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Full Length Article

# Effect of cross-flow on spray structure, droplet diameter and velocity of impinging spray

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ABSTRACT

The air flow and wall impingement in a direct-injection spark-ignition (DISI) gasoline engine affect the fuel-air mixture formation and the quality of fuel combustion. In this work, a comprehensive experimental investigation on the effect of cross-flow on the spray structure, droplet diameter and velocity distributions was carried out. The transient impinging spray behavior at different cross-flow velocities was recorded using high-speed photography with a continuous wave laser sheet. It was seen that a higher cross-flow velocity significantly increases the spray area, i.e., the cross-flow favors spray dispersion. Moreover, the spray outline distortion caused by cross-flow in the leeward side is larger than that in the windward side. By employing the particle image analysis (PIA) optical diagnostic method, the Sauter mean diameter (SMD) and the droplet velocity components were investigated. The results show that a higher cross-flow velocity causes an increased proportion of large droplets in the windward side of spray, and the enhanced droplet breakup, resulting in a larger SMD in the windward side of spray and smaller SMD in the leeward side of spray. In the leeward side of spray, the droplet horizontal velocity gradually increases along the cross-flow direction, and after it reaches approximately the cross-flow velocity, the droplet horizontal velocity shows a large fluctuation in the downstream region. Moreover, the droplet vertical velocity decreases sharply from the center line of the main spray body to the spray periphery. By comparing the velocities of droplets, we found that compared with larger droplets, the smaller droplets are more easily affected by a cross-flow owing to the effect of drag acceleration.

## 1. Introduction

Owing to the application of direct injection technology, direct-injection spark-ignition (DISI) gasoline engines exhibit excellent performances in advancing the fuel economy and power output compared to regular gasoline engines; therefore, they are widely used in the automotive field [1]. It is generally known that stratified charge combustion and homogeneous combustion models are critical in DISI gasoline engines. For a light-load operation, the stratified charge combustion mode is used. Fuel is injected into a cylinder during the compression stroke. For the moderate or heavy load conditions, the homogeneous combustion mode is started. Fuel is injected at the intake stroke, and a homogeneous fuel–air mixture is formed [2,3]. In either mode, the air motion in the combustion chamber is sufficiently strong to induce a series of variations in the spray. Characteristics such as the spray structure, droplet size and velocity are affected by the air motion [4]. It is exceptionally difficult to directly investigate the effects of air flow on the fuel spray in a cylinder owing to the complicated and changeable air flow field [5]. Moreover, the insufficient fundamental studies based on a single-condition is another important reason. The cross-flow, which is perpendicular to the spray direction, was applied as a typical air flow condition in previous studies [6].

Concerning the interactions between cross-flow and spray/jet, Guo et al. [7] measured the spray area and spray volume of a free spray and evaluated the effect of the air–fuel momentum flux ratio on the spray profiles. They reported that the spray volume showed an approximately linear increasing trend with the development of the free spray under a constant cross-flow velocity. Based on a spray structure observation, Getsinger et al. [8] investigated the stability characteristics of jets in a cross-flow. They indicated that a counter-rotating vortex pair appeared behind a jet column under the cross-flow condition. Sinha et al. [9] performed experimental studies utilizing a laser shadowgraph and particle tracking velocimetry to derive the spray trajectory and droplet velocities. They proposed a novel correlation for the spray trajectory combining the momentum ratio with the liquid surface tension. These works had only focused on the effect of cross-flow on free spray;

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however, in a real DISI gasoline engine, impingement also heavily affects spray. Owing to the high injection pressure and downsized cylinder, the fuel spray might impinge on the piston cavity wall before being fully vaporized. Fuel spray impingement generally influences fuel atomization and combustion, and will lead to excessive hydrocarbon (HC) and soot emissions [10]. Therefore, the study of the effect of cross-flow on impinging spray is more relevant than that of free spray for a DISI gasoline engine.

As for the impinging spray characteristics in cross-flow, Panão et al. [11,12] obtained impinging spray profiles in a cross-flow using Mie-scattering and shadowgraph methods. They found that the main spray body shifted downstream with the increase in the cross-flow velocity. Their results showed that the droplet velocity was very low in two stagnation points in the impingement region and windward side of spray, respectively. Moriyoshi et al. [13] used the interferometric laser imaging droplet sizing (ILIDS) measurement to study the impinging spray development process in a cross-flow. Their results indicated that the relative mean velocity between cross-flow and droplet had a marked impact on the spray atomization, and small droplets were guided downstream by the cross-flow. Arcoumains et al. [14] investigated a liquid film distribution of an impinging spray under different cross-flow velocities. They reported that the wall film became thicker with increasing cross-flow velocity and the wall-jet vortex structure could severely influence the movement track of post-impinged droplets. Panão and Moreira [15] measured the droplet sizes and two velocity components of an impinging spray using a phase-Doppler anemometer (PDA) system. They analyzed the contribution of cross-flow to the interaction mechanism of individual droplets with the wall surface. These works clarified that the number of droplets in the stick regime decreased under the cross-flow condition. Our previous studies revealed that cross-flow led to a non-uniform distribution of droplets in the spray leeward side [16]. To analyze the spray structures in the three-dimensional (3D) space, a continuous wave laser sheet was applied. This work is confined to a low cross-flow velocity and only focuses on the impinging spray structure.

From the earlier studies, the impinging spray characteristics in a cross-flow were not completely clarified, especially for the droplet diameter and velocity. The present work attempts to examine the effects of cross-flow velocities on the spray structure, droplet diameter and velocity of the impinging spray in a cross-flow wind tunnel. Tomographic images of the impinging spray were obtained using laser sheet technology and the droplet diameter and velocity were measured by applying a particle image analyzer (PIA) system. The spray tip penetration and vortex height were acquired from the tomographic images for quantitative analysis. In addition, the effects of cross-flow velocities on the droplet diameter and two velocity components are also examined.

## 2. Experimental setup

The detailed cross-flow wind tunnel system and spray generation system have been described previously [17], and only a brief description is given here. Fig. 1 shows the schematic diagram of the cross-flow wind tunnel that can provide a uniform cross-flow field for an impinging spray. It includes primarily the diffusion section, the rectification section, the contraction section, and the observation section. Mesh screens are used in the rectification section to improve the uniformity of the cross-flow. The uniform cross-flow with a proper velocity can be acquired in the observation section by controlling the open area of valve 1, and valve 2 was fully opened in this experiment. The timing sequences of the valve control, spray injection, and camera record have been reported previously [16].

For the impinging spray structure investigation, a continuous wave laser sheet with wavelength of 532 nm and thickness of 1 mm was used as the light source. A high-speed video camera (Photron FASTCAM SA-Z) was employed to obtain the impinging spray images with a frame rate of 20,000 frames/s and resolution of 896 × 760 pixels. As shown in Fig. 2(a), the laser sheet illuminated the fuel spray from the bottom of the observation section to record the impinging spray movement in the vertical plane. Fig. 2(b) shows the details of the observation section and the coordinate system definition. Three windows on two sides and the bottom provided an optical access for the impinging spray visualization, and the windows are composed of Pyrex. A valve covered orifice (VCO) type nozzle with 0.15 mm hole diameter was installed on the upper wall of the section. The angle between the vertical direction and the axial line of the nozzle was 25° to maintain the vertical injection of the spray. In the observation section, a hot-wire anemometer and high sensitivity pressure sensor were employed to measure the cross-flow velocity and ambient pressure, respectively. The impinging wall was constructed using transparent acryl with the size of 140 mm × 90 mm, and the surface roughness Ra of the flat wall was 0.5 μm. The impinging distance was maintained at 50 mm in this study. The origin, O of the coordinate system is at the nozzle tip location. The positive x-axis is along the cross-flow direction, and the positive y-axis is along the injection direction.

Fig. 3 shows the schematic diagram of the PIA system for the detection of microscopic spray characteristics. A Nd: YAG laser with the wavelength of 532 nm was employed as the light source. A laser pulse of 6 ns duration has an energy of 10 mJ, and the interval between two laser pluses is 0.6 μs. The light beam was expanded by a diffuser with the diameter of 100 mm to provide a uniform backlighting. A charge-coupled device (CCD) camera (Flowtech Research Inc., FtrNPC) linked with a long-distance microscope was used to capture the droplet distributions. The exposure time of the CCD camera is 200 μs. In order to acquire high quality images, the camera axis was collinear with the laser beam, resulting in a high illumination intensity and uniform illumination. The triggering pulses of the laser, the injection, and the CCD camera were synchronized by a synchronizing signal generator VSD 2000.

In this study, dry-solvent was used as a test fuel because its physical property is similar to that of gasoline. Dry-solvent is petroleum hydrocarbons (C9-C11), its molecular weight is about 14 g. The fuel density and viscosity are 0.76 g/cm$^3$ and 1.2 mm$^2$/s (at 25 °C), respectively. The fuel boiling temperature (1atm) is 433 K. This experiment

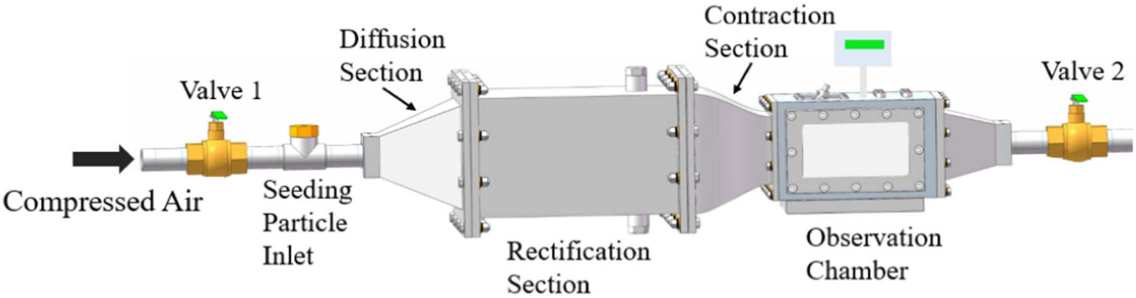

**Fig. 1.** Schematic diagram of wind tunnel.