International Journal of Multiphase Flow 89 (2017) 277–289

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Low-pressure twin-fluid atomization: Effect of mixing process on spray formation

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ARTICLE INFO

Article history:
Received 20 January 2016
Revised 18 September 2016
Accepted 30 October 2016
Available online 18 November 2016

Keywords:
Low-pressure
Atomization
Twin-fluid
Droplet dynamics
Liquid breakup
Back illumination

ABSTRACT

The present work comparably examines four different twin-fluid atomizers operated under the same operating conditions. Spray formation was examined by several approaches. The internal flow pattern was estimated using a simplified analytical approach, and the results were supported by the observation of the liquid discharge in the near-nozzle region. A high-speed back illumination was used for visualisation of the primary breakup. In the region of fully developed spray, the dynamics of droplets was studied using a phase-Doppler analyser (PDA). The information obtained from all methods was then correlated. Results show that the spray formation process depends mainly on the internal design of twin-fluid atomizer at low gas to liquid ratios (GLR). The amount of gas influences the character of the internal two-phase flow, a mechanism of the liquid breakup, droplet dynamics and a resulting drop size distribution. Differences among the atomizers are reduced with the increase in GLR. Moreover, it was shown that a certain mixing process can inherently create the annular internal flow which generates a stable spray characterized by relatively low mean droplet size.

1. Introduction

Twin-fluid atomization is a method for spraying of liquids using an additional medium – pressurized gas that enhances the liquid breakup. Twin-fluid atomizers are common in various industrial applications, e.g. liquid fuel spray, drying in food processes, etc. According to the mixing process, the twin-fluid atomizers can be divided into internal-mixing and external-mixing types. This work focuses on the variations of the internal-mixing nozzles.

Featured designs of internal-mixing atomizers have been examined in detail, such as the effervescent atomizer (Sovani et al., 2001; Konstantinov et al., 2010) or the Y-Jet atomizer (Mullinger and Chigier, 1974; Song and Lee, 1996; Pacifico and Yanagihara, 2014). It was proved that effervescent atomizers can operate at relatively low-pressures compared to conventional pressure atomizers, and at a low consumption of gas in comparison with air-blast atomizers as noted in Sovani et al. (2001). Moreover, they are relatively insensitive to rheological parameters of liquid due to a specific mechanism of liquid breakup – bubble explosions (Konstantinov et al., 2010). This breakup mechanism is conditional by the bubbly internal two-phase flow. When this two-phase flow passes through the exit orifice, the gas bubble expands rapidly and shatters the liquid into the smaller fractions. Mullinger and Chigier (1974) showed that the liquid breakup mechanism in the Y-jet atomizer is relatively insensitive to the operating regime. Because of these advantages, together with a simple construction and large exit orifices, these techniques are now frequently used in industry; the main domain of their use is spraying of highly viscous liquid fuels for combustion applications (Konstantinov et al., 2010).

Formation of the spray generated by an internal-mixing twin-fluid atomizer begins inside its body. The internal flow determines the way the liquid disintegrates and how the spray develops in time and space. The character of the internal two-phase flow depends mainly on the gas to liquid ratio (Konstantinov et al., 2010) and, as noted in Mlkvik et al. (2015), on the internal design of the atomizer. Main features of the internal design are the diameter of mixing chamber, the number of aerator holes and the way the fluids mix inside (Gadgil and Raghunandan 2011a; Jedelsky et al., 2009). Further parameters, such as the operating pressure (Li et al., 2012) and fluid's physical properties, have a lesser influence on the flow pattern (Liu et al., 2011; Lund et al., 1993; Stähle et al., 2015a).

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.10.015
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The internal two-phase flow was examined by several approaches: The experiments were conducted using transparent atomizers (Song and Lee, 1996; Huang et al., 2008; Li et al., 2012; Ju et al., 2015; Stähle et al., 2015a). These studies confirmed the hypothesis of transition from a bubble flow (low-GLR) to a plug flow and further to the annular flow (high-GLR). However, an experimental approach is not always possible so numerical simulations, theoretical two-phase flow maps (Jedelsky and Jicha, 2008) or a simplified description based on liquid/gas momentum ratio have been used to estimate the internal flow patterns (Song and Lee, 1996; Mlkvik et al., 2015).

The relation between the internal two-phase flow and the primary breakup mechanism was investigated in several publications, (e.g. Buckner and Sojka, 1991; Santangelo and Sojka, 1995; Catlin and Swithenbank, 2001; Gadgil and Raghunandan, 2011b). At low-GLR regimes, the breakup is based on the gas bubble explosions. When a gas bubble passes through the exit orifice, it expands in both radial and axial direction. It means that the liquid film, which surrounds the gas, is stretched out which causes film thinning. As the GLR increases, and consequently also the gas mass flow, the bubbles become larger, and the thickness of the liquid film is reduced. This forms a shape similar to an annular liquid sheet, which results in the creation of the so-called tree-like structures producing individual droplets (Santangelo and Sojka, 1995; Sutherland et al., 1997).

Even though there is a sufficient number of publications aimed at the breakup of basic liquid structures (streams, liquid sheets or single droplet breakup), (e.g. Dumouchel, 2008; Eggers and Villermaux, 2008), a detailed description of such a complex process as the effervescent atomization has not been previously made (Konstantinov et al., 2010). Studies which describe the breakup low-pressure regimes are still relatively rare, and a deeper understanding of the spray formation is needed. Moreover, the effect of different atomizer designs on liquid breakup and spray properties has been studied only in several cases, (e.g. Stähle et al., 2015b). Therefore, it is difficult to choose and design the atomizer for a specific application (Ferreira et al., 2009; Diego-Marin et al., 2009; Mujumdar et al., 2010).

It was shown that at low-pressure and low-GLR regimes the design of atomizers plays an important role (Mlkvik et al., 2015). The mixing process heavily influences the character of the internal two-phase flow at low-GLR and low-pressure regimes. It was revealed that the atomization efficiency, defined as the ratio of energy to increase the surface area of the liquid to the energy applied to the spraying atomizer (Bayvel and Orzechowski, 1993), grows when the operating pressure and GLR decrease (Jedelsky and Jicha, 2013). The relation between the atomization efficiency and GLR has an approximately inverse logarithmic tendency. A similar relationship was also found between the efficiency and pressure. Thus the low-GLR and low-pressure regimes are considered as highly-effective. Therefore, it is important to comparably examine various designs of atomizers under these conditions.

The present paper examines four different internal-mixed atomizers. These are the two common types: the Y-jet atomizer and the “outside in gas” effervescent atomizer (OIG). Other two atomizers are newly developed ones: specific construction of the “outside in liquid” effervescent atomizer (OIL) and the atomizer which was designed on the basis of previous designs of twin-fluid atomizers by workers: Chin (1995), Ferreira et al. (2001) and Tamaki et al. (2004), so-called CFT atomizer. All four atomizers were studied in the previous work of Mlkvik et al. (2015) where a mixing process and an analysis of breakup of liquid structures (ligaments) were described for several different liquid viscosities. However, due to limited optical access, the study of the liquid breakup mechanism has not yet been conducted. Moreover, we examined the atomizers at lower pressures, half the magnitude of the minimal pressure examined in Mlkvik et al. (2015), and lower GLR, from 2.5% to 20%. The low-GLR regimes were not fully described because the atomizer’s exit orifices were blocked due to the crystallization of the liquid and no spray was generated. Thus we could extend the previous description by studying the influence of the internal design on the liquid breakup and discuss its effect on the spray characteristics. Our aim is to examine various designs of twin-fluid atomizers under high-efficient regimes and to point out the aspects influencing the spray characteristics. Due to the opaque body of atomizers, an assumption of the internal flow was made by a simplified analytical approach based on findings of Song and Lee (1996) and Mlkvik et al. (2015). We used a high-speed camera with a long-distance microscope for examination of the liquid breakup. Droplet dynamics was analysed using the data from the PDA system. In this paper, the results are chronologically ordered according to the spray formation in internally-mixed twin-fluid atomizers.

Table 1
Parameters of operating regimes.

Name	p_L [kPa]	p_G [kPa]	m_L[kg·h^{-1}]	GLR [%]
CFT	71	70	4.30	2.4
	70	70	3.04	5.0
	70	70	1.88	10.2
	71	71	1.24	20.2
OIG	70	70	4.08	2.5
	70	69	2.65	5.0
	67	70	1.70	10.2
	69	70	1.14	19.8
OIL	69	71	3.75	2.5
	68	69	2.55	5.1
	72	71	1.72	10.3
	71	72	1.12	20.8
Y-jet	74	71	3.49	2.5
	71	71	2.54	5.2
	69	69	1.68	10.2
	69	71	1.11	20.4

Table 2
Physical properties of fluids at room temperature.

Fluid	p [kg/m^3]	μ [kg/(m·s)]	σ [kg/s^2]
LHO	874	0.0185	0.0297
Air	1.23	1.81·10^{-5}	

2. Experimental setup

Atomizers were operated on a cold test bench at a room temperature of 23 °C and still ambient conditions. A detailed description of the test bench can be found in Jedelský et al. (2014). Table 1 shows the measured values of operating regimes. The pressure chosen was 70 kPa and GLR from 2.5 to 20%. In twin-fluid atomizers, GLR is calculated by dividing the liquid and gas mass flows. It is defined as the ratio of mass flowrate of atomizing gas through the atomizer to that of liquid (Sovani et al., 2001). We then can express the GLR in percentages, which shows how much of the total mass flow is occupied by the gas. To control the GLR value during the measurement, we used a mass flow meter for liquid (combined uncertainty of measured value 1% for a confidence level of 95%), mass flow meter for gas (5%) and pressure sensors (0.4%).

We assume that the selected atomizers were designed for liquid fuel combustion; thus we used light heating oil (LHO), and pressurized air as the tested fluids. Physical properties of the fluids are documented in Table 2.

2.1. Atomizers

A detailed description of selected atomizers can be found in Mlkvik et al. (2015). In internal-mixing twin-fluid atomizers, the