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Atomization of high viscosity liquids through hydraulic atomizers designed for water atomization

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ABSTRACT

Many authors studied water and gasoline atomization. The literature provides many experimental and theoretical works about this subject. However, hydraulic atomization of high viscosity liquids through atomizers originally designed to work with water or gasoline is a topic that is less covered and detailed studies on this subject are harder to find. It is of big interest to test the behavior of high viscosity liquids injection through hydraulic atomizers designed for water atomization because these atomizers are and could be used to atomize fluids more viscous than water. This paper provides a step further in describing and understanding the behavior of high viscosity liquids injection through hydraulic atomizers under different conditions related to the properties of the receiving gas and the viscosity of the liquid. Under these conditions, the mass flow rate, the discharge coefficient, the quality of the jet and droplets size are evaluated and existing correlations are adjusted to take into consideration viscosity range change and changes in the properties of the receiving gas using hydraulic atomizers with known performances for water. The viscous liquid used is the compressor lubricant POE oil (Emkarate RL32-3 MAF) usually used in heat pumps and in chillers.

1. Introduction

Atomization and sprays are needed and utilized in varied industrial applications, but till these days physical mechanisms determining atomization characteristics are not fully developed [1–3] because they are highly complex [4]. Mechanisms of liquid breakup are still not well understood, even for the relatively simple case of a constant pressure injection through a single hole nozzle into a high density gas [5]. The dispersion of spray drops is important since it improves mass and heat transfer efficiency between liquid and gas phases [5] and it improves heat transfer between liquid and solid [6].

To atomize high-viscous liquid, generally twin fluid atomizers are used [7,8]. Many researches study viscous liquids atomization using twin fluid jet atomizers such as Aliseda et al. [1], Tsai et al. [9], Zhouhang et al. [8] and many others. But few researches study atomization of high viscosity liquids through hydraulic atomizers, we can quote for example Tamaki et al. [7], Toublanc [10] and Yao et al. [3]. In our application, we are not able to use twin fluid atomizers principally because it is not allowed to use any other fluid then oil for injection, also this choice is due to geometrical and spatial constraints is our application.

Tamaki et al. [7] showed in their study that in normal or single hole nozzle with a 3 mm diameter atomization almost disappeared by passing from a liquid with kinematic viscosity of $0.66 \times 10^{-6}\,\mathrm{m^2/s}$ to a liquid with kinematic viscosity of $20 \times 10^{-6}\,\mathrm{m^2/s}$ even at an injection pressure of 15 MPa. To achieve a good atomization they invented an atomization enhancement nozzle with modified geometry that permits cavitation phenomenon to take place in the nozzle hole independently of viscosity. In their test with the modified nozzle, increasing viscosity leaded to a small increase in Sauter mean diameter which is defined in Eq. (1) and a small decrease in spray angle.

$$D_{32} = \frac{\sum N_i D_i^3}{\sum N_i D_i^2} \quad (1)$$

Yao et al. [3] observed in their study that the cone of the spray became smaller for high viscosity fluids and that the breakup became more difficult for high viscosity flows. They mentioned the important role of viscosity in the structure of the spray and the atomization of the liquid. They encountered a problem with atomization of water glycerol mixture with 80% of glycerol which has as dynamic viscosity of $79.488 \times 10^{-3}\,\mathrm{kg/m/s}$ against $0.937 \times 10^{-3}\,\mathrm{kg/m/s}$ for water under their experimental conditions.

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Nomenclature

A	area [m^2]
C_d	discharge coefficient
d	diameter [m]
D_{32}	Sauter mean diameter [m]
L	length [m]
LSD	least significant digit of the readout
M	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n	nozzle coefficient
N_i	number of droplets of diameter D_i
Oh	Ohnesorge number
P	pressure [kPa]
POE	polyol-ester oil
Re	Reynolds number
SMD	Sauter mean diameter [m]
t	time [s]
T	temperature [K]
V	velocity [m/s]
We	Weber number

Greek characters

μ	dynamic viscosity [kg/m/s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
σ	liquid/gas surface tension [N/m]

Subscripts

drop	droplet
Liq	liquid
max	maximal
o	orifice
r	relative

Buckner et al. [11] studied sprays of glycerin-water solutions with viscosity ranging from 400 to 970 mPa·s and found that the D_{32} was almost independent of liquid viscosity at a measuring axial distance of 150 mm.

Sutherland et al. [12] studied liquids with viscosity of 1–80 mPa·s and in their study they observed a small effect of viscosity on droplet size at an axial distance of 150 mm.

Lund et al. [13] found that at an axial distance of 150 mm the D_{32} increased about 15% when viscosity increased from 20 to 80 mPa·s

Loebker et al. [14] sprayed liquids with viscosity up to 7 Pa·s and found that at an axial distance of 1300 mm, droplet mean size increased sharply with viscosity.

Broniarz-Press et al. [15] tested liquids with viscosity ranged between 1.92 and 26.4 mPa·s, they measured droplets size at an axial distance of 600 mm and they found that the D_{32} increased with the viscosity increase.

Sataphthy et al. [16] also showed that the droplets size increased with the viscosity at high injection pressure between 11 and 33 MPa.

Lefebvre [17] elevated the ambient air pressure to more than 600 kPa and he observed an increase in droplets size with an increase of the viscosity from 1 to 100 mPa·s.

Toublanc [10] has injected a synthetic oil at 9.3 MPa and at a temperature of almost 25 °C (under these conditions, the viscosity of this oil is about 60.3 mPa.s) in CO_2 at 3.6 MPa and 25 °C, he obtained a mean D_{32} of 22 μm.

Suh et al. [18] studied spray characteristics of dimethyl ether and diesel fuels. They found that the SMD of diesel fuel is larger than that of dimethyl ether since the lower viscosity of dimethyl ether enhanced atomization.

Park et al. [19] found that the injection rate of biodiesel fuel is lower than that of diesel fuel due to the higher dynamic viscosity and density of the biodiesel fuel. Also, biodiesel fuel has a slightly larger droplet size than fuel.

Seykens et al. [20] reported a decrease in volumetric mass flow rate when Rapeseed oil Methyl Ester is used instead of diesel fuel and they attributed this decrease to a decrease of the kinematic viscosity from 6.57 to 4.59 mm/s^2 and to a decrease of the density from 1522.5 to 1390.0 kg/m^3 when diesel fuel is used.

Dernotte et al. [21] experimented the injection of different fuels over operating conditions from 30 to 180 MPa of injection pressure and from 1 to 9 MPa of back pressure. Fuel viscosity increase from 0.6 to 7 mm/s^2 induced a decrease in discharge coefficient up to 10% at low pressure difference but for high pressure differences fuel density was the unique fuel property driving the mass flow rate.

So according to many studies, increasing viscosity makes harder and more difficult the atomization and in some cases it degrades the spray quality.

Also, before bringing up atomization issue, it is important to predict or extend the mass flow rate and some other aspects of a hydraulic atomizer for various liquid viscosities or for different liquids with different viscosity ranges and under different injection pressures. It is of great importance to estimate the mass flow rate for a specific liquid with known properties knowing the mass flow rate for another liquid. Because, manufacturers usually provide mass flow rate data for a specific liquid, and for hydraulic atomizers in many cases this liquid is water. As seen before, in the literature some studies showed the influence of fluid viscosity and density on mass flow rate, but not in the viscosity range studied in this paper.

In this paper, we study the behavior of hydraulic atomizers when used with a high viscosity fluid with a viscosity range of 55.9–134.9 mm^2/s. It should be mentioned that the used hydraulic atomizers are swirl atomizers. The study is split in two parts. The first one is dedicated to the mass flow rate correlation as a function of operating conditions and of fluid properties, while the second part is dedicated to the atomization study.

2. Mass flow calculation

Atomizers manufacturers [22] suggest Eq. (2) as a relation between the flow rate and the injection pressure.

$$\frac{\dot{V}_1}{\dot{V}_2} = \frac{P_1^n}{P_2^n} \tag{2}$$

For the hollow cone spray nozzle studied in this paper, the manufacturer [23] suggests the relation given by Eq. (3) which derives from Eq. (2) for $n = 0.5$.

$$\dot{V}_2 = \dot{V}_1\sqrt{\frac{P_2}{P_1}} \tag{3}$$

The maker [22] suggests Eq. (4) to estimate the flow rate for a liquid that has a different density than water.