Measurements of droplet size distribution and in-cylinder mixture formation from a slit injector in a direct-injection gasoline engine

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Abstract. The droplet size distribution and in-cylinder mixture formation of a slit injector were investigated under varied fuel temperature and air flow conditions. This variance in fuel temperature and air flow represents the altered spray momentum and external forces acting upon the spray. Phase Doppler anemometry (PDA) was used to investigate the effect of fuel temperature and air flow on droplet size distribution. The in-cylinder mixture formation process and the factors affecting the in-cylinder mixture distribution were analyzed under various fuel temperature and air flow conditions using laser induced fluorescence (LIF). When the fuel temperature and air flow velocity increased, the smaller droplets were entrained to the upper and central parts of the spray altering the initial droplet size distribution. The reduced spray momentum decreased the spray penetration in the combustion chamber, and the interaction between the spray and piston bowl was degraded. This phenomenon eventually caused a relatively lean and dispersed mixture distribution near the spark plug at high fuel temperatures. The optimal spray momentum and external force depend on the fuel quantity (air-fuel ratio) and piston bowl shape. Consequently, the spray momentum and the external forces acting upon the spray should be optimized to form the stoichiometric and well-distributed mixture near the spark plug.

1. Introduction
The direct-injection spark-ignition (DISI) engine has become an alternative to the conventional port fuel injection (PFI) engine due to its potential for improving fuel consumption and emission characteristics [1]. The uniqueness of DISI engines is stratified mode operation during low loads and idling conditions by the injection of a small amount of fuel in a limited region within the combustion chamber to form a combustible mixture. Two major combustion systems, wall-guided and spray-guided systems, have been introduced to achieve a stratified mixture near the spark plug. In the wall-guided system, the fuel impinges on the piston cavity that guides the post-impinged spray towards the spark plug with the assistance of airflow. In the spray-guided system a compact spray is injected close to location of the spark plug. In this case, the spray geometry should be consistent enough to avoid inducing engine misfiring. In all cases, achieving a well-atomized, compact spray with strong
boundary concentrations close to the spark plug [1, 2] is necessary for stable combustion and minimal engine-out emissions. The spray momentum and external forces are the main parameters affecting the mixture distribution near the spark plug. When the initial injection velocity is fixed, the droplet size is a representative parameter for spray momentum, while airflow velocity is a representative parameter for the external force.

The slit injector, which produces a fan spray, is a well-known injector employed in wide spacing DISI combustion systems [3]. Recently, a two-slit injector was applied to a Toyota 2GR-FSE engine with the fusion injection system, which simultaneously utilizes direct injection and port fuel injection (PFI) [4]. It indicates that the droplet size distribution and mixture formation of fan spray under various operating conditions, such as with varied air flow velocity and fuel temperature, need to be investigated. The effect of airflow on fan spray characteristics has been studied using linear instability analyses [5, 6] and experimental investigation of macroscopic and microscopic spray development [7]. In addition, there has been much research on the effect of fuel temperature on fan spray characteristics [8, 9]. However, the spatial distribution of droplet sizes and the mixture formation of fan spray at various fuel temperatures and air flow conditions, critical factors in optimizing homogeneous and stratified charge combustion, have not yet been sufficiently investigated.

This study aims to investigate the droplet size distribution and in-cylinder mixture formation of a fan spray under various fuel temperatures and airflow conditions. Phase Doppler anemometry (PDA) and laser induced fluorescence (LIF) are applied to measure the droplet size distribution and mixture formation, respectively.

2. Experimental Setup and Test Conditions

2.1. Experimental setup for PDA and LIF
To measure droplet size distribution at various fuel temperatures and airflow velocities, the injector was installed in a wind tunnel made of acryl (Fig. 1). The wind tunnel cross section was 200 mm by 200 mm. The injector was installed 150 mm from the exit of the contractor. The transmitting and receiving optics of a PDA system were fixed onto a 3-dimensional traverse mechanism moving relative to the injector. The main setup parameters for the PDA system are given in Table 1. This setup enables measurement of the sizes of droplets with velocities between -5m/s and 56m/s.

![Fig. 1 Experimental setup for droplet size measurement](image)
Table 1 Specifications of the phase Doppler anemometry system (TSI APV)

| Specifications                  | Value   |
|--------------------------------|---------|
| Measurement Maximum Diameter   | 90.5 μm |
| Volume Length                  | 1.31 mm |
| Fringe Spacing                 | 3.73 μm |
| Number of Fringes              | 24.2    |
| Received data range            | 3–20MHz |
| Frequency shift                | 5MHz    |
| Scattering angle               | 30°     |

Fig. 2 Experimental setup for LIF

2.2. Experimental setup for LIF
Figure 2 shows the experimental setup for the LIF. The experiments were performed in an optical single-cylinder engine created by modifying a production engine. This engine enables the laser sheet to access the combustion chamber vertically and horizontally. For the LIF experiments, the laser light sheet at 266nm, generated from a Nd:YAG laser, mirrors and lenses, was vertically induced to the combustion chamber. The fourth harmonic of the Nd:YAG at 266nm was used to excite a dopant in the fuel. Iso-octane and 3-pentanone were used as the base fuel and dopant, respectively, and their mixing ratio was 80% iso-octane to 20% 3-pentanone, by volume [10]. The LIF images were digitally recorded with an intensified CCD (ICCD) camera. To separate the fluoresced signal from scattered signal indicating fuel concentration, a 280-nm high-pass filter was installed in front of the ICCD camera.

2.3. Test conditions
The test conditions are presented in Table 2. The fuel temperature was varied from 298 to 358K and the air flow velocity is fixed as 10m/s under altered temperature conditions. The air flow velocity was...
changed from 0 to 15m/s, the general reverse tumble velocity across the spray inside the combustion chamber. The injection pressure is fixed to 9MPa. The 14.3 mg of fuel, which is the injection quantity at part load condition, was injected to the steady flow rig and combustion chamber. The engine speed is set to 800rpm under varied fuel temperature conditions.

| Table 2 Test conditions |
|-------------------------|
| Fuel temperature (K)    | 298, 328, 358 |
| Air flow velocity (m/s) | 0, 5, 10, 15  |
| Injection pressure (MPa)| 9             |
| Injection quantity (mg) | 14.3mg (1.6ms)|
| Engine speed (rpm)      | 800           |

3. Results and Discussions

3.1. Droplet size distribution

3.1.1. Effect of air flow velocity

To investigate the influence of airflow speed on spray droplet sizes, the droplet diameters were measured at various points along a vertical line and a horizontal line located on a vertical and horizontal plane, respectively, 50 mm distant from the injector tip (Fig. 3(a)). The droplet size data were integrated through the whole time range and merged through all the test points to obtain a representative value of droplet size under each airflow condition. The probability density function (PDF) of the droplet size at various airflow velocities are plotted in Fig. 3(b). The droplet distribution is shown to skew toward smaller sizes as airflow velocity increases, resulting in a reduction in the calculated mean droplet diameters. The smaller droplet size at high air flow velocity is due to the reinforced entrained air motion and enhanced shear between air flow and spray.

As shown in Fig. 4(a), the spatial droplet size distributions at various air flow velocities show that that entrained air motion was enhanced at high air flow velocity. Analysis of the effect of airflow on droplet sizes over a specific period of time yielded no specific trend because of the dynamic variation
of droplet velocity during the injection period. Therefore, the $D_{32}$ values at different locations were calculated using the droplet sizes integrated through the whole time range. Figure 4(a) shows that the droplets within the spray tend to be larger near the two edges than in the central part. The airflow rearranges droplets not only along the horizontal direction but also in all other directions. This rearrangement changes continuously with time, and the droplets sizes within the spray therefore exhibit varying stratifications. The variation in droplet distributions along the vertical direction is depicted in Fig. 4(b), where it is seen that smaller droplets are more likely to be located in the upper part, while larger droplets, which have higher momentum, move along the main spray trajectory and are mostly located in the downstream region of the spray.

Fig. 4 $D_{32}$ distribution at different locations under varied air flow velocities
[(a) Horizontal line, (b) Vertical line; Fuel temperature: 298K]

Fig. 5 $D_{32}$ distribution at different locations under varied fuel temperatures
[(a) Measuring points, (b) Probability density function, (c) $D_{32}$ distribution at different vertical locations; Air flow velocity: 10m/s]
3.1.2. Effect of fuel temperature

Figure 5(a) shows the measuring points for the PDA at different fuel temperatures. In this case, the applied air flow velocity is fixed at 10m/s. The droplet size data are integrated through the whole time range and merged through all the test points. The probability density function (PDF) of droplet size at various fuel temperatures is plotted in Fig. 5(b), where it is seen that the droplet distribution skews towards the smaller sizes and that the occurrence of large droplets (those with a size of more than 30 µm) is significantly reduced as fuel temperature increases. This occurs because of bubble nuclei formed inside the nozzle, and because of the reduced viscosity and surface tension at higher temperatures. The droplet size distribution at different vertical locations is plotted in Fig. 5(c). The droplet size is reduced upstream of the spray as a result of entrainment of small droplets, and this reduction is reinforced at high fuel temperature. This indicates that the small droplets are more entrained upstream of the spray at high fuel temperature.

3.2. In-cylinder mixture formation

The reduced droplet size at fast air flow speeds and high fuel temperatures generally improves the mixing quality and the homogeneity of charge combustion. However, droplet size distribution plays an important role in optimizing stratified charge combustion. The cross air flow is not a major concern near the nozzle area, because the initial cross flow velocity is approximately 10m/s, while the spray-induced flow velocity is more than 30m/s. By contrast, the effect of cross flow is very significant downstream, after droplets have lost their initial momentum. If the spray interacts with the piston bowl downstream, the piston bowl shape plays an important role in optimizing mixture formation. The flow induced from the piston bowl will concentrate or diffuse the mixture near the spark plug. In this case, the flow, induced from the piston bowl, has more significant effects than fuel impingement. Moreover, the liquid fuel may exhibit enhanced evaporation when the flow velocity increases, because the liquid and vapor phases will be separated. When the flow is too strong, however, the mixture will be too diffuse to form a lean mixture near the spark plug. The air flow velocity should be optimized to form a near-stoichiometric and well-distributed mixture distribution near the spark plug.

Fig. 6 In-cylinder mixture distribution at different fuel temperatures

[Engine speed: 800rpm, Injection quantity: 14.3mg]
The altered droplet size, caused by varied fuel temperature, also plays an important role in mixture formation for a fixed air flow velocity. When the droplet size is relatively large (that is, when the spray momentum is relatively strong), the spray will interact with piston bowl with less influence from the air flow. Therefore, it will generate a relatively rich and well-concentrated mixture near the spark plug. By contrast, the interaction between the piston bowl and spray will be weakened when the droplet size is relatively small (that is, when the spray momentum is relatively weak). It indicates that the mixture will be more highly diffused and that the mixture near the spark plug will be leaner when the spray momentum is weak. Figure 6 shows the in-cylinder mixture distribution in terms of fuel concentration indicated by fluorescence intensity at various fuel temperatures. At a temperature of 358K, the axial penetration decreased and the radial penetration increased as a result of reduced spray momentum at high fuel temperature. The time at which the spray begins to interact with piston bowl is delayed and the mixture is more diffused to the combustion chamber at a fuel temperature of 358K.

(a) Fluorescence intensity at A-A’ plane

(b) Fluorescence intensity at a plane for fuel-concentration analysis

Fig. 7 Analysis of fluorescence intensity under varied fuel temperatures

To further explain this trend, the fluorescence intensity and spatial distribution of mixture under varied fuel temperatures are analyzed. Figures 7(a) and 7(b) show the fluorescence intensity and spatial distribution of mixture at an A-A’ plane and a plane for fuel-concentration analysis under varied fuel temperatures. The definition of the A-A’ plane and plane for intensity analysis are shown in Fig. 7(a). The higher fluorescence intensity and the narrower mixture area were observed at a fuel temperature of 298K due to relatively strong spray momentum, while the reverse trend was observed at a fuel temperature of 358K owing to relatively weak spray momentum. In addition, X-axis location of the highest intensity was positioned at left-hand side (intake-side) under a fuel temperature of 298K.
compared to that of 328K and 358K. These results confirm that the reduced spray momentum, caused by the smaller droplet size, weakens the interaction between spray and piston bowl and eventually diffuses the mixture to the combustion chamber. The highest combustion velocity and low engine-out emissions were observed at a fuel temperature of 328K where the near-stoichiometric and well-dispersed mixture is formed near the spark plug [11].

From the above results, it was concluded that the spray momentum should be optimized for stable stratified charge combustion. The optimized spray momentum and fuel temperature may be different for each injection quantity and engine speed.

4. Conclusions

The droplet size distribution and in-cylinder mixture formation from a slit injector was investigated under varying air flows and fuel temperatures. The main findings from this study are summarized as follows:

1. The mean droplet size is reduced under high air flow velocities and at high fuel temperature conditions.
2. The entrained air motion is enhanced under high air flow conditions, and the small droplets are entrained to the upper and central parts of the spray.
3. A relatively lean, diffuse mixture is formed near the spark plug at high air flow velocities, while a relatively rich, concentrated mixture is formed at low velocities.
4. Droplet size should be optimized for the formation of a near-stoichiometric mixture near the spark plug.

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