An Experimental Study on the Spray Characteristics of a Dual-Orifice Type Swirl Injector at Low Fuel Temperatures

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The objective of this study is 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, the spray characteristics of a dual-orifice type swirl injector are investigated by varying fuel temperature from −30℃ to 120℃ and injection pressure from 0.29 to 0.69 MPa. Two kinds of fuel having different surface tension and viscosity are chosen as atomizing fluids. As a result, injection instability occurs in the low fuel temperature range due to icing phenomenon and fuel property change with a decrease of fuel temperature. As the injection pressure increases, the range of kinematic viscosity for stable atomization becomes wider. The properties controlling the SMD of spray is substantially different according to the fuel temperature range.

Key Words: Spray, Fuel Temperature, SMD, Equivalent Spray Angle, Injection Instability

Nomenclature

D : Droplet diameter
L : Left side in patternator
N : Rosin-Rammler distribution parameter
Q : Volume fraction
R : Right side in patternator
X : Rosin-Rammler size parameter
y : Liquid volume in mass cylinder
ϕ : Equivalent spray angle
θ : Angle from the center of a nozzle to a bin in patternator

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1. Introduction

Spray characteristics of fuel including distributions of particle size, volume concentration, and spray angle play an important role in the combustion performance of a gas turbine, 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 (Datta et al., 1999; Koo, 2003; Kang, 2002). In addition, spray characteristics are greatly influenced by fuel temperature especially at a lower temperature (Lefebvre, 1989). Fuel temperature entering into an injection nozzle in the gas turbine combustors of aircraft and rocket engines varies in a wide range due to locations, severe climate conditions, regeneration cooling of rocket engine, and lubricant cooling.

The effects of operating conditions and geometry on spray characteristics during the injection process of fuel has been measured and analyzed by several researchers to enhance the combustion performance in a gas turbine. Datta et al. (1999) reported that the combustion efficiency was greatly influenced by initial droplet diameter (SMD) and spray cone angle. Knubben et al. (2001) measured the droplet size distributions of fuel sprays for butane and propane with temperature variations of fuel and inlet air. They showed that the inlet air temperature was the most important factor during the evaporation process. Yule et al. (1996) reported that injection pressure in the high pressure range affected the discharge coefficient, droplet diameter, and spray angle. Koh et al. (2001) examined the effects of liquid injection temperature on the spray characteristics of subcooled water in a condensable environment. Jazayeri et al. (2000) studied the spray characteristics generated by the breakup of thin liquid sheets in co-flowing air streams. They explained that the axial mean velocities of droplets at a given spray cross-section showed a maximum value at the spray center.

Most previous researches reported that the viscosity showed the greater influence on SMD as compared with the surface tension (Jasuja, 1979 ; Simmons et al., 1981 ; Dodge et al., 1986 ; Lefebvre, 1989). In addition, the effects of density were relatively small (Simmons et al., 1981 ; Lefebvre, 1989). Jasuja (1979) experimentally studied the effects of fuel properties on the mean droplet size using kerosene, gas oil, a heavy residual fuel oil, and their mixtures. He reported that the existing correlations for droplet-size were not sufficiently accurate for use with high-viscosity residual fuel oils.

Since the variations of fuel properties caused by temperature change affect significantly the spray characteristics, the understanding of droplet diameter, volume distribution and spray cone angle is required to get a stable ignition and combustion in the low fuel temperature range. However, the study on the spray characteristics at low fuel temperatures is very limited in open literature. 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. Two kinds of fuel are used as atomizing fluids. Discharge coefficient, spray cone angle, volume distribution and SMD are measured at various combinations of operating conditions in atomizing flow field. In addition, the injection instability at low fuel temperatures is provided based on the visualization tests.

2. Experimental Apparatus and Test Methods

The schematic diagram of experimental apparatus is shown in Fig. 1. Pressurized fuel by nitrogen gas in a tank is provided to the heat exchanger submerged in a temperature control bath. After adjusting fuel temperature, the fuel is supplied to the atomizing nozzle, and consequently injected into ambient air. A pressure transducer and thermocouples are installed in the fuel supply pipe between the heat exchanger and the nozzle to measure injection pressure and fuel temperature, respectively.

A Malvern particle sizer, which measures the SMD based on the Fraunhofer diffraction of a parallel beam of monochromatic light by moving drop, is installed downstream of the injector tip.

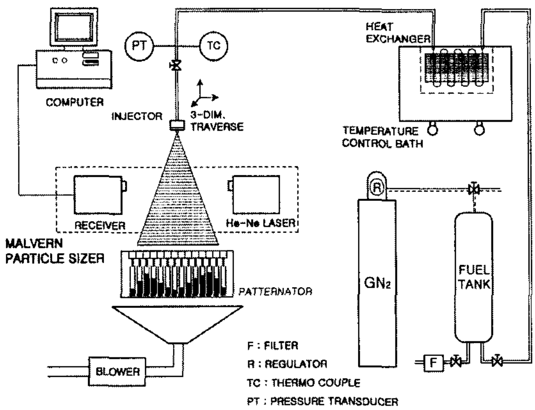


Fig. 1 Schematic diagram of the test setup

Analyzing the diffraction pattern produced by continuous laser beam passing through the spray cloud and fitting the data to a Rosin-Rammler distribution yield the SMD. The Malvern particle sizer consists of three modules ; a transmitter, a receiver, and a computer. The transmitter includes a 5 mW He-Ne laser, a power supply and beam expanding optics. The receiver contains a lens, detector, associated electronics and computer interfaces. In this study, a 9 mm beam expander, and a 300 mm lens are used. Measured particle size ranges from 5.8 μm to 564 μm, and cut-off distance is 400 mm. The detector can monitor an average value of light scattering characteristic based on the data for millions of individual particles. The spray cone angle is measured at 3 cm downstream from the injector tip by using the spray images captured from a CCD camera. A Stroboscope is used to illuminate spray patterns. The volume distribution of spray is measured by an 1-D patternator as shown in Fig. 2. The 1-D patternator consists of 30 collecting bins, connecting tubes, and mass cylinders. Induced fuel is collected in a mass cylinder through the connecting tube.

As shown in Fig. 3, a dual-orifice type swirl injector including pilot and main nozzles is used to spray fuels. Two separated swirl chambers are provided for the primary and secondary flow, respectively. Inner nozzle is called a pilot nozzle, and the other is a main nozzle. For low flow rates, all the fuel passes through the pilot nozzle. For high flow rates, the fuel continues to flow through the pilot nozzle but most of the fuel passes through the main nozzle. The pilot nozzle is solely operated during the ignition process and the small-thrust mode, but both nozzles are operated in the cruise mode.

Atomized fluids are kerosene-based fuels, (fuel A and fuel B) and their properties are shown in Fig. 4. As the fuel temperature increases, the

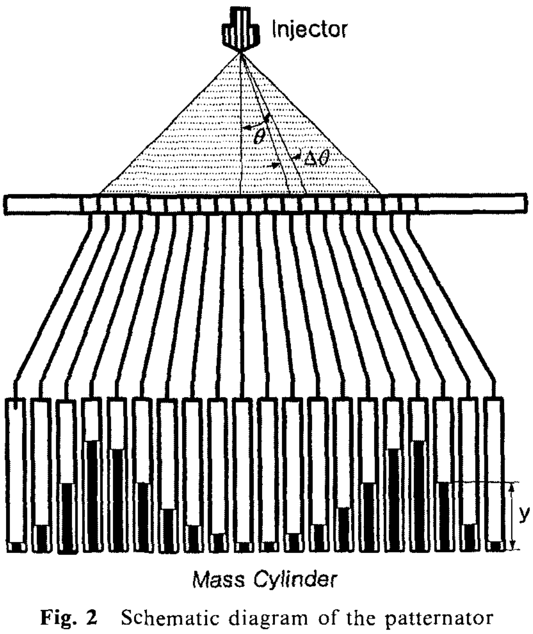
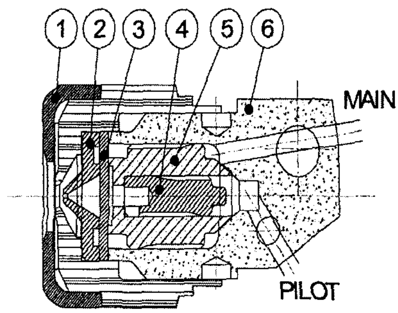


Fig. 2 Schematic diagram of the patternator



① Main nozzle(Ø1.9) ② Pilot nozzle(Ø0.4)
③ Pilot swirler ④ Pilot filter
⑤ Main filter ⑥ Case and tube

Fig. 3 Schematic diagram of the injector

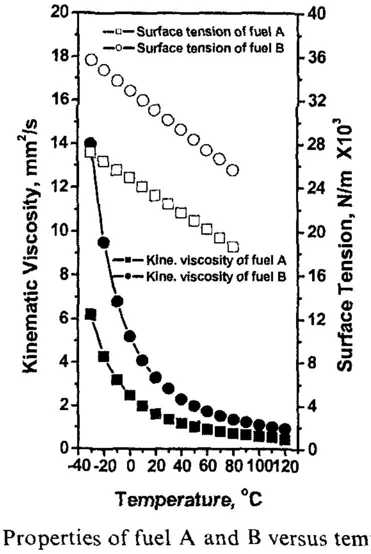


Fig. 4 Properties of fuel A and B versus temperature

surface tensions of fuel A and fuel B linearly decrease with temperature. In this study, the fuel temperature is classified into three groups; a low temperature range for fuel temperature below 0℃, a medium temperature range from 0 to 30℃, and a high temperature range above 30℃. The kinematic viscosity decreases drastically in the low fuel temperature range, while it drops gradually in the high fuel temperature range with increase in fuel temperature. The kinematic viscosity and surface tension of fuel B are much larger than those of fuel A. In the experiments, the fuel temperature and injection pressure are varied from −30℃ to 120℃ and from 0.29 to 0.69 MPa, respectively.

To describe more succinctly the effects of operating parameter on droplet distribution, a radial distribution curve can be converted to a single numerical value called an equivalent spray angle (Lefebvre, 1989). As shown Fig. 2, the equivalent spray angle is a summation of two angles, ϕ_L and ϕ_R, which is given by

$$\phi_L(\text{or } \phi_R) = \frac{\sum y_i \theta_i \Delta\theta_i \sin\theta_i}{\sum y_i \Delta\theta_i \sin\theta} \quad (1)$$

where $\Delta\theta$ is an angle between the sampling bins, and y is a liquid volume measured at the corresponding mass cylinders. The physical meaning of the equivalent spray angle is that ϕ_L(or ϕ_R) is the value of θ corresponding to the position of the mass center of a material system for the left (or right) lobe of the distribution curve.

3. Results and Discussion

Figure 5 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 air core (Lefebvre, 1989). The discharge coefficient of the main nozzle remains nearly constant at 0.06, but that of the pilot nozzle decreases with rise of fuel temperature in the low fuel temperature range and gradually converges to 0.37. The discharge coefficient of the pilot nozzle is greater than that of the main nozzle. As shown in Fig. 6, the volume distribution of the pilot nozzle shows a

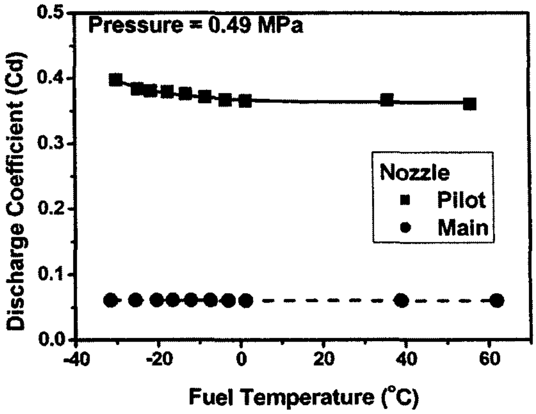


Fig. 5 Effects of fuel temperature on discharge coefficient for the pilot and main nozzles

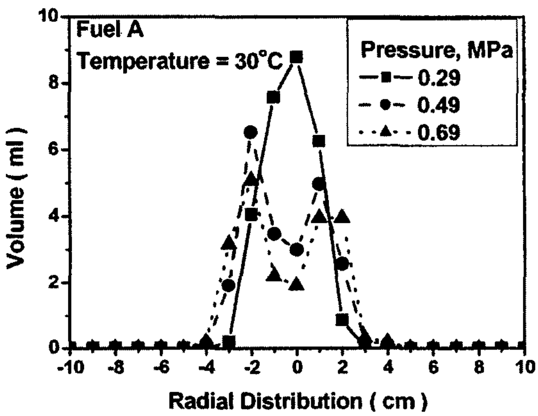


Fig. 6 Volumetric distributions of the pilot nozzle with injection pressure

typical distribution observed in a solid-cone type injector. Therefore, it can be assumed that air-core in the pilot nozzle orifice does not exist in the tested injection pressure range. Due to smaller nozzle diameter and absence of air-core in the pilot nozzle orifice, the discharge coefficient of the pilot nozzle is more strongly affected by viscosity. Diameters of the pilot nozzle and main nozzle are 0.4 mm and 1.9 mm, respectively.

Figure 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 from the main-pilot and main nozzles increase gradually due to reduction of fuel viscosity and friction loss. The friction force generated by velocity gradient tends to reduce

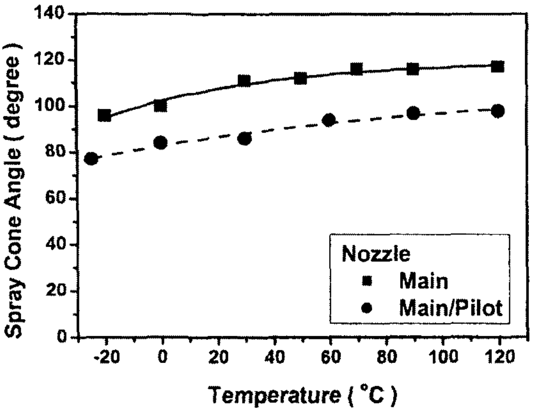
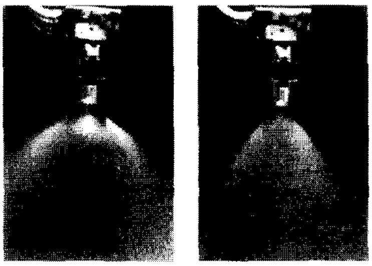
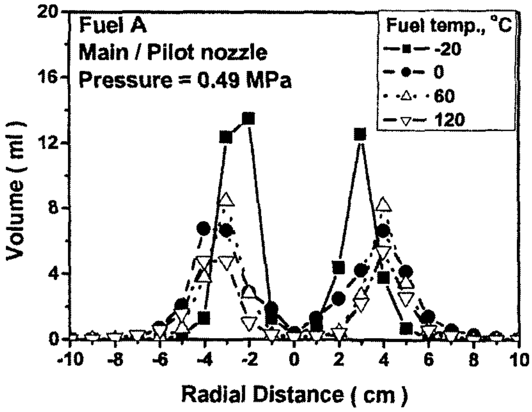


Fig. 7 Effect of fuel temperature on spray cone angle for the main and main-pilot nozzles (Fuel A, P=0.49 MPa)

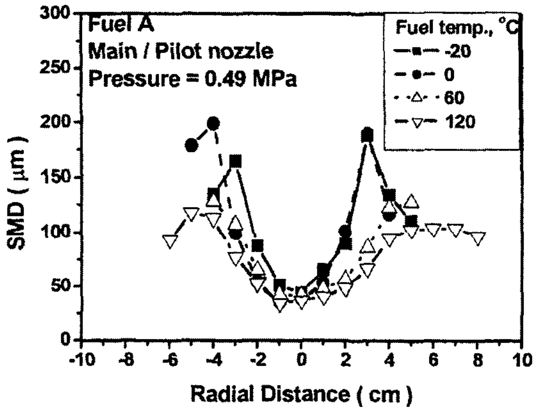


(a) Main nozzle (b) Main-pilot nozzle

Fig. 8 Direct images of spray for the main nozzle and main-pilot nozzles



(a) Volume distribution



(b) SMD distribution

Fig. 9 Radial distributions of volume and SMD with fuel temperature

the tangential velocity (Lefebvre, 1989). In the case of simultaneous spray from the main-pilot spray nozzle, the atomizing stream injected from the pilot nozzle collides with spray stream injected from the main nozzle, forming a hollow cone spray. As shown in Fig. 8, the spray angle of the main-pilot nozzle is smaller than that of the main nozzle because the spray of the pilot nozzle has a smaller rotational momentum.

Figures 9(a) and (b) show the radial distributions of volume concentration and SMD for the main-pilot nozzle at various temperatures of fuel A, respectively. As shown in Fig. 9(a), the maximum volume concentration decreases gradually with increase of fuel temperature. The location of maximum volume concentration moves toward the outward direction from the center. As shown in Fig. 9(b), the SMD is reduced with increase of fuel temperature. The location of the maximum droplet volume that corresponds to the main stream of the spray coincides with that of the peak SMD.

Figure 10 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 fuel temperature range, but it remains relatively constant in the high fuel temperature range. For high fuel temperatures, the spray cone angle increases gradually with fuel temperature, while the SMD drops as shown in Fig. 9(b) and droplet evaporation rate enhances. Therefore, the penetration depth of droplets decreases with increase of fuel temperature, which causes a constant equivalent spray angle at high fuel temperatures.

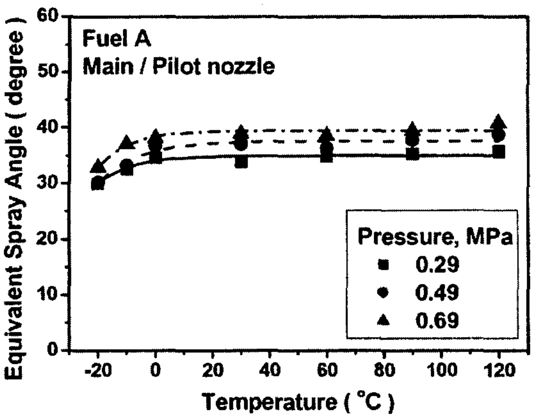


Fig. 10 Effects of fuel temperature on equivalent spray angle

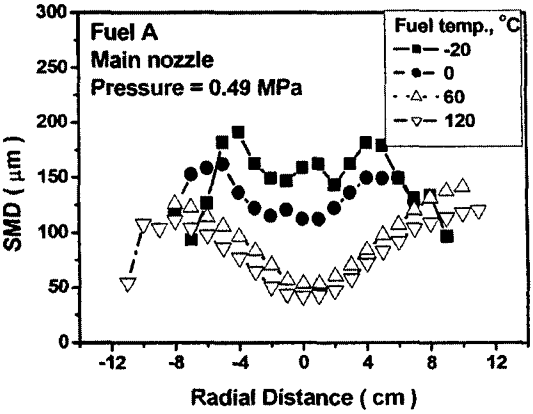


Fig. 11 Radial distributions of SMD with fuel temperature

Figure 11 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 fuel temperature range, the larger SMD value and the more severe change of distribution curve are observed as compared with those in the high fuel temperature range. As shown in Fig. 4, the kinematic viscosity decreases drastically in the low fuel temperature range, while it drops gradually in the high fuel temperature range even though the surface tension is reduced linearly with increase of fuel temperature. Therefore the spray characteristics, especially spray SMD, are more strongly influenced by viscosity than surface tension in the low fuel temperature range, while those are more influenced by surface tension in the high fuel temperature range. These trends are consistent with the results of Jasuja (1979) and Choi et al. (2001).

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

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

It should be noted that this study considers only the variations of fuel temperature, causing the change of fuel properties in an atomizer.

The droplet size distribution can be expressed in the following form that was developed for powders by Rosin and Rammler.

$$1-Q=\exp[-(D/X)^{N}] \quad (3)$$

where Q is the total volume fraction of droplets, whose diameter is less than D, and X and N are constants. By applying the Rosin-Rammler relationship to sprays, the exponent N provides a measure for the distribution of droplet sizes. As the value N increases, the spray becomes more uniform.

Figure 12 shows the variations of maximum SMD and Rosin-Rammler parameter N along the main stream. As the distance from the injector tip to the location of measurement increases, the width of spray increases and the location of maximum SMD moves outward in radial direction. As the spray moves to downstream, the maximum SMD and parameter N at the point of maximum SMD in the main stream of spray increase slowly. In general, the complex interactions among the droplets in a dense spray zone such as evaporation of droplets, coalescence and break-up of droplets after collisions due to velocity differences between large and small droplets occur in the main stream of spray. It can be presumed that the rapid evaporation of small droplets and coalescence of droplets by collision lead to increase the maximum SMD and Rosin-Rammler parameter N in the main stream of spray as the flow moves to downstream.

Figure 13 shows direct spray images of fuel B injected from the main nozzle at −10℃. In the early stage of injection, the spray shows the tulip

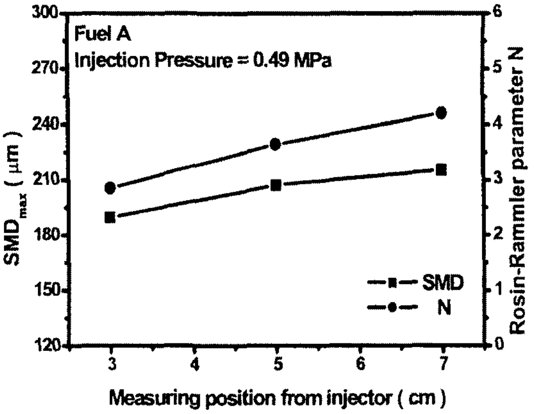
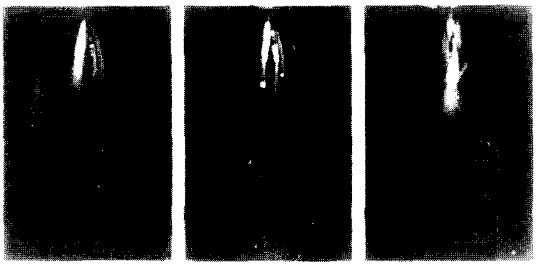


Fig. 12 Variations of SMD and Rosin-Rammler parameter N along main stream

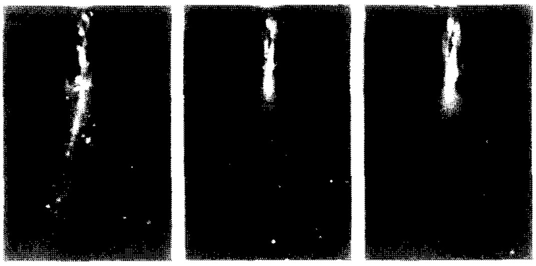


(a) t=1 sec (b) t=5 sec (c) t=15 sec

Fig. 13 Direct spray images of fuel B injecting from the main nozzle at P=0.69 MPa and T=−10℃

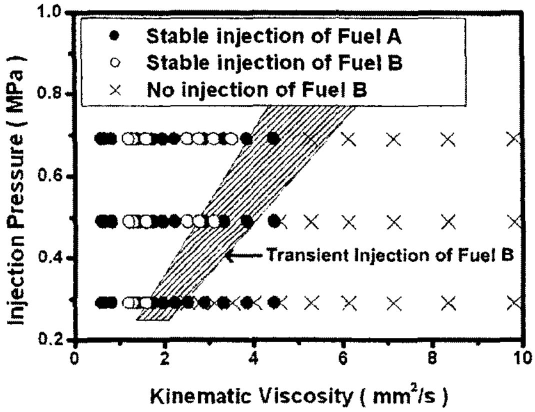
stage in spray development. As the injection proceeds, it changes to the onion stage in spray development. Finally, the injection of the main nozzle for fuel B becomes very unstable.

Figure 14 shows the direct spray images of fuel B injected from the main nozzle at various injection pressures with −10℃. 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, finally stopping the injection. The elapsed time is defined as the time between the beginning and the ceasing of the injection. The elapsed time increases with injection pressure. The ice crystals are found in the face of the injector orifice. Kim et al.(2001) also reported that choking at the nozzle outlet was not observed due to icing phenomenon, but

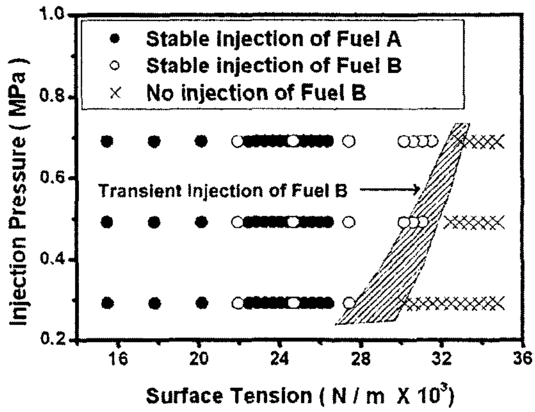


(a) P=0.29 MPa (b) P=0.49 MPa (c) P=0.29 MPa

Fig. 14 Direct spray images of fuel B injecting from the main nozzle at various injection pressures with T=−10℃



(a) Kinematic viscosity-injection pressure



(b) Surface tension-injection pressure

Fig. 15 Injection instability maps for fuel A and fuel B

the grown ice partially covered at the nozzle outlet.

During the experiments, fuel A is atomized stably in the entire fuel temperature range from

−30℃ to 120℃, but the injection of the main nozzle for fuel B is very unstable in the low temperature range. Figures 15(a) and (b) show injection stability maps in pressure-kinematic viscosity and pressure-surface tension planes for fuel A and B, respectively. Hatched area in Figs. 15(a) and (b) represent the transient region between stable and unable injection. For a lower injection pressure, the stable injection is observed only at a lower kinematic viscosity. As the injection pressure increases, the viscosity range for the stable atomization becomes wider. Figure 15(b) shows that the stable region increases with injection pressure at a given surface tension. Unstable injection may occur at a larger surface tension. As shown in Fig. 4, the surface tension and kinematic viscosity of fuel B are sufficiently larger than those of fuel A. Therefore, fuel A yields stable atomization even in the low temperature range.

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. Discharge coefficient, spray cone angle, volume concentration, and SMD are measured at various operating conditions. Direct spray images for fuel A and B are visualized to determine injection stability. The spray SMD is more strongly influenced by kinematic viscosity than surface tension in the low fuel temperature range, while it is more influenced by surface tension in the high fuel temperature range. Furthermore, an empirical correlation for the SMD at the location of a maximum volume concentration is derived based on the present experimental data. The visualization results show that 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.

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