SPRAY CHARACTERISTICS OF GEL PROPELLANTS IN OPEN-END SWIRL INJECTOR

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Abstract

Gel propellants, which behave both liquid and solid propellant characteristics, have broad application prospects. Gel propellant is a kind of power-law fluid, and its high viscosity and difficulty in atomization have restricted its application in the aerospace field. Open-end swirl injectors can be combined with other nozzles to form gas-liquid coaxial nozzles. At present, there are few studies on the application of gel propellants to open-end swirl injectors. A set of gel simulant spray system was set up to investigate the spray characteristics of gel propellants in open-end swirl injector. Three kinds of gel simulants with different rheological parameters were used. Three open-end swirl injectors with different tangential channel diameters were designed to change the geometrical characteristics constant A of the swirl injectors. The thickness of the liquid film in the open-end swirl injectors and their spray characteristics were experimentally studied. The liquid film thickness of the gel propellant was measured by the conductance method. The details of the liquid film break-up and spray development were recorded using a high-speed camera. The effects of the above rheological and geometrical parameters on liquid film thickness, discharge coefficient, spray cone angle and liquid film breakup length, etc. were obtained, and the empirical equations were summarized.

Keywords: power-law fluid, thickness of liquid film, geometrical characteristics constant

1 Introduction

Gel propellant is a kind of propellant which is different from solid and liquid propellant. It combines the advantages of liquid propellant and solid propellant, i.e. it has not only the characteristics of high specific impulse, controllability like liquid propellant, but also the properties of easy storage and safety like solid propellant. It is a new type of propellant with research and application value in recent decades. Gel propellants are non-Newtonian fluids with rheological properties that are shear thinning, and the rheological properties are usually expressed using a power law fluid constitutive equation. Due to the high viscosity of the gel and the presence of yield stress, it is more difficult to atomize the gel propellant, and it also limits the application of the gel propellant in the aerospace field. So far, many researchers have been studying the atomization of gel propellants [1-10]. Today's research methods are mainly experimental research and theoretical analysis. However, the difficulty in atomization of gel propellants remains a major problem.

For the gel atomization method, the impinging-jet injectors are widely used. Two identical cylindrical jets impinge and produce a film of liquid perpendicular to the two jet planes and then rapidly break into liquid ligaments and droplets. The atomization characteristics of the impinging jet injector have been studied by many researchers. Kampen et al. [11] identified three different spray patterns in the case of three different generalized Reynolds numbers. Fakhri et al. [12] used nongelled and gelled water as working fluids and studied the effect of nozzle geometry, such as orifice inlet shape and aspect ratio, on jet stream surface dynamics and break-up processes before and after jet impingement. Yang et al. [13] used a linear stability analysis model to predict the breakup characteristics of a power-law liquid sheet, and compared the results of the theoretical predictions to experimental results concerning critical wave lengths and break-up lengths. Fu et al. [14] discussed the effect of the temperature on the breakup and spray characteristics of the liquid sheet formed by the impinging jet injectors. Ma et al. [15] studied the effects of pre-impinging parameters, geometry parameters and physical parameters on the atomization characteristics of impinging jets of power law fluid.
In addition to the impinging-jet injector, the swirl injector was also used for gel propellant atomization. The swirl injectors have been found to work very well for low viscosity fluids such as water, however, for gel propellant the rheology of the fluid would greatly change the spray characteristics. Bai et al. [16] used high-speed photography and 3D phase Doppler methods to investigate the spray characteristics of power-law fluid in a swirl injector. They obtained the swirl jet images, 3D velocities and size distribution of different droplets. Yang et al. [17] studied the flow structure and breakup characteristics of thin liquid sheets produced by a series of pressure swirl injectors for a gelled propellant simulant. Guan et al. [18] investigated the effects of different injection pressures on the vortex nozzle flow coefficient, spray cone angle, breakup length, Sauter mean diameter, and the droplet size distribution. Zhang et al. [19] proposed an image-processing based method for the measurement of the film thickness of swirl atomizer. The spray field of a swirl atomizer was photographed with a single-lens reflex camera, then the 2-D images were reconstructed to 3-D images using Abel inversion method. Based on the reconstructed images, the outlet liquid film thickness of swirl atomizer was obtained.

In summary, the application of the open-end swirl injector to the atomization of gel propellants is still being explored. And the current researches are mostly found in the study of the atomization characteristics. However, the liquid film thickness and the relationship between the liquid film thickness and the spray characteristics of the gel propellant atomization is also rarely studied. In this paper, the liquid film thickness inside the open-end swirl injector with different geometric sizes and gel simulants with different rheological parameters were measured experimentally. According to the experimental results, the empirical equations were summarized.

2. Experimental system

The experimental system used in this paper is shown in Fig. 1. The experimental working fluid was a gel simulant. The experimental environment was at atmospheric pressure. The experimental system consists of a working fluid supply system, a piping system, an open-end swirl injector, an anti-fog collecting system, a measuring system, and a data acquisition system. The supply system was a gas pressure feed system. The high-pressure nitrogen gas in the high-pressure gas tank was depressurized and then introduced into the working fluid storage tank. It forced the working fluid into the main pipe. The working fluid flowed into the injector after passing through a regulating valve, a pressure gauge, a flow meter, etc. The Coriolis flow meter was used to measure the mass flow rate of the gel. The measurement range is 0-5000g/min and the precision is 0.2%. The pressure transducer was installed on the inlet section of the front cavity of the injector to measure the pressure drop signal. The pressure transducer had the measuring range of 0-1MPa and the precision of 0.5%. The conductivity liquid film thickness measuring sensor was installed at the outlet of the injector to measure the liquid film thickness signal in the injector. The sampling frequency was 20 kHz. A high-speed camera was placed at the outlet of the injector to record the state of the liquid film.

![Figure 1: Experimental setup](image-url)
In order to study the influence of the rheological parameters of the gel on the liquid film thickness and spray characteristics, three gel simulants with mass fractions of 0.1%, 0.5% and 1.0% were used instead of the gel propellant for the sake of safety. A gel simulant is an aqueous polysaccharide solution that has similar physical and rheological properties as a gel propellant. It is a shear thinning fluid which shows the shear viscosity decreases with the increase of shear rate. The rheological properties of gel simulants are usually represented by the power law equation:

$$\eta = K \cdot \dot{\gamma}^{n-1}$$  \hspace{1cm} (1)

where $\eta$ and $\dot{\gamma}$ denote the shear viscosity and shear rate, $K$ denotes consistency coefficient, and $n$ is flow index.

The rheological curves of the three mass fractions of the gel simulant are shown in Fig. 2. The values of $K$ and $n$ in the respective concentrations can be obtained from Fig. 2, as shown in Table 1.

![Figure 2: Shear viscosity versus shear rate for the gel simulant](image)

<table>
<thead>
<tr>
<th>Mass fraction</th>
<th>$K$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1%</td>
<td>0.097</td>
<td>0.647</td>
</tr>
<tr>
<td>0.5%</td>
<td>1.84</td>
<td>0.191</td>
</tr>
<tr>
<td>1.0%</td>
<td>3.25</td>
<td>0.169</td>
</tr>
</tbody>
</table>

In order to study the effect of injector geometry on liquid film thickness and spray characteristics, the geometrical characteristics constant $A = R_i R_o/i R_p^2$ of the injectors was changed by changing the diameter of the tangential channel of the injector. The schematic diagram of the nozzle model is shown in Fig. 3, where $R_{in} = R_e R_p$ is the distance from the nozzle axis to the center of the tangential channel, $R_e$ is the injector exit radius, $i$ is number of tangential inlets, $R_p$ is the radius of tangential inlets. The geometric parameters of the nozzle are shown in Table 2. $L_i$ is the injector length.

![Figure 3: Schematic of model injector](image)

<table>
<thead>
<tr>
<th>Injector number</th>
<th>$R_i$ (mm)</th>
<th>$L_i$ (mm)</th>
<th>$R_p$ (mm)</th>
<th>Number of tangential inlets $i$</th>
<th>$R_o$ (mm)</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>4</td>
<td>38.5</td>
<td>0.80</td>
<td>1</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>S2</td>
<td>4</td>
<td>38.5</td>
<td>0.95</td>
<td>1</td>
<td>4</td>
<td>13.5</td>
</tr>
<tr>
<td>S3</td>
<td>4</td>
<td>38.5</td>
<td>0.99</td>
<td>1</td>
<td>4</td>
<td>12.3</td>
</tr>
</tbody>
</table>

The conductance measurement method was used to measure the thickness of the liquid film. Specific methods refer to the literature [21]. The method was to place two ring electrodes near the outlet of the injector. The electrode position is shown in Fig. 3. The electrode material is porous titanium, which...
increases the contact area with the fluid surface. When the gel simulating liquid flows between the two electrodes, the conductance between the two electrodes changes due to the change of the thickness of the liquid film, so that the voltage changes and is collected and recorded by the data acquisition card.

The liquid film thickness measurement system is calibrated by inserting cylindrical plastic rods of different diameters into the axis of the swirl chamber. When the gel simulation flows through the swirl chamber, different liquid film thicknesses are generated between the calibration rods of different diameters and the swirl chamber, and the corresponding voltage signal size at this time is recorded. As is shown in Fig. 4, it is the calibration curve of liquid film thickness and output voltage signal.

3. Results and discussion

The thickness of the liquid film at the outlet of the injector usually characterizes the performance of a swirl injector and determines the size of the fluid parcel after the liquid film breaks up. In the injectors with different geometrical characteristic constants, the variation of the liquid film thickness with the pressure drop of three different concentrations of the gel simulation liquid is shown in Fig. 5.

As can be seen from Figure 5, the liquid film thickness slowly decreases with increasing pressure drop at each operating condition. In addition, for different gel simulating liquid mass fractions, the liquid film thickness increases with the increase of the mass fraction of the gel simulants. According to the empirical equation of the literature [20]:

$$h = 2.7(2RM\mu/\rho\Delta p)^{0.25}$$  \hspace{1cm} (2)

where $M$ and $\mu$ denote the mass flow rate and dynamic viscosity respectively, as the pressure drop increases, the film thickness slowly decreases. The trend of experimental data changes is the same as the literature. For different concentrations of gel simulants, the consistency coefficient increases with the mass fraction, so the high-mass fraction of the gel will have a greater viscosity. This results in a slower swirling flow in the nozzle and a thicker film thickness.

Figure 6 shows the scatter plot of liquid film thickness with pressure drop for different injectors (mass fraction of 0.1% gel simulant). It can be seen from Figure 6 that the liquid film thickness of the gel simulator increases with increasing geometrical characteristics constant of the injector. This result is consistent with the literature [21]. At the same pressure drop, the flow rate of the injector decreases with the increase of the geometric characteristic constant. When the gel simulator flows in the injector, the momentum is more dissipated due to its greater viscosity, and the axial velocity of the flow is decreased more significantly. According to the mass flow equation, the thickness of the liquid film increases with increasing geometrical characteristic

![Figure 5: Variation of liquid film thickness with pressure drop in different injectors](image1)

(a) S1

(b) S2

Fig. 5: Variation of liquid film thickness with pressure drop in different injectors

![Figure 6: Scatter plot of liquid film thickness variation with pressure drop for different injectors (mass fraction of 0.1% gel simulant)](image2)
constant $A$. Factors affecting the flow characteristics of swirl injectors include turbulence, viscosity, and the stability of air core [22]. The thickness of the liquid film will also be subject to indefinite deviations, and the deviations of some experimental results of this experiment are consequential.

In the classical non-viscous theory, the geometric characteristic constant of the swirl injector is used to characterize the swirling intensity of the fluid. According to the principle of maximum flow [23],

$$A = \sqrt[21]{\frac{1-\Phi}{\phi \Phi F}},$$

where $\phi$ denotes the flow area coefficient. If viscosity is considered, the liquid film thickness obtained by this empirical equation will be biased. For power law fluids, the generalized Reynolds number $Re_{gen} = \frac{\rho \sigma^{0.25 + 0.25 \frac{n}{K}}}{0.75 + 0.25 \frac{n}{K}}$ [24] is introduced, and the empirical equation for the thickness of the liquid film $h$, the geometric characteristic constant of the swirl injector $A$ and the generalized Reynolds number $Re_{gen}$ are summarized:

$$\frac{h}{2R} = 1.14 + 1.13 \times 10^{-6} Re_{gen} - 0.14 A - 3.07 \times 10^{-10} Re_{gen}^2 + 4.76 \times 10^{-7} A^2 + 3.13 \times 10^{-8} A Re_{gen}$$

(3)

4. Conclusions

In order to study the gel film thickness and atomization characteristics of the open-end swirl injector, 0.1%, 0.5% and 1.0% of the gel simulants were used to change the power law index $n$ and the consistency coefficient $K$ of the rheological parameters, three injectors with different tangential channel diameters changed the geometrical constants of the injector. The variation of liquid film thickness, discharge coefficient, liquid film spray cone angle, and liquid film breakage length was found. The thickness of the liquid film decreases slowly with increasing pressure drop, increases with increasing $A$, and increases with increasing gel mass fraction; the discharge coefficient does not change with increasing pressure drop, decreases with increasing $A$, and decreases with gel mass fraction increased; the liquid film spray cone angle increased with the increase of pressure drop, increased with the increase of $A$, and decreased with the increase of the gel mass fraction; the breakup length decreased with the increase of pressure drop, increases with $A$ increases, and decreases with increasing gel mass fraction. For the gel propellant liquid film thickness, discharge coefficient, liquid film spray cone angle, and liquid film breakage length in the open-end swirl injector, the empirical equations for the geometric characteristic constant $A$ and the general Reynolds number related to the gel rheological parameter can be fitted based on the experimental results.

Acknowledgements

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References


Bazarov, V.: Dynamics of Liquid Injectors, Mashinostroenie, Moscow, 1979.