Aerospace Science and Technology 39 (2014) 552–558

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Spray of gelled propellants from an impinging-jet injector under different temperatures

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ARTICLE INFO

Article history:
Received 20 October 2013
Received in revised form 23 June 2014
Accepted 1 July 2014
Available online 7 July 2014

Keywords:
Impinging jet injector
Gelled propellant
Power-law fluid
Liquid sheet
Liquid temperature

ABSTRACT

This paper presents the results of an experimental study on the spray characteristics of gelled propellant from an impinging jet injector under different liquid temperatures. A high-speed camera was used to record detailed information about the liquid sheet breakup process and spray development. The rheological characteristics of the gel simulant under different temperatures were tested. It was found that the consistency coefficient decreases and the flow index increases as the liquid temperature increases. The flow characteristics and spray patterns for injectors with tapered orifices and straight orifices were tested, respectively. Because the injection of fluid through tapered orifices can decrease the viscosity of the fluid, the mass flow rate is increased and the liquid sheet behaves more unstably for injector with tapered orifices. The influence of liquid temperature on the mass flow rate for both injectors is minor. The spray photos showed that the liquid sheet is more unstable and easier to break up at higher temperature for both injectors. Generally, the liquid sheet breakup length decreases and the disturbance wavelength increases as the liquid temperature increases.

1. Introduction

Impinging-jet injectors are widely used in liquid propellant rocket engines because of the relative simplicity of their fabrication and their good atomization and mixing characteristics. For like-doublet impinging-jet injectors, the impingement of two equal cylindrical coplanar jets produces a thin expanding liquid sheet in the plane perpendicular to the plane containing their axes. This liquid sheet quickly disintegrates into unstable arc-shaped liquid ligaments and finally breaks into droplets.

Extensive studies on the shape and the thickness of the sheet formed by the impinging jet injector have been performed [2,5,6,8,10,11,19]. Besides, the breakup characteristics of the liquid sheet are mainly studied. Li and Ashgriz [12] defined two major breakup regimes according to the type of instability which causes the breakup, namely the capillary instability and Kelvin–Helmholtz instability. Bremond and Villermaux [4] examined the processes of sheet destabilization—either triggered artificially by an external perturbation, or naturally via the disturbances injected by the jets themselves in the sheet. Heislbetz et al. [9] compared their experimental results concerning critical wave lengths and breakup lengths with the theoretical results. The experiments show a good agreement to an introduced approximation method in the case of high viscous liquid.

Beside the common used storable liquid propellant, the impinging-jet injector is also widely used to atomize gelled propellants. Gelled propellant is a promising option for future aerospace application because it combines the advantages of the solid propellant with those of the liquid propellant. From the view of fluid mechanics, gels behave as non-Newtonian shear-thinning fluids, whose rheological characteristics are often better described by a power-law model $\tau = \eta\dot{\gamma}$, where τ is stress tensor, $\dot{\gamma}$ is the rate of strain tensor, and the apparent viscosity η is given by the second invariant of the rate of strain tensor $\eta = K(\frac{\dot{\gamma}:\dot{\gamma}}{2})^{\frac{n-1}{2}}$. The flow index number n is dimensionless and the fluid consistency number K has dimension of Pa·s^n. Shear thinning behavior corresponds to $n < 1$, whereas shear thickening behavior exists when $n > 1$. Newtonian behavior corresponds to $n = 1$. Gelled propellants usually behave as the shear thinning fluid propellants, that is, the apparent viscosity would decrease as the rate of strain increased. By conducting experiments with gelled propellants in an impinging jet injector setup, von Kampen et al. [20] found some different spray patterns which were not reported in previous publications concerning Newtonian fluids, e.g. a ray-shaped pattern, and a ligament pattern. Yang et al. [21] used a modified empirical equation combining the linear instability analysis method to investigate the instability and breakup characteristics of the sheet formed by a gelled propellant impinging jet injector. Fu et al. [7] studied the

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http://dx.doi.org/10.1016/j.ast.2014.07.001
1270-9638/

effects of nozzle geometrical characteristics on sheet formation, breakup and atomization for gels from an impinging jet injector.

It is known that, for the fuels which behave as Newtonian fluids, the fuel properties, such as density, viscosity, and surface tension, can be influenced by the fluid temperature. There are some studies [1,14,15] reporting the effects of fluid temperature on the internal flow of injector and spray characteristics for fuel ejected from injectors. The variation of fuel properties according to the temperature were studied by Yoon et al. [22]. They found that the fuel density decreases linearly and the kinematic viscosity decreases exponentially with increasing fuel temperature. However, the fluids used in these studies are all Newtonian. Comparatively, the effects of fluid temperature on the spray characteristics of gel propellant (non-Newtonian fluid) are less studied. Also, the flow index number and the fluid consistency number of the power-law model are dependent on the fluid temperature greatly [3]. Hence the rheological behavior would vary a lot when the temperature changes. Subsequently the spray of the gelled propellant can be affected by the variation of fluid temperature. Rahimi et al. [16] investigated the rheological properties of gelled fuels, oxidizers, and inert simulants in the relevant range of operating temperatures, showing that the temperature has influences on the power-law parameters. Rahimi et al. [17] also discussed the temperature sensitivity of three types of gel propellants. The detonation temperatures of Nitromethane Aluminum gels were investigated in Ref. [18]. However, all these researchers did not perform the spray tests for gelled propellants under varying temperatures. This paper reports the experimental observations of the sprays from a series of impinging jet injectors for a gelled propellant simulant with different fluid temperatures. The flow structure and breakup characteristics of thin liquid sheets formed by the impinging jet injectors have been studied. The effect of the temperature on the breakup and spray characteristics of the liquid sheet is predominantly discussed.

2. Experimental setup and procedures

The experimental setup consists of a fluid tank, which can adjust the temperature of the fluid; the injector unit, the pressure and flow measurement system and a high-speed camera. The fluid was fed to the injector unit using high pressure gas. The temperature of the fluid in the tank and the injector unit was recorded by thermocouples. The mass flow rate of the fluid was measured by a Coriolis mass flowmeter. A high speed video camera was used to observe the liquid sheet; a 1300 W steady halogen lamp was the light source. The high speed video camera was a MS75K from Mega Speed, Inc. The frame resolution was set at 504 pixels by 504 pixels, and the shutter speed was 10 μs. A frame rate of 6000 frames per second (fps), was selected to capture the majority of time scales observed during testing. The light source and camera were in line with the liquid sheet.

The modular injector configuration allows easy assembly of the injector exit nozzle and the manifold case. Two types of impinging jet injectors were tested in this experiment. Both injectors have circular exit nozzles with the diameter of 0.6 mm, one of which has the tapered orifices with the tapered angle of 20° and the other has the straight wall orifices. All the injector has an impingement angle of 60°. The length from injector to collision point is 11.6 mm for all injectors tested. A pressure sensor was installed in the manifold to measure the pressure drop across the injector.

For safety considerations, a gel simulant was used instead of real gelled propellant in the experiments. The working fluid was an aqueous solution of polysaccharide with a mass concentration of 2%. Gel simulant has physical properties similar to gelled propellants: density of 1010 kg/m^3, and surface tension of 0.07 N/m; they also have similar rheological characteristics. The steady shear

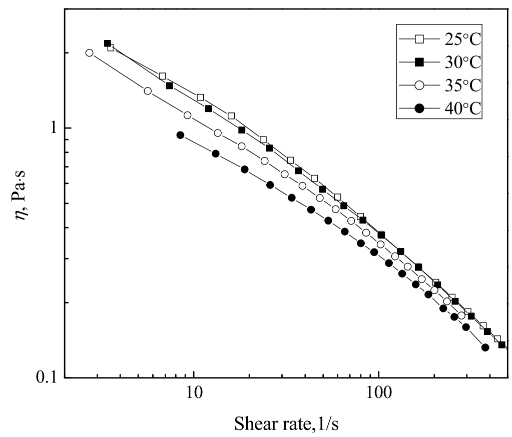

Fig. 1. Shear rheology for the working fluid under different temperatures.

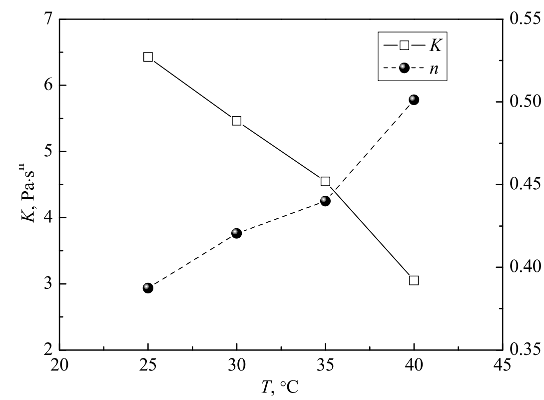

Fig. 2. Variation of the power-law model parameters with the temperature.

rheology of the gel simulant was characterized using a Bohlin cone-and-plate controlled stress rotational rheometer (CS50). Fig. 1 shows the shear rheological properties for the working fluid under different fluid temperatures. It shows in Fig. 1 that the working fluid was a shear thinning fluid which showed decreasing viscosity with increasing shear rates under the temperatures tested. The rheological parameters can be obtained by fitting the measured rheological curve to the power-law model; then the consistency coefficient K and flow index number n can be obtained. The rheological parameters of the liquid at different temperatures are shown in Fig. 2. As shown in Fig. 2, the consistency coefficient K varies between 2 and 7 Pa·s^n for the measured temperature range, and decreases with increasing of the temperature. Moreover, the flow index n generally increases as the temperature increases. n gets closer to 1 means that the fluidity is better, and n get closer to 0 means that the plasticity intensifies. Hence, the high temperature makes the viscosity of the simulant gel decrease, and the fluid becomes more like Newtonian fluid.

3. Results and discussion

The flow characteristics of the model injectors have been examined at first. As shown in Fig. 3, the mass flow rates of both injector increase as the pressure drop increases for all the temperatures tested. The sectional area of the exit orifice for the two injectors is equal, but the mass flow rate of the injector with tapered orifices is larger than that of the injector with straight orifices under the same pressure drop and temperature, e.g. the condition under the temperature of 25 °C is shown in Fig. 4. As we know, the gel propellant has the property of shear-thinning and injection of the power-law fluid through a tapered orifice causes the shear rate to