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Experimental study on fuel spray characteristics under atmospheric and pressurized cross-flow conditions

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ABSTRACT

The air flow and ambient pressure in the cylinder affect the spray significantly when the fuel is injected into the cylinder in direct injection gasoline engine. To investigate the effects of air flow at ambient pressure on the fuel spray, a critical air flow called cross-flow was tested. The cross-flow is the air flow whose direction is perpendicular to the fuel injection direction. A special wind tunnel was designed to provide the controllable cross-flows with various pressures and velocities, and the spray was injected into the cross-flow field by a mini sac injector using dry solvent as the test fuel. The high speed photography and particle image velocimetry technology were employed to observe the fuel spray and measure the velocity distribution of the spray. When the ambient pressure is increased, the bended spray profile is compressed; namely, the penetrations decrease. The cross-flow provides horizontal momentum for the droplets of the spray. When the ambient pressure is increased the velocity distribution of fuel spray becomes more uniform; furthermore, the magnitude of the vertical velocities can exceed the cross-flow velocity. This study is an experiment investigation which is aimed at understanding the fundamental phenomena and accumulating the theoretical supports for the real engine conditions.

1. Introduction

The past decade has seen a rapid increase of renewable energies [1]; however, the transport fuel will continue to be dominated by oil for a long time in the future [2]. Therefore, improving the fuel efficiency and economy is a perpetual goal of the researchers in this field [3]. The internal combustion engine is widely used in the transport combusting the oil; however, the energy conversion ratio of the engine still stayed on a low level, especially the gasoline engine [4]. The direct injection (DI) gasoline engine was developed from the 1990s, and it benefits gasoline engine dramatically in advancing the fuel efficiency and power output [5]. Thus the direct injection technology is considered as an important developing direction in the gasoline engines since the DI gasoline engine appeared [6]. The excellent performances of the DI gasoline engine are attributed to the two switchable combustion modes, the stratified charge mode (or ultra-lean burn mode) and the homogeneous charge mode (or stoichiometric mode and full power mode) [7,8]. On the one hand, for the light-load running and constant or reducing road speeds, the stratified charge mode is started. Instead of injecting fuel at the intake stroke, the fuel is injected into cylinder at the latter stages of the compression stroke [9]. The small amount of air-fuel mixture is optimally placed near the spark plug by the air or cavity guides [10]. On the other hand, for the moderate load or heavy conditions the homogeneous charge mode is used. Fuel is injected during the intake stroke, and a homogeneous fuel-air mixture is created in the cylinder [11]. The amount of fuel is calculated depending on the different load conditions, and the air-fuel mixture ratio under the moderate load is slightly higher than that under the rapid acceleration and heavy loads. Because the injector position in DI gasoline engine and the flexible injection timings are different from the port fuel injection engine and diesel engine. The air flows in the cylinder during the fuel injection under various conditions are more complicated, such as the air flow changes of velocity and pressure [12].

Due to the complicated air flow field and varied conditions, the investigations of the effects of the air flow on the spray in the real cylinder become difficult [13]. One important reason is that the theoretical and fundamental studies based on the single conditions are insufficient.

The air flow which is perpendicular to the direction of injection is called cross-flow [14]. The cross-flow is a critical air flow in the

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Nomenclature

d	nozzle hole diameter, m	t_{break}	time when liquid jet begins to disintegrate, s
P_{inj}	injection pressure, Pa	t_d	injection duration, s
L_x	droplet horizontal movement after impingement, m	U_x	mean velocity of cross-flow, m/s
L_w	vertical length from nozzle hole to wall, m	U_l	initial injection velocity, m/s
P_a	ambient pressure, Pa	ΔP	$\Delta P = P_{inj} - P_a$, pressure drop across the nozzle, Pa
q	liquid to air momentum flux ratio	ρ_g	gas density, kg/m^3
S	spray tip penetration without cross-flow, m	ρ_l	liquid densities, kg/m^3
S_x	spray tip penetration with cross-flow, m	PIV	particle image velocimetry
t	time after the start of injection, s	ASOI	after start of injection

cylinder of DI gasoline engine. The injector is placed in the cylinder wall near the intake port, and there is a large acute angle between directions of the spray and intake air. When the intake valve is opened during the homogeneous combustion mode, the main air flow which can affect the spray is from spray lateral. Even the spray occurs after the intake valve closing, and the strong swirling air flow in the cylinder also affects spray mainly in lateral. Therefore to understand the effects of the air flow like cross-flow on the spray is significant for the fundamental study.

The spray/jet injected into a cross-flow field are investigated profoundly in modern propulsion and power applications, such as gas turbine, ramjet, and scramjet engine [15]. The interactions between the cross-flow and spray are also studied for the chemical spray in agricultural field [16]. However, the effects of the cross-flow on the spray in DI gasoline engine begin to be attended recently [17]. The spray formation process in cross-flow was explained by Moriyoshi et al. [18] using interferometric laser imaging for droplet sizing technique with a fan-shaped injector of the DI gasoline engine, and they considered that the relative mean velocity between the droplet and ambient flow determines the atomization. Some researchers found the cross-flow has a significant effect on the bottom part of the spray [13] and promotes secondary atomization [19,20]. The entrance of the spray enhances the turbulence in the cross-flow [21], and the cross-flow only increases the penetrations along the direction of the cross-flow [17] while it does not change the spray tip penetrations [19].

The atomization of the spray in DI gasoline engine is totally different from that in the propulsion system, and in DI gasoline engine the atomization depends on the pressure difference between injection and ambient (pressure drop) [22] while the cross-flow is the energy source of the liquid disintegration in the propulsion system [15]; meanwhile, the velocity of the cross-flow in the propulsion system is much higher than that in DI gasoline engine [23,24]. The researches in DI gasoline field focus on the cross-flow velocity effects on the spray [25], but in the real condition, the velocity is only one of the conditions and the ambient pressure is another important factor that affects the cross-flow. In the previous work, the effects of cross-flow under atmospheric condition were investigated; however, in the real engine the air pressure in the cylinder is changing over time. So it is not enough to test the effects of the cross-flow on spray only under atmospheric conditions, and the effects of the ambient pressure and the cross-flow on spray should be investigated simultaneously. In this study, the experiments are taken under the various velocities and ambient pressure of the cross-flow, which is more relevant to the real DI engine.

2. Experimental setup

2.1. Pressure wind tunnel

A special pressure wind tunnel was designed to provide a uniform cross-flow with various pressure [26]. Schematic of the system is shown in Fig. 1, a high pressure wind tunnel was connected with a pressure tank, and the pressurized air was provided by a compressor. The structure of the high pressure wind tunnel is shown in Fig. 2. There were four main sections in this wind tunnel: diffusion section, rectification section, contraction section and observation section. The guide vanes and mesh screens were utilized to diffuse and uniform the air flow. After the contraction section, the uniform air flow was obtained in the observation section. The air flows with various velocities and pressures can occur in observation section by controlling the open areas of the valve 1 and valve 2.

Three windows, which were made of Pyrex, were embedded in the front, back and bottom walls (see Fig. 3). A mini-sac hole type injector was fixed in the top wall with 25° to the vertical direction, and it made the spray direction perpendicular to the cross-flow. A hot wire probe was used to detect the air velocity in this section, and a high sensitive pressure sensor was assembled to monitor the pressure. The coordinate system is defined followed the right-hand rule as shown in Fig. 3, the origin is the nozzle hole position, and the cross-flow is along the positive x while the injection direction is along the positive y. The experimental conditions are listed in Table 1.

According to the theoretical calculation, when the valve 2 is set in a constant open area (or open angle, 90° is full opened, 0° is closed) and then open valve 1, the pressure in wind tunnel will increase rapidly to a peak and then decrease gradually while the velocity in the observation section will increase to a constant value and then decrease. The spray and test system can be triggered when the pressure drops to the experimental condition with the right cross-flow velocity. In the real experiments, the velocity measurement in an environment with the rapid changing pressure is not easy. Pitot tube is a possible prober, but it depends on a high sensitive differential pressure gauge with a very short responsive time. Another option is the hot wire anemometer, which owns short enough responsive time. The hot wire anemometer was used as the velocity detector in this study. The hot wire anemometer was calibrated by PIV system under experimental conditions (pressures and velocities). The error of the hot-wire system is ±0.015 m/s. For instance, when the valve 2 is set at an open area and full open

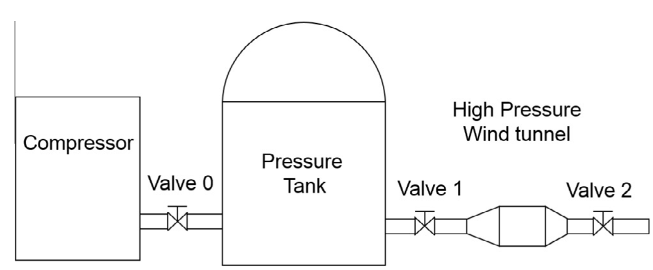

Fig. 1. Cross-flow wind tunnel system.