Fuel 97 (2012) 306–314

Contents lists available at SciVerse ScienceDirect

Fuel

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

Mixing and atomization characteristics in an internal-mixing twin-fluid atomizer

Zhouhang Li[a], Yuxin Wu[a,*], Chunrong Cai[a], Hai Zhang[a], Yingli Gong[a], Keiji Takeno[b], Kazuaki Hashiguchi[b], Junfu Lu[a]

[a] *Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China*
[b] *Nagasaki R&D Center, Mitsubishi Heavy Industries, Ltd., Japan*

ARTICLE INFO

Article history:
Received 17 June 2011
Received in revised form 14 November 2011
Accepted 6 March 2012
Available online 18 March 2012

Keywords:
Twin-fluid atomization
Internal mixing
GLR
SMD distribution

ABSTRACT

Twin-fluid atomizers have been successfully used in many industrial applications. This paper presents experimental studies on internal mixing and atomization in a water–air internal-mixing atomizer. Two-phase mixing process and flow patterns in the internal mixing chamber were visually studied through high speed CCD. Observation reveals that internal mixing was dominated by Gas to Liquid mass Ratio (GLR). As GLR increased, the flow patterns changed from slug flow to annular flow. The Oshinowo and Charles' map can be used to predict the flow patterns for the designed atomizer. Droplet Sauter Mean Diameter (SMD) spatial distributions were measured with Phase Doppler Analyzer (PDA) at different operating conditions. Droplet SMD decreased with the increase of GLR at all operating pressure and locations. In the undeveloped region, a close relationship was observed between flow pattern transformation in internal mixing chamber and droplet SMD distribution, and there was an optimized pressure ranging from 0.2 MPa to 0.3 MPa for atomization since liquid films became thicker under a higher pressure. In the developed region, pressure promoted to generate finer atomization. Possibility Density Function (PDF) distribution of droplet size at different axial locations was analyzed to quantitatively represent the effect of droplet coalescence and breakup. As axial distance increased, PDF of both fine droplets and large droplets decreased. The particle size with the maximum PDF increased with the axial distance as well. The results imply that best atomization performance was acquired in the undeveloped region.

1. Introduction

Twin-fluid atomizers have been widely used in many industrial applications such as oil burners and spray drying [1]. This kind of atomizer generates high relative velocity between gas and liquid by employing a relatively high gas velocity, which helps the formation of the smaller liquid sheets and ligaments. Then fine droplets come into formation due to sheet breakup. This process can be explained by the wavelengths that grow on the surface of the sheet, which are affected by surface tension, aerodynamic forces, and liquid viscosity [2]. Meanwhile, the introduction of gas phase may help dispersion of liquid and prevent from droplets coalescence.

There are many types of twin-fluid atomizers, such as internal mixing [3,4], medium mixing ('Y' type) [4,5] and outside mixing atomizers [6]. In a boiler plant, the generally design of the oil/heavy oil burners are internal mixing or medium mixing atomizers. The characteristic of the medium mixing atomizers is that liquid and gas are mixed inside the atomizer within a limited space before they are injected out. The advantages of such kind of 'Y' type atomizer are that it can be operated either keeping a constant steam-to-fuel flow rate ratio or a fixed fuel-to-steam pressure ratio. However, internal mixing process shall be strengthened further so that finer droplets can be acquired at a low GLR. Ferreira [4] has indicated that adding an internal mixing chamber may improve the performance of 'Y' type atomizer.

In an internal mixing chamber, liquid and gas are mixed and interacted intensively before they are discharged out. Atomization in the internal mixing atomizer can be explained as follows [7]: liquid has to share flow area with gas, resulting in acceleration of liquid and formation of finer droplets. In addition, relative motion between two phases increases the flow instability at the interface, so that ligaments and sheets formation is accelerated. It is well recognized that atomizer geometry [4,8–10], fluid physical properties [11,12] and operating conditions [13,14] such as GLR and injection pressure have effects on the mixing process as well as atomization of internal mixing atomizers. Nguyen and Rhodes [9] found that length and diameter of the mixing chamber have little effect on atomization during a range of 20–45 mm and 1.7–2.3 mm, respectively. However, Kushari [10] showed that droplet size decreases with increase of mixing chamber length. Both Ferreira's [4] and Kushari's [10] results show that the ratio of the exit orifice area to the air injection area influences spray mean drop size in internal

---

* Corresponding author. Tel./fax: +11 8610 62788523.
E-mail address: wuyx09@tsinghua.edu.cn (Y. Wu).

0016-2361/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2012.03.006

Nomenclature

A	factor, $A = \frac{\mu_l}{\mu_w}\left(\frac{\rho_l}{\rho_w}\right)^{-0.25}\left(\frac{\sigma_w}{\sigma_l}\right)^{-0.75}$
$d_{i,l}$	mixing chamber's inlet diameter (mm)
d_0	exit orifice diameter (mm)
$\mathrm{Fr_{TP}}$	two-phase Froude number, $\mathrm{Fr_{TP}} = \frac{(Q_a+Q_l)^2}{D^3 \cdot g(\pi/4)^2}$
g	gravitational constant (m/s^2)
G	gas mass flux (kg/m^2 s^{-1})
GLR	Gas to Liquid mass Ratio
L	liquid mass flux (kg/m^2 s^{-1})
$\dot{m}$	mass flow rate (kg/h)
Q	volumetric flow rate (m^3/s)
p	operating pressure (MPa)
r	radial distance from spray axis (mm)
r^*	non-dimensional radial distance, r/d_0
SMD	Sauter Mean Diameter, D_{32} (μm)
x	axial distance from the exit orifice (mm)
x^*	non-dimensional axial distance, x/d_0

Greek letters

λ	factor, $\lambda = (\rho_g \rho_l / \rho_a \rho_w)^{0.5}$
ψ	factor, $\psi = \frac{\sigma_w}{\sigma_l} \cdot \left[\frac{\mu_l}{\mu_w} \cdot \left(\frac{\rho_w}{\rho_l}\right)\right]^{1/3}$
ρ	density (kg/m^3)
σ	surface tension (N/m)
μ	dynamic viscosity (N/s m^2)

Subscripts

a	air
l	liquid
g	gas
w	water

mixing twin-fluid atomizers, the same with effervescent atomizers [15]. Slant angle and specific shape of the liquid ports have little effect on atomization [4]. Broniarz-Press et al. [12] studied atomization of internal mixing atomizer using water and different oil emulsions, concluding that physical properties of liquid have significant influence on the spray characteristics.

Flow patterns in internal-mixing twin-fluid atomizer were also investigated. Kufferath et al. [16] studied atomizer's performance under different flow conditions of the liquid jet leaving the inlet port, including laminar and turbulent flows, and found that flow conditions have a strong influence on droplet mean size. Karnawat and Kushari [17,18] investigated different spray patterns in the developed jet regime and concluded correlations between spray patterns and operating conditions. The mixing process within the internal chamber is important for internal-mixing atomizer's performance. Based on classical two-phase flow pattern maps, Lefebvre and Chin [19] investigated different flow patterns within the mixing chamber. Kim et al. [8] studied effects of GLR on flow patterns within the internal chamber and they reported breakup of water column was complicatedly changed with the increase of GLR. Ferreira et al. [20] found that flow patterns within the chamber change with internal mixing chamber geometry configuration.

Although research work listed previously give useful information for internal mixing atomization design and research, the correlation between flow patterns in internal mixing chamber and droplet mean diameter has not been investigated in previous literatures. Operating pressure's effect on internal mixing was seldom studied experimentally. Besides, most previous researchers (Whitlow and Lefebvre [21], Panchagnula and Sojka [22], and Jedelsky et al. [23]) reported droplet SMD at axial locations where are in the far-field region and spray is fully developed, while droplet SMD distribution in the near nozzle region was paid little attention. For oil burners, it's important to acquire the axial distance where droplets have the smallest SMD in order to get an optimized condition. Moreover, spray with high velocity sometimes cools down excessively the reaction zone, leading to local flame extinction [24]. A reasonable atomization flow field is very important for oil burning.

In present work, liquid–gas flow patterns in a water-inside–air-outside internal mixing twin-fluid atomizer were visually investigated through high speed CCD. The SMD spatial distribution and velocity profile in the near nozzle region and fully developed region were measured through Phase Doppler Analyzer (PDA). Effects of GLR and pressure on SMD spatial distribution were studied. The correlation between flow patterns in internal mixing chamber and droplet SMD was discussed. Droplet breakup and coalescence effects were quantitatively expressed by SMD spatial distribution and possibility density distributions.

2. Experimental

2.1. internal-mixing twin-fluid atomizer and test rig system

The geometry configuration of the internal-mixing twin-fluid atomizer is shown in Fig. 1. The atomizer is made by acrylic glass so that the internal mixing can be captured by high speed CCD. The overall length of the atomizer is 600 mm. The diameter of mixing chamber's liquid inlet ($d_{i,l}$) is 4 mm. Liquid inlet is surrounded by four 1 mm air inlet holes with a slant angle of 45°. Atomizer's exit orifice diameter, d_0, is 3 mm.

Fig. 2 shows the schematic drawing of the air–water atomization system. Both water and air were fed into the atomizer at an elevated operating pressure. A ball valve and a needle valve were installed on each route in order to control the flow rate of pressurized water and air. Metal tube rotameters with a maximum error of 1.5% were adopted to acquire the volume flow rate of water and air.

2.2. Measuring apparatus

A high speed CCD, the PCO.dimax made by COOK Company, was used to capture the internal flow patterns and two-phase mixing process inside the chamber. The CCD has a high ISO value of 50,000. The minimum exposure time is 2 μs. Up to 1297 frames per second (fps) can be acquired with the size of 2016 × 2016 pixels for each frame. In this work, pictures and videos of the mixing processes were captured at an fps of 10,000 so that change of the two-phase flow can be analyzed in detail.

A Phase Doppler Analyzer (PDA) system of Dantec Dynamics was used to measure droplet size and velocity distributions. The PDA was set in refractive scattering mode with the receiver positioned at 30° from the transmitter axis. The focal length for the

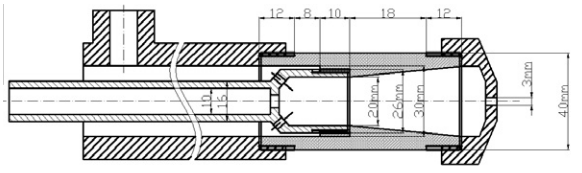

Fig. 1. Geometry configuration of the research atomizer.