Journal of Non-Newtonian Fluid Mechanics 217 (2015) 49–57

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

journal homepage: http://www.elsevier.com/locate/jnnfm

An experimental study on the atomization characteristics of impinging jets of power law fluid

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ARTICLE INFO

Article history:
Received 19 July 2014
Received in revised form 19 November 2014
Accepted 6 January 2015
Available online 31 January 2015

Keywords:
Power law fluid
Impinging jet
Atomization
Droplet velocity
Sauter mean diameter

ABSTRACT

To investigate the atomization characteristics of power law fluid, an impingement jet system is developed in this study. High-speed photography and 3-D phase Doppler methods are used to obtain the breakup regimes, 3-D velocities and size distribution of the droplets. The effects of pre-impinging parameters (injection pressure and pre-impingement length), geometry parameters (orifice diameter and impingement angle) and physical parameters (fluid viscosity) on the atomization characteristics are studied. The spray patterns could be qualitatively categorized into six types: open rim without shedding droplet, closed rim, open rim with shedding droplets, rimless sheet, bow shaped ligament and fully developed. With the increment of injection pressure, the droplet velocity of each direction increases, the droplet Sauter mean diameter (SMD) decreases, the non-dimensional mean droplet size (SMD/D) converges to 0.14, and X_0/SMD becomes about 1.3–1.5 (D is the orifice diameter, and X_0 is the Rosin–Rammler diameter). The axial velocity (W) increases as the impingement angle decreases. Smaller droplets are produced by larger impingement angles, smaller pre-impingement lengths and lower liquid viscosities. The particle size distribution fits in the Rosin–Rammler function.

1. Introduction

The special working conditions require rocket engines to carry both fuel and oxidant, and impinging jet injectors are commonly used in liquid-fuel rocket engines due to the simple design and good mixing characteristics for liquid fuel and oxidant [1,2].

Gelled propellant as a new type of liquid fuel or oxidizer in liquid rocket engines has received considerable attention in recent years. Compared with conventional fuel or oxidant, it has many advantages such as easier and safer storage, less particle sedimentation (when metal particles are added to enhance energy density) and lower risk of fire or explosion. It behaves as non-Newtonian power law fluid, whose absolute viscosity is a function of shear rate [3,4].

Many experimental studies on the atomization characteristics of impinging jet of Newtonian fluid (traditional fuel) have been carried out. Heidmann et al. [5] evaluated different factors that may influence the spray patterns, such as the orifice diameter, pre-impingement length (the distance from the outlet of nozzle to impinging point of two jets) [6], jet velocity, impingement angle and fluid properties. They pointed out the importance of the effect of impingement velocity and impingement angle on spray structures. Dombrowski and Hooper [7] studied the effect of impingement angle, and noted that disintegration is generally resulted from the unstable waves caused by the aerodynamic or hydrodynamic disturbance. Panao and Delgado [8] analyzed the influence of pre-impingement length and jet misalignment on the structure of liquid sheet and droplet size. Kang et al. [9] revealed that the liquid viscosity affects the spray structure significantly but has unnoticeable effect on the droplet size. Yi et al. [10] used high-speed photography and 3-D phase Doppler methods to achieve the simultaneous measurement of spray pattern, droplet velocity and size distribution.

In the field of non-Newtonian power law fluid impingement, the studies were mainly focused on the investigation of spray patterns and size distribution. Lee and Koo [11] investigated the breakup process of simulant gelled propellant of Carbopol 940 with various gelling agent contents. Yang et al. [12] made a comparison between the experimental and theoretical results and showed that the linear instability analysis method could be applied to predict the breakup length and wavelength of liquid sheet. The comparison of Newtonian and non-Newtonian fluid atomization behaviors was carried out by Kampen et al. [13]. The regime diagrams for Newtonian and non-Newtonian fluids were given as well. After that they [14] studied the spray and combustion characteristics

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http://dx.doi.org/10.1016/j.jnnfm.2015.01.001

of aluminized gelled propellants. Yang et al. [15] investigated the spray patterns of gelled propellants in a swirl injector. Baek et al. [3] measured the droplet size based on image processing method. Then they gave the size distribution of water and C934 Carbopol gels with and without SUS304 nanoparticles. The results revealed the atomization difference of water and power law fluid, although the results could be influenced by the image intelligibility.

In addition to the studies on the spray pattern of impinging jet of power law fluid, the velocity of droplet is critically important. Therefore, in this study, we develop an impingement jet system with high-speed photography and 3-D phase Doppler subsystems to obtain the breakup regimes, 3-D velocities and size distributions of the droplets. To the best of the authors' knowledge, there has been nearly no study to use phase Doppler technology to obtain the 3-D velocities and size distribution of impingement jet for power law fluid, which is achieved in this study. The effects of pre-impinging parameters (injection pressure and pre-impingement length), geometry parameters (orifice diameter and impingement angle) and physical parameters (fluid viscosity) are taken into account. We expect that this research will be helpful to obtain a deeper understanding on the impingement of power law fluid, and to guide the design and optimization of combustion chamber.

2. Experiments

2.1. Working fluids

The most widely used form of the general viscous constitutive equation is the power law model, and its expression is as follows [4]:

$$\eta = K(\dot{\gamma})^{n-1} \tag{1}$$

where η is the non-Newtonian viscosity, K is the consistency coefficient, $\dot{\gamma}$ is the shear rate, and n is the power law exponent. For Newtonian fluid, $n = 1$. To prepare the non-Newtonian power law liquid, Carbopol 934 powders are dissolved by de-ionized water and stirred with an air-operated homogenizer. It is neutralized by 15 wt.% NaOH solution. The viscosity of the Carbopol gels is measured by a Bohlin cone-and-plate controlled stress rotational rheometer (CS50, Malvern Instrument). Fig. 1 shows the rheological property fitting curves of the power law fluid used in this experiment. Their physical properties are presented in Table 1. For each fluid the power law exponent is less than 1 ($n < 1$), this indicates that they are shear thinning non-Newtonian fluids. They are water-based liquids, and the concentrations of Carbopol 934 and NaOH are very low. The solution physical properties are therefore similar to water, and the solution density (ρ) is assumed to be 1000 kg/m^3.

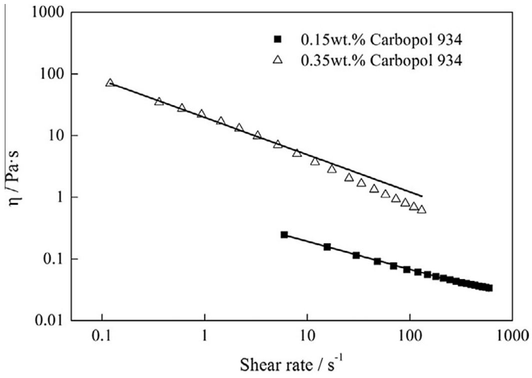

Fig. 1. Rheological characteristic curve of various fluids.

Table 1
Physical parameters of working fluids and the values of calibration constants *A*, *B* and *C*.

Carbopol mass fraction (wt.%)	K (Pa s^n)	n	A	B	C
0.15	0.551	0.546	36.36	0.036	0.47
0.35	19.612	0.398	34.33	0.073	0.60

2.2. Experimental apparatus and methods

The schematic diagram of the experimental system used in this study is shown in Fig. 2. It consists of an impinging jet system, a high-speed photography system and a 3-D phase Doppler system.

Fig. 3 shows a schematic diagram of the impinging jet system and the detailed design of injectors. The origin is the impinging point (O); the positive directions of X, Y and Z axis are in accordance with 3-D velocities of U, V and W. The impingement of two coplanar jets produces an expanding sheet in a plane, perpendicular to the plane containing the two liquid jets [7,16]. For base case, the experiment is conducted with an orifice diameter of $D = 0.6$ mm, a nozzle length of $L = 10.3$ mm, a pre-impingement length of $L_j = 10$ mm, an impingement angle of $2\theta = 90°$. In our experiment, 0.15 wt.% Carbopol 934 was used to study the effect of fluid viscosity on SMD, and for the other cases, 0.35 wt.% Carbopol 934 was used as the working fluid. All experiments are taken at the ambient temperature of 25 ± 2 °C and the ambient pressure of 0.1 MPa.

Shadowgraph images are taken in the plane of the sheet. Photron SA1.1 high-speed camera is used to obtain the shadowgraph images of the impingement of power law fluid. The frame rate is 5400 fps and the frame resolution is 1024 × 1024 pixels.

Dantec's 3-D Fiber PDA system is employed to acquire the 3-D velocities and size distribution of droplets; it can realize continuous measurement in a single spatial point. The measuring points are taken from the position of 30 mm below the impinging point, in X and Y directions the interval is 5 mm, and in Z direction it is 10 mm. The precision of the 3-D coordinate system is 0.01 mm for accurate control of the measuring location, and the unit of measuring position in experiment is millimeter. The effective sampling number for each measuring point is 5000 [11], the acquisition time is 7 s, and if either term is satisfied, the sampling is stopped.

In our PDA system, the maximum allowable deviation from sphericity rate is 5%. Since the shape of droplets is not always a spherical, in our experiment, at each measuring point there are about 40–60% droplets in the range of maximum allowable deviation rate. The calculated droplet size is within the effective value. Considering that the shape of power law fluid droplets is more irregular than Newtonian fluids, the results are reasonable. The measuring range of droplet diameter is 0–209 μm.

Fig. 4 shows the fitting curves of the flow characteristics of different fluids with an orifice diameter of 0.6 mm. A correlation is used to fit the experimental results:

$$V_j = A|P - B|^C \tag{2}$$

where V_j is the jet velocity, P is the injection pressure (gauge pressure) and A, B and C are constants, the values of them are shown in Table 1. The results are achieved by using the volume flux method, in which the pulse control equipment and the electronic balance are employed. The fluid mass in a certain time instance under a given pressure is measured. According to the cross section area of the nozzle and the density of fluid, the jet velocity could be calculated.