International Journal of Multiphase Flow 92 (2017) 150–160

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Atomization of glycerin with a twin-fluid swirl nozzle

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ARTICLE INFO

Article history:
Received 19 December 2016
Revised 24 February 2017
Accepted 16 March 2017
Available online 19 March 2017

Keywords:
Atomization
Glycerin
Atomizing nozzles

ABSTRACT

Atomization of liquids with high viscosity is always a challenge, especially when small diameter droplets and high liquid flow rates are simultaneously required. In the present research, the performance of a Venturi–vortex twin-fluid swirl nozzle is examined, attending to its capabilities to generate droplets with diameters below 20 µm when atomizing pure glycerin at room temperature. In this nozzle, air is injected tangentially in a central convergent section, and discharges suctioning the liquid fed to a coaxial chamber, here using a gear pump. The resulting spray is visualized and analyzed. Droplet size distributions are measured with a laser diffractometer. As expected, droplet diameter increases with liquid flow rate, and quickly diminishes when air flow rate is increased. Sauter mean diameters (SMD) below 15 µm can be obtained even when atomizing pure glycerin. However, these values are obtained for relatively low glycerin flow rates (~5 l/h), and with rather wide distributions. For 10 l/h and an air-to-liquid mass flow rate ratio (ALR) of 13.7 more than 26% of the glycerin volume is atomized in droplets smaller than 20 µm. Liquid ligaments are observed near the nozzle exit, but they tend to break up while moving downstream.

1. Introduction

From all the fluid physical properties, viscosity is one of the most influential on the atomization process. Atomization of liquids of high viscosity is always a challenge (Kitamura and Takahashi, 1992; Watanabe et al., 2003), especially when small diameter droplets and high liquid flow rates are simultaneously required (Buckner and Sojka, 1991). Pressure atomization is conceptually simple, but handling elevated viscosities normally require pressures over 100 bar (Plesniak et al., 2004), so in many cases liquid viscosity has to be first reduced by heating. Working pressure can be dramatically reduced using twin-fluid nozzles. In them, a high-velocity gas stream (normally air) impinges on a relatively low-velocity liquid stream, either internally or externally to the nozzle. The interaction between both fluids destabilizes the liquid flow causing its rupture in droplets. In twin-fluid nozzles droplet diameter inversely depends on the air to liquid mass flow rate ratio (ALR). For a given geometry, diameter can only be reduced by increasing gas speed, and/or decreasing the liquid flow rate (Lefebvre, 1989). The flow patterns in internal-mixing air-assisted atomizers and the effects of varying the ALR have been the subject of numerous studies (Schmidt and Sojka, 1999; Chin and Lefebvre, 1993; Barreras et al., 2006). As expected, gas-assisted atomization is also hindered by viscosity. Mlkvik et al. (2015) have recently analyzed the performance of several internal mixing twin-fluid atomizers, including some effervescent configurations for liquids with a maximum viscosity of 0.308 Pa·s but droplet mean diameter values are not provided. Other alternative atomization methods suitable to generate micron-sized droplets, for example the use of ultrasonic resonators, can hardly handle kinematic viscosities above 3×10^{-6} m^2/s (Lozano et al., 2010). More complex systems, such as spinning disks or rotary bells are often used in spray painting applications (Domnick and Thieme, 2006). Sauter mean diameters, SMD or D_{32}, below 10 µm can be obtained for rotation frequencies of 50,000 rpm. Still, it has to be considered that dynamic viscosity of paint solutions is commonly below 0.1 Pa·s. However, there are numerous applications for which small diameter droplets of highly viscous fluids are either required or preferable, for example in combusting flows.

A suitable substance to test how a nozzle can handle operation with highly viscous fluids is glycerin. The term glycerin is normally used to denote crude glycerol that has undergone purification and treatment processes. Crude glycerol is typically 70% - 80% pure (Pagliaro and Rossi, 2008). Dynamic viscosity of glycerin at 20 °C is 1.32 Pa·s. Its kinematic viscosity at the same temperature is 1042×10^{-6} m^2/s. This is even higher than the corresponding to slightly preheated heavy fuel oils whose typical kinematic viscosities at 50 °C are below 640 m^2/s. As glycerin can be mixed with water, working with it is much cleaner than using fuel oils, but atomization results should be comparable in both cases. On the other hand, combustion of crude glycerol is becoming a subject of increasing interest. The main reason is because it is produced in

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.03.010
0301-9322/

large quantities as a byproduct of the synthesis of biodiesel (about 10% of the resulting biodiesel mass). This non-refined glycerol can be used as a fuel, but it has some inconveniences (Bohon et al., 2011; Metzger, 2007; Angeloni et al., 2016; Jiang and Agrawal, 2014). Glycerol low heating values (LHV) is about 16.7 MJ/kg, substantially lower than values corresponding to gasoil, gasoline or fuel oil which are around 43 MJ/kg. Water content can decrease the flame temperature, which can lead to the formation of acrolein, which is toxic (Steinmetz et al., 2013). Volatility is low, and presence of salts (primarily sodium and potassium) is also a drawback that has to be considered. Bohon et al. (2011) burn crude glycerol using a commercial twin fluid nozzle, but at laboratory scale with maximum flow rates of 1.3 l/h. Another set of experiments is performed in a semi-industrial scale furnace with a different commercial air-assisted nozzle, but in this case glycerol is preheated to 93 °C, and its viscosity is reduced to $\sim 2 \times 10^{-2}$ Pa·s. The works of Queiro et al. (2013) and Sallevelt et al. (2015) atomize glycerol as well. In the first, a mixture with other liquids is also heated up to 80 °C to reduce its viscosity. In the second a mixture with water is sprayed to obtain a viscosity lower than 0.2 Pa·s, and a pressure swirl nozzle is used, yielding SMD values over 65 µm. Jiang and Agrawal (2014) report the use of a novel "flow blurring" (Gañán-Calvo, 2005) injector to burn crude glycerol with and without methane. For the case without methane, glycerol flow rate is set to 1.26 l/h with an atomizing air flow rate of 1.5 m^3/h. For atomization purposes, viscosity of crude glycerol is lower than that of refined glycerin, especially if it contains a significant percentage of methanol (Thompson and He, 2006), hence spraying it should be easier.

Continuing an ongoing project (Lozano et al., 2015; García et al., 2016), in the present research, the performance of a Venturi–vortex twin-fluid swirl nozzle atomizing pure glycerin at room temperature is examined. Attention is focused on its capabilities to generate droplets of small size, here established in diameters below 20 µm. In this nozzle, air is tangentially injected in a central convergent section, and discharges suctioning the liquid fed to a coaxial chamber. In principle, the nozzle can operate without including a pump to feed the liquid, which is ingested by the depression caused by the air flow. However, in this case the liquid flow rate obviously decreases with viscosity, and when pure glycerin is used it can hardly reach values above 1 l/h (Lozano et al., 2015). To increase the flow rate, in the experiments here described a gear pump has been included to supply the liquid, resulting in rates as high as 30 l/h. If it could be completely burned up, such a glycerin flow would generate a power of 175 kW.

The generated sprays are visualized and analyzed. Droplet size distributions are measured with a Spraytec laser diffractometer. The Sauter mean diameter is used to characterize the atomizer performance. Measurements for glycerin atomization are compared to those obtained when the nozzle is operated with water. Variations in the atomizer geometry are studied to achieve the proposed targets.

2. Experimental setup

The atomizer design in this study is inspired in some nozzles intended to produce oil mists for lubrication purposes (Mannhardt and Hierta, 1970; Burns et al., 1982). A sketch of its main components is presented in Fig. 1. The complete assembly is formed by three pieces that can be changed to study different geometrical modifications. The upper plate incorporates two tangential gas inlets. The central body has a conical conduct to accelerate the swirling gas flow towards the exit, increasing its tangential velocity. In its base, a receded annulus forms the chamber that contains the liquid to be atomized. An orifice in the lateral wall, connected to the chamber constitutes the liquid inlet. Finally, the lower plate

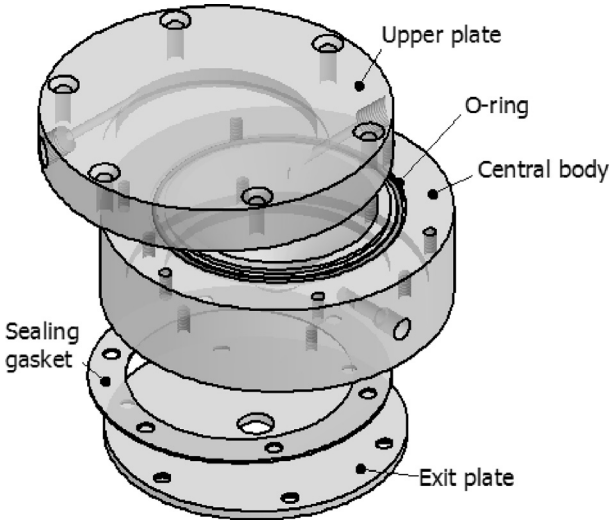

Fig. 1. Exploded sketch of the atomizer head.

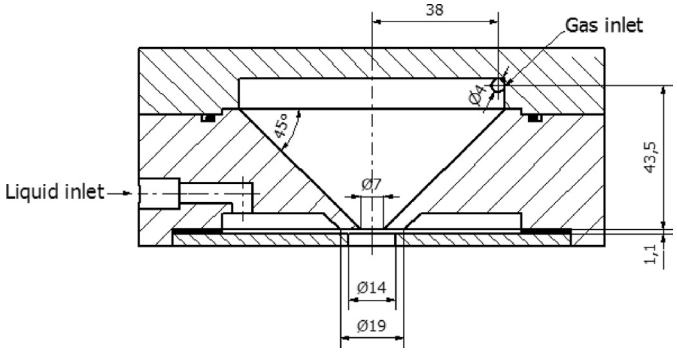

Fig. 2. Drawing of the nozzle.

has a central orifice with a diameter of 14 mm. The gap between the cone tip and the lower plate is 1.1 mm wide. This gives a total exit area for the liquid flow of 48.4 mm^2, equivalent to a circle with a diameter of 7.85 mm, which is a relatively large value. This is interesting in order to reduce the pressure drop and to avoid any possible clogging, two issues that become especially important when atomizing liquids of high viscosity or with diluted solid particles, as crude petroleum. A scaled drawing of the complete assembly is depicted in Fig. 2. In this configuration the inner swirling air flow interacts with the liquid that flows through the exit slit in the form of an annular sheet. Although a gas tangential velocity is not required to produce atomization, Leboucher et al. (2009) report that the air swirl decreases the break up length, homogenizes the droplet axial velocity and increases the half width at half maximum of the radial profile of the mean axial velocity. It is to be noted that unlike other annular liquid sheet atomization studies (Li and Shen, 2001; Leboucher et al., 2012), in this case liquid is either suctioned or injected perpendicular to the gas flow instead of moving in parallel.

In all the experiments air is used as atomizing gas, with a maximum flow rate of 35 Nm^3/h, which in this experimental setup corresponds to 323.28 kg/h. For comparison purposes, the nozzles are characterized operating both with water and glycerin. The glycerin employed is bi-distilled with purity over 99.5%. Table 1 summarizes the main physical properties of both fluids.

A sketch of the complete experimental setup is depicted in Fig. 3. Water is supplied by the line in the Laboratory with a maximum pressure of 4 bar Pressure is measured with a Bourdon manometer. Flow rate is controlled with a needle valve, and