Effects of Fuel Temperature on the Spray Characteristics of a Dual-orifice Type Swirl Inejector

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Fuel temperature shows strong influence on the spray characteristics especially at a lower temperature. An experimental study is conducted to investigate the effects of fuel temperature on the spray characteristics of a dual-orifice type swirl injector used in a gas turbine. The major parameters affecting spray characteristics are fuel temperature and injection pressure entering into the injector. In this study, fuel temperature is varied from –30 to 120°**C** and injection pressure is altered from 3 to 7 kg_f/cm^2. Two kinds of fuel, which have different surface tension and viscosity, are chosen as an atomizing fluid. As a result, injection instability occurs in the low temperature range due to icing phenomenon and fuel properties. As the injection pressure increases, the kinematic viscosity range for stable atomization becomes wider. The factor controlling the SMD of spray is substantially different according to the fuel temperature range.

1. Introduction

Fuel temperature entering into an injection nozzle in the gas turbine combustors of aircraft and rocket engines varies in the wide range due to the locations, severe climate conditions, regeneration cooling of rocket engine, and lubricant cooling. Spray characteristics of fuel including distributions of particle size, volume concentration, and spray angle play an important role in the gas turbine combustion performance, such as combustion efficiency. Especially, the droplet size has been considered to be one of the major factors in determining combustion performance because it is closely related to the dynamics and evaporation processes of fuel sprays and consequently the combustion processes. Spray characteristics are greatly influenced by fuel temperature especially at a lower temperature [1]. In order to ensure the stable ignition and combustion, the distribution of spray including droplet size, concentration, and spray angle should be controlled at suitable conditions.

Yule et al. [2] showed that injection pressure in the high pressure range affected on the discharge coefficient, droplet diameter, and spray angle. Especially, they reported that spray characteristics were significantly influenced by inlet port geometry, swirl chamber length, and diameter. Koh et al. [3] examined the effects of liquid injection temperature on the spray characteristics in a condensable environment. Subcooled water, which was used as an injection fluid, was discharged from a pressure swirl nozzle placed in a saturated steam environment. Liquid temperature was varied from 30 to 80°C.

Jazayeri et al. [4] studied the spray characteristics generated by the breakup of thin liquid sheets in co-flowing air streams. They explained that axial mean velocities of the droplets at a given spray cross-section showed a maximum value at the spray center, and it decreased by deviating from the center. However, the SMD showed a minimum value at the center and then increased monotonically towards the spray periphery. In addition, the SMD at the spray center had a complex variation along the flow direction due to a secondary atomization at a higher air velocity near the nozzle exit, and droplet entrainment, migration, and possible coalescence at further downstream. Knubben et al. [5] measured the droplet size distributions of fuel sprays for butane and propane with a temperature variation of fuel and inlet air. They showed that the inlet air temperature was the most important factor during the evaporation process, and the SMD increased as the droplets moved toward downstream with continuous injection.

In this study, the effects of fuel temperature on the spray characteristics are experimentally investigated in a dual-orifice type swirl injector used in a gas turbine combustor. Fuel temperature and injection pressure are chosen as the major parameters influencing on the spray characteristics. Two kinds of fuel are used as an atomizing fluid. Discharge coefficient, dispersion angle, distribution of volume concentration, and SMD are measured at various combinations of operating conditions in atomizing flow field.

2. Experimental apparatus and test methods

In the present study, the dual-orifice type swirl injector including pilot and main nozzles is used to spray fuel. The pilot nozzle is solely operated in the ignition and small-thrust mode, but operated together with the main nozzle in the cruise mode. The schematic diagram of experimental apparatus used in this study is shown in Fig. 1. Pressurized fuel by nitrogen gas in the tank is provided to a heat exchanger submerged in a temperature control bath. Then, the fuel is sent to the atomizing nozzle, and consequently injected into ambient air. Fuel temperature and injection pressure are varied from -30 to 120°C and from 3 to 7 kg_f/cm^2, respectively. A Malvern particle analyzer is installed downstream of the injector tip to measure SMD and volume concentration of spray [6]. The dispersion angle of spray is measured by the spray images captured by a CCD camera. The volumetric distribution of spray is measured by an 1-D patternator, which consists of 30 collecting bins, connecting tubes, and mass cylinders. During the measurement of mean droplet size, suction from the bottom of the fuel collector is carried out.

Atomized fluids are kerosene-type fuels, and the properties are shown in Fig. 2. As the fuel temperature increases, the surface tensions of fuel A and B linearly decrease corresponding to the temperature. The kinematic viscosities decrease drastically in the low temperature range, while decrease gradually in the high temperature range with an increase in fuel temperature. Kinematic viscosity and surface tension of fuel B are much larger than those of fuel A.

To describe more succinctly the effects of operating parameter variations on droplet distribution, a radial distribution curve may be reduced to a single numerical value called an equivalent spray angle [1]. The equivalent spray angle is a summation of two angles, f_L and f_R, which are given by

$$f_L(or f_R) = \frac{\Sigma y q \Delta q \sin q}{\Sigma y \Delta q \sin q} = \frac{\Sigma y q \sin q}{\Sigma y \sin q} \qquad (1)$$

Where Δq is an angle between the sampling tubes, and y is a liquid volume measured at the corresponding tubes. The physical meaning of the equivalent spray angle is that $f_L \ (or f_R)$ is the value of θ that corresponds to the position of the center of mass of a material system for the left (or right) lobe of the distribution curve.

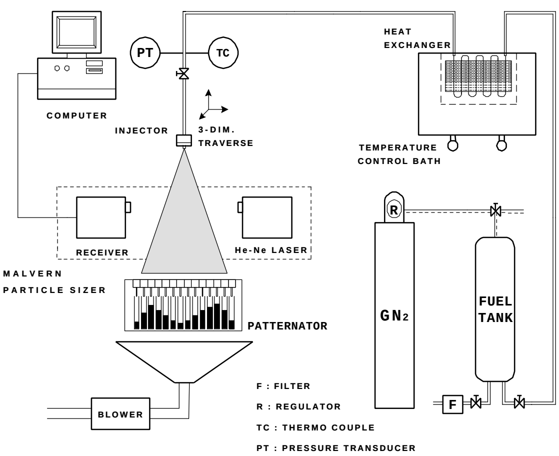


Fig. 1 Schematic diagram of test setup.

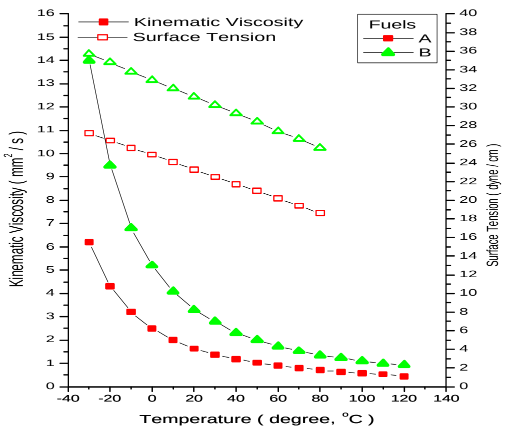


Fig. 2 Properties of fuel A and B versus temperature.

3. Results and discussion

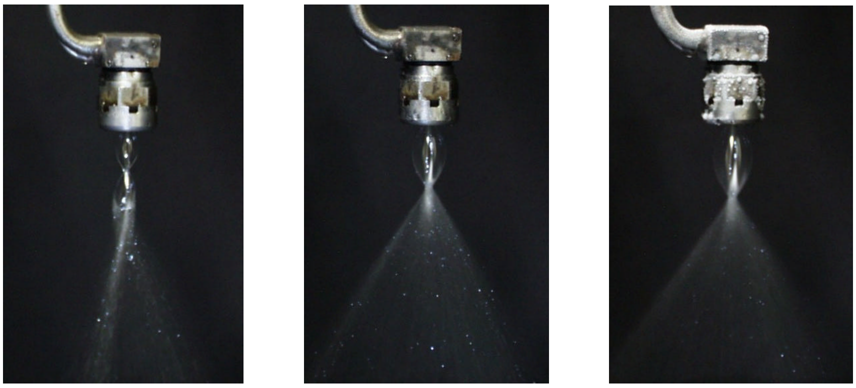
Fig. 3 shows direct spray images of fuel B injecting from the main nozzle at -10°C. In the early stage of injection, the spray shows the tulip stage in spray development. As the injection proceeds, it changes to the onion stage in spray development. Finally, the injection of the main nozzle for fuel B becomes very unstable.

Fig. 4 shows direct spray images of fuel B injecting from the main nozzle at various injection pressures with -10°C. The spray shapes in the whole range of injection pressure show the onion stage in spray development. The atomization is gradually deteriorated with time and then the spray becomes very unstable, stopping the injection. The elapsed time is defined as the time between the beginning and ceasing of the injection. The ice crystals are found in the face of the injector orifice. According to Kim et al. [7], choking at the nozzle outlet was not observed due to icing phenomenon, but the grown ice partially covered the nozzle outlet.

During the experiments, fuel A is atomized stably in the entire fuel temperature range from -30 to 120°C, but the injection of the main nozzle for fuel B is very unstable in the low temperature range. Figs. 5 (a) and (b) show injection stability maps in pressure-kinematic viscosity and pressure-surface tension planes for fuel A and B. Hatched area in Fig. 5 (a) and (b) represent the transient regions between stable and unable injection. At a lower injection pressure, stable injection is observed only at a lower viscosity. As the injection pressure increases, the viscosity range for a stable atomization becomes wider. Fig. 5 (b) shows that the stable region increases as the injection pressure rises at a given surface tension. With a larger surface tension, unstable injection may occur. As shown in Fig. 2, the surface tension and kinematic viscosity of fuel B are sufficiently larger than those of fuel A. Therefore, fuel A yields a stable atomization even in the low temperature range.

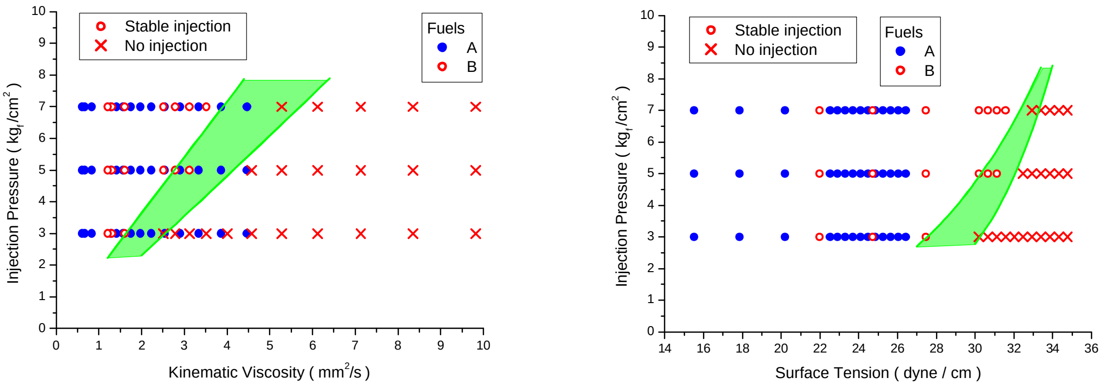
(a) t = 1 sec (b) t = 5 sec (c) t = 15 sec

Fig. 3 Direct spray images of fuel B injecting from main nozzle at P=7 kg_f/cm^2 and T= -10°C.



(a) P = 3 kg_f / cm^2 (b) P = 5 kg_f / cm^2 (c) P = 7 kg_f / cm^2

Fig. 4 Direct spray images of fuel B injecting from main nozzle at various injection pressures with T= -10°C.



(a) Kinematic viscosity-injection pressure (b) Surface tension-injection pressure

Fig. 5 Injection instability maps for fuel A and fuel B.

Fig. 6 shows the effects of fuel temperature on the discharge coefficient. Generally, the discharge coefficient of a swirl atomizer is inevitably low due to the presence of the air core [1]. The discharge coefficient of the main nozzle remains almost constant at 0.06, but that of the pilot nozzle decreases with a rise of fuel temperature in the low temperature range and gradually converges to 0.37. A pilot nozzle diameter of 0.4 mm is smaller than a main nozzle diameter of 1.9 mm. Because of a smaller nozzle diameter, the discharge coefficient of the pilot nozzle is more strongly affected by viscosity as compared with the main nozzle having a larger nozzle diameter.

Fig. 7 represents the effects of fuel temperature on the spray angle for the main-pilot and main nozzles. As the fuel temperature increases, the spray angles for the main-pilot and main nozzles increase gradually due to a reduction of fuel viscosity. The friction force generated by velocity gradient tends to reduce the tangential velocity [1]. In the case of the simultaneous spray from the main-pilot spray nozzle, the atomizing streams injecting from the pilot nozzle collide to the spray streams injecting from the main nozzle, forming a hollow cone type spray. The spray angle of the pilot-main nozzle is smaller than that of the main nozzle because the spray of the pilot nozzle has a smaller rotational momentum.

Figs. 8 (a) and (b) show the radial distributions of volume concentration and SMD for the main-pilot nozzle at various temperatures of fuel A. As the fuel temperature increases, kinematic viscosity and surface tension preventing fuel atomization drop. In Fig. 8 (a), as the fuel temperature increases, the location of the maximum droplet volume concentration moves to outward, and the maximum value of volume concentration decreases gradually. As the fuel temperature increases, the SMD reduces as shown in Fig. 8(b). The location of the maximum droplet volume where can be identified as the main stream of the spray coincides with that of peak SMD.

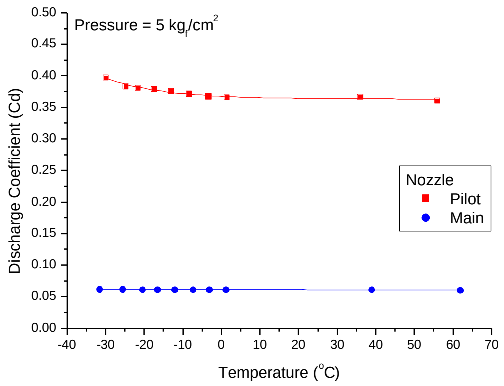


Fig. 6 Effect of fuel temperature on discharge coefficient for pilot and main nozzles.

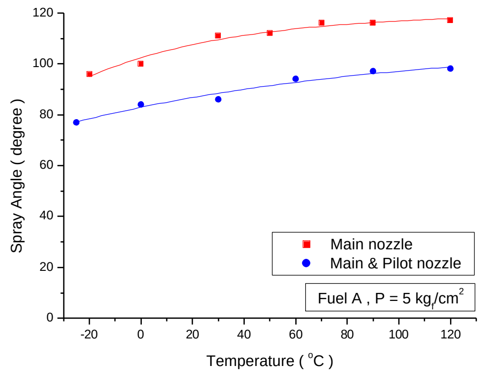
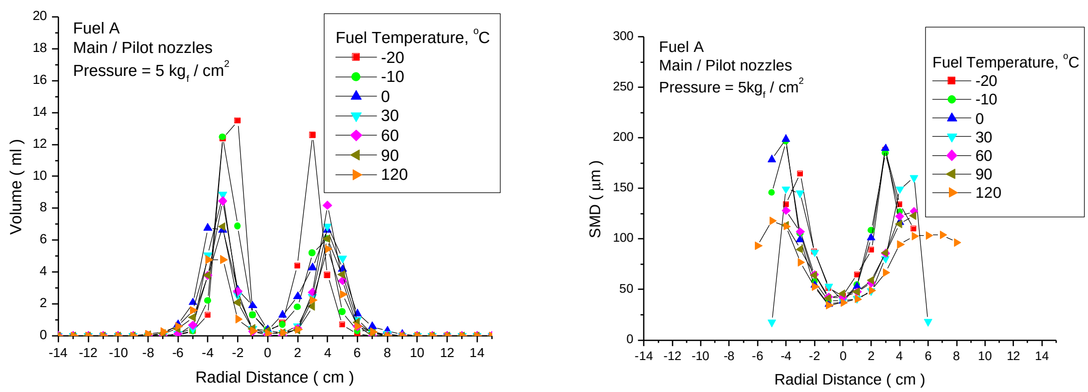


Fig. 7 Effect of fuel temperature on spray angle for main and main-pilot nozzles.



(a) Volume distribution (b) SMD distribution

Fig. 8 Radial distributions of volume concentration and SMD at various fuel temperatures.

Fig. 9 represents the effects of fuel temperature on equivalent spray angle for the main-pilot nozzle. As the fuel temperature increases, the equivalent spray angle increases in the low temperature range and then remains almost constant. In the high temperature range, a drop of SMD causes a rise of vaporization rate and a decrease of penetration depth. Therefore, the equivalent spray angle remains constant in the high temperature range.

Fig. 10 shows the radial distributions of SMD from the main nozzle at various fuel temperatures. There are two groups of SMD distribution curves evidently divided by fuel temperatures. For the low temperature range, the larger SMD value and the more severe change of distribution curve are shown as compare with those in the high temperature range. As shown in Fig 2, kinematic viscosities decrease drastically in the low temperature range and drop gradually in the high temperature range even though surface tension is reduced linearly with an increase of fuel temperature. Therefore spray characteristics, especially spray SMD, are more strongly influenced by kinematic viscosity than surface tension in the low temperature range, while those are more influenced by surface tension in the high temperature range.

Based on experimental data, a correlation for the SMD at the locations of maximum volume concentration appeared in droplet volumetric distribution is derived as given by

$$SMD = 111.2745 s^{0.2125} n^{0.3313} \Delta P^{-0.4203} \quad (2)$$

It should be noted that the present study considers only the variation of fuel temperature resulting the change of fuel properties for an atomizer.

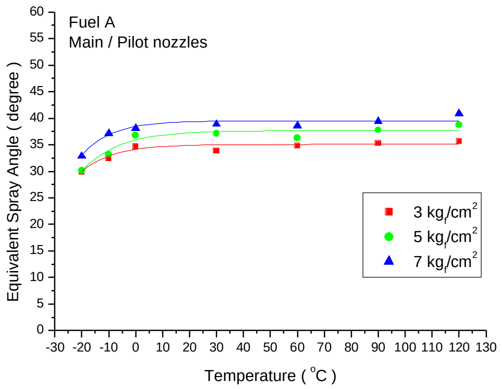


Fig. 9 Effect of fuel temperature on equivalent spray angle.

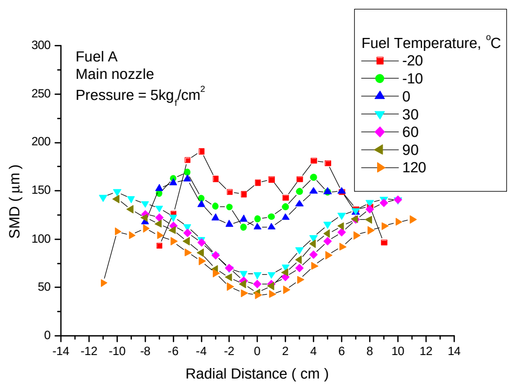


Fig. 10 Radial distributions of SMD at various fuel temperatures.

4. Conclusions

The influence of fuel temperature and injection pressure on the spray characteristics is experimentally investigated in a dual-orifice type swirl injector used in a gas turbine combustor. Two kinds of fuel, which have different surface tension and viscosity, are used as an atomizing fluid. Direct spray images for fuel A and B are visualized to determine injection stability. Discharge coefficient, dispersion angle, volume concentration, and SMD are measured at various operating conditions. As a result, the injection of the main nozzle for fuel B is unstable in the low temperature range due to icing phenomenon, a higher surface tension and kinematic viscosity. In addition, as the injection pressure increases, the viscosity range for stable atomization becomes wider. The spray SMD is more strongly influenced by kinematic viscosity than surface tension in the low temperature range, while it is more influenced by surface tension in the high temperature range. Furthermore, an empirical correlation for the SMD is derived.

Acknowledgements

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