsch GmbH & Co. Holding KG, Selb, Germany) was used at a constant rotation speed to

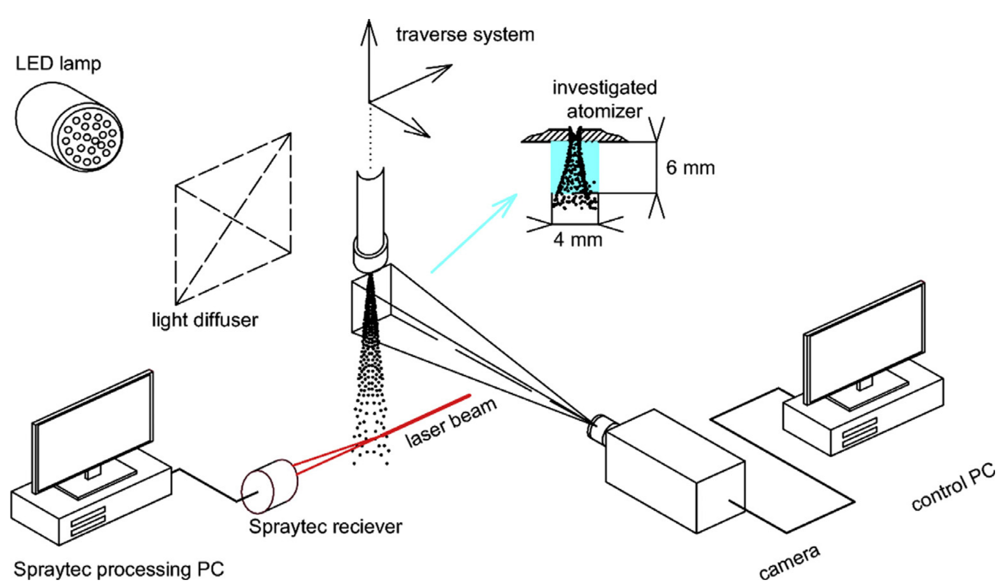

Fig. 1. Arrangement of the measurement and visualization systems.