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The instability and droplet size distribution of liquid-liquid coaxial swirling spray: An experimental investigation

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ABSTRACT

An experimental study is performed to study the effect of inner and outer injection pressure on spray characteristics and the detailed structure of interacted liquid sheets of a coaxial swirl injector. A high speed camera is used to visualize the transition merging process of the coaxial swirling liquid sheet. A laser reflection system is set up to analyze the wave frequency of liquid sheet. A Malvern RTSizer is used to measure the droplet size of the coaxial spray. It is found that the structure of the interacted spray is considerably different from the individual spray, the interaction between the inner and outer liquid film promoted the breakup. At the same injection pressure, the temporal instability of a liquid sheet does not change spatially. For both individual and coaxial spray, the wave frequency increase as the injection pressure increase. The individual inner spray is more unstable and easier to breakup. Furthermore, the relationship between the surface instability and the droplet size distribution of the coaxial liquid spray is investigated quantitatively. For both individual spray and coaxial sprays, the Sauter Mean Diameter (SMD) decrease as the inner injection pressure increase. The inner spray has a higher weighing factor that influences the SMD of the coaxial spray. For coaxial spray at low inner injection pressure, the liquid film thickness would be the dominate factor to the SMD.

1. Introduction

The atomization process and mixing of propellants greatly influences combustion in liquid rocket engines. Coaxial swirl injectors are widely used in liquid rocket engines due to its better quality of atomization and efficient mixing of propellants [1,2]. A coaxial swirl injector consists of an inner injector encircled by a concentric annular outer injector. Fuel and the oxidizer are injected into the swirl chamber under high pressure through tangential slots, which form two coaxial hollow cone sprays at the exit of the injector. The inner and outer liquid sheets interact and merged near the exit of the injector, forming a conical sheet. Then, the sheet becomes unstable and breaks up into ligaments and droplets.

Over the past decades, several investigations have been carried out to understand the breakup phenomenon of the swirl liquid sheet [3–5]. Theoretically, studies on the instability of liquid sheet were conducted. Ponstein [6] investigated the growth of disturbance of an annular swirling liquid sheet based on instability analysis. In his study, the viscosities of both phases were neglected. Liao et al. [7] investigated the instability of an inviscid, swirling annular liquid sheet and developed a theoretical model to predict the performance of simplex atomizer. Ibrahim and Jog [8] studied the nonlinear instability and breakup of an annular liquid sheet using a perturbation expansion method. They investigated the effect of liquid Weber number, initial disturbance and gas swirl strength on the liquid sheet breakup characteristics. Experimentally, studies are carried out to predict the atomization characteristics of swirling spray using several measurement techniques, most of them focus on the macroscopic properties (spray angle, liquid film breakup length and drop size distribution) of atomization [9–13]. Broniarz-Press et al. [14] and Ochowiak [15] studied the twin-fluid atomization process of pressure-swirl atomizers by the use of the digital microphotography method. The spray characteristics of emulsion spray at different stages have been observed. In addition, Broniarz-Press et al. [16] used a laser diffraction technique to analyze the droplet size distributions and mean droplet diameters. The relationship of Sauter mean diameter with atomizer shape and injection pressure has been proposed. Experimental investigation on the instability of swirling spray was conducted by Yao et al. [17]. Spatiotemporal diagrams were used to analyze the surface wave frequency and the effect of liquid viscosity on the liquid sheet instability has been investigated.

For the coaxial swirl injector, the interaction between the inner and the outer liquid sheets make these spray characteristics quite

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different from the hollow cone swirl liquid sheet. A series of studies have been carried out to investigate these spray characteristics over the past decades. Hardalupas and Whitelaw [18] used a Phase Doppler Anemometer (PDA) to investigate spray characteristics of coaxial injectors, in which spray characteristics at different exit Weber (We) numbers and gas-to-liquid velocity ratios were studied. In another study, Seol et al. [19] investigated the interaction of inner and outer sheets of a dual-orifice fuel injector at low injection pressure, and observed that the interaction was affected by ambient pressure. Furthermore, Sivakumar and Raghunandan [20–22] studied the interaction between two thin coaxial sheets, which were formed by coaxial swirl injectors. The merging and separation processes were visualized by still photographic technique. Results indicated that the hysteresis phenomenon would influence the spray characteristics of combined spray. Moreover, Kim et al. [23] investigated the influence of recess on spray characteristics of a liquid-liquid swirl coaxial injector, and revealed that the interaction between two conical liquid sheets influence spray characteristics grievously.

As mentioned above, a series of investigations have been conducted on coaxial swirl injectors. These studies provided meaningful conclusions on the effects of injector geometric parameters, injection conditions and liquid properties on spray characteristics such as spray structures, spray angle and breakup length. Limited studies have been reported in literature on the instability of coaxial swirling spray, which influence the combustion instability directly. Besides, the droplet size distribution is also an important characteristic parameter that needs to be further investigated.

In the present study, high speed camera was used to visualize the structure of the coaxial sprays; a laser reflection system was set up to analyze the wave frequency of liquid sheet. A Malvern RTSizer was used to measure the droplet size of the coaxial spray.

At the rest of the present paper, the effect of inner and outer injection pressure on the detailed structure of the interacted liquid sheet and the surface wave frequencies were investigated to better understanding of coaxial swirling sprays. In addition, the relationship between the surface instability and the droplet size distribution of the coaxial liquid spray were investigated quantitatively. Finally, some conclusions were summarized based on these results.

2. Experimental setup

The experimental schematic of the present investigation is shown in Fig. 1. The system contains high-pressure gas tanks, liquid tanks, test injectors and a measure and control system. The spray is illuminated by a LED light source and visualized using a high-speed camera at a frame rate of 8000 Hz and a resolution of 512 ∗ 512 pixels. The surface wave frequency is measured by laser reflection method as shown in Fig. 1. The reflected laser beam is received by an optical sensor and the signal is analyzed by fast Fourier transform so that the wave frequency can be obtained. Droplet size is measured with Malvern RTSizer at the measure frequency of 5000 Hz. The mean droplet size at different locations (20–70 mm) downstream the nozzles exit is measured.

The sketch of the coaxial swirl injector is shown in Fig. 2. The coaxial swirl injector consists of the inner and outer injector, whose geometrical properties are listed in Table 1. Where L_o is the nozzle length, D_o is the nozzle diameter, D_s is the swirl chamber diameter, *n-slot* is the number of inlet slot and D_{slot} is the inlet slot diameter. The inner injector was the oxidizer injector and the outer injector was the fuel injector and the O/F ratio was fixed at 3/1. In the present investigation, water was used as the simulant of LOX and the fuel was kerosene. Injection pressure of each injector varied from 0.1 MPa to 0.6 MPa.

3. Results and discussion

3.1. Spray structure

The developed stage of individual sprays at different injection pressures are illustrated in Fig. 3. In the present study, for the swirl injector at injection pressures, after the fluid leaves the nozzle, a cone is formed due to the swirl motion in the swirl chamber. The relative velocity between the liquid and gas phase induces a surface instability, in which surface wave propagates and grows along the axial direction. As wave magnitude increases and liquid film becomes thinner due to expansion, the wave breaks up into ligaments and small droplets. At low injection pressures, the liquid film at the near nozzle region is smooth; and long wavelength instability occurs, as shown in Fig. 3. At the downstream of the nozzle, a quantity of holes shapes up and expands, the liquid film is torn, and ligaments are formed due to surface tension force. As the injection pressure increase, short wavelength instability occurs at the exit of the nozzle, and grows along the axial direction. At the downstream of the nozzle, rim-like structures are formed and finally break up in the form of ligaments.

The transition merging process of the coaxial swirling liquid sheet is shown in Fig. 4. As shown in the first frame, at the

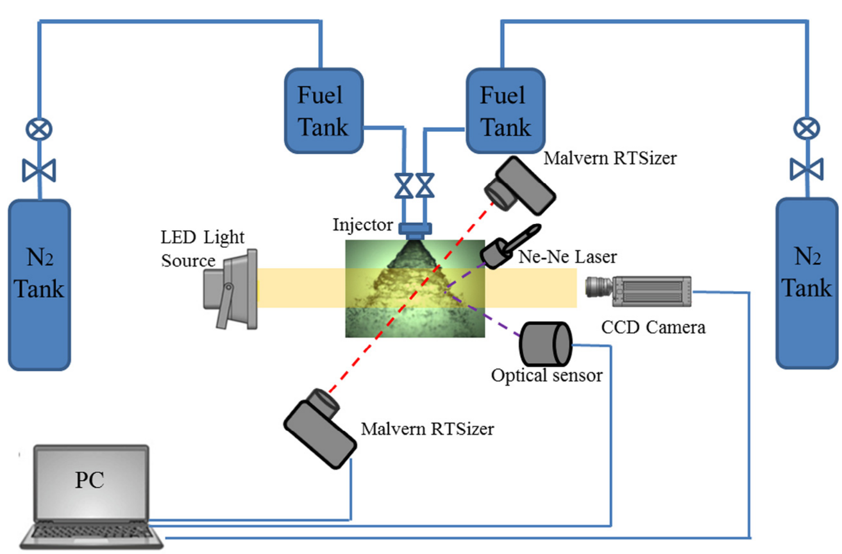

Fig. 1. Schematic of the experimental setup.