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Experimental study on fuel spray characteristics under atmospheric and pressurized cross-flow conditions, second report: Spray distortion, spray area, and spray volume

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HIGHLIGHTS

- The spray diffusion slightly decreases with the increase in ambient pressure.
- The spray area and spray volume decrease when the ambient pressure is increased.
- The effect of cross-flow on small size droplets is larger than that of large size droplets.

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ABSTRACT

It is proved that fuel efficiency promotion is an important method to improve the fuel economy and power output of direct-injection (DI) gasoline engines; moreover, the quality of fuel combustion is a critical factor for fuel efficiency. In DI gasoline engines, the diffusion and atomization of fuel spray are influenced by the airflow in cylinder when the spray is injected into the cylinder. The experimental measurements and theoretical analyses in this study are based on the conditions of cross-flow whose direction is perpendicular to the direction of spray. The spray images under various velocities and pressures of cross-flow were recorded using high-speed photography; besides, the spray area and spray volume were calculated from the spray images. To understand the movements of spray under the cross-flow conditions, the movements of single droplets with various diameters were deduced using aerodynamics methods. Under a constant velocity of the cross-flow, the diffusion of spray under a low ambient pressure is more distinct than that under a high ambient pressure.

1. Introduction

Fossil energy is mainly consumed in transportation [1]. Although new types of energy are being developed rapidly, their applications are scarce [2], and it is difficult to replace fossil energy in the next half century [3,4]. Besides, electrical energy has been increasingly utilized in urban transportation; however, the total energy efficiency has not been improved [5]. Electric vehicles are responsible for the pollution caused by power plants; it is difficult to determine whether the energy utilization rate in electric vehicles is higher than that in internal combustion engines if the original energy is fossil energy [6,7]. Therefore, it is important to improve the efficiency of internal combustion engines. Engine fuel efficiency has been refurbished in the past several decades [8], especially when the direct-injection technique was applied to gasoline engines [9].

The good performance of direct-injection (DI) gasoline engines can be attributed to the flexibility of injection time and injection mass according to different loadings [10], i.e., the injection ambient conditions became complex such as the change in airflow and ambient pressure [11]. It is difficult to directly analyze the effects of conditions on the spray in a cylinder because of insufficient fundamental study on the effects of single conditions and difficulties in real measurements [12]. Most studies focused on CFD simulations [13–15]; however, the results are difficult to understand without experimental calibrations. Honda [9] reported that the spray injected by a swirl injector is easier to be affected by an in-cylinder airflow than that injected by a multihole injector. Moon [16] reported that the airflow in a cylinder can affect the spray atomization and ignition point by measuring the spray injected

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Nomenclature

a_h	Horizontal acceleration (m^2/s)
g	Gravitational acceleration (m^2/s)
x_0	Length of spray in horizontal ($y_0 = 50$ mm) (m)
A	Section area of the droplet (m^2)
A_y	Spray area in the horizontal section y (m^2)
C_d	Drag coefficient
D	Diameter of droplet (m)
F_h	Horizontal force (N)
P_a	Pressure of ambient air (MPa)
U	Relative velocity between the droplet and air (m/s)
U_I	Initial velocity of spray (m/s)
U_v	Vertical velocity of droplet (m/s)
V_{spray}	volume of the spray under cross-flow (m^3)
μ_a	Viscosity of air (Pa·s)
μ_r	Viscosity rate of fuel and air (Pa·s)
ρ_l	Fuel density (kg/m^3)
a_v	Vertical acceleration of droplet (m^2/s)
q	Air fuel momentum flux ratio
y_0	Vertical length $y_0 = 50$ mm
A_0	Spray area of $y = 50$ mm (m^2)
ASOI	After start of injection
CFD	Computational Fluid Dynamics
F_d	Upward aerodynamic drag (N)
M	Mass of droplet (kg)
Re	Reynolds Number
U_h	Horizontal velocity of droplet (m/s)
U_{limit}	Vertical limited velocity when a droplet falls into air (m/s)
U_x	Velocity of cross-flow (m/s)
μ	Viscosity of fuel (Pa·s)
μ_l	Viscosity of fuel (Pa·s)
ρ_a	Air density (kg/m^3)

by a slit injector using Mie scattering images and phase Doppler anemometry. However, certain phenomena are difficult to explain without additional fundamental and detailed studies [17]. Therefore, single-condition experimental investigations are the first and essential step for evaluate the spray characteristics in DI gasoline engine cylinders. The cross-flow flowing perpendicular to the direction of spray was used as a typical airflow condition for the experiments conducted in previous studies [18].

Spray under cross-flow conditions has been widely studied in modern propulsion and power applications [19,20]. Penetration height, similar to distortion in this study, is a critical parameter for evaluating the cross-flow effects. No [21] investigated the empirical equations of penetration height and found that the liquid-to-air momentum flux ratio q determines the penetration height. However, the injection pressure in a propulsion system is lower than that in a gasoline engine, and the cross-flow velocity is much higher than that in a gasoline engine cylinder [22,23]. This shows that the fuel atomization in a propulsion system can be attributed to high-speed cross-flow, whereas the fuel atomization in a gasoline engine can be attributed to injection pressure [24,25]. Moriyoshi et al. [26] evaluated the effects of cross-flow on fuel-spray atomization using the relative velocity between spray droplets and cross-flow. The droplet size significantly changed by the cross-flow compared to the free-spray condition [27]. A vortex occurred in the upper part of the spray downstream the cross-flow [17]. Another important difference is ambient pressure; the ambient pressure (cross-flow pressure) changes in the stroke cycle of gasoline engine [28]. To complement fundamental studies on spray characteristics under cylinder airflow conditions, the cross-flow flowing perpendicular to the spray direction was used as a basic experimental condition in this study. High-speed video photography was used to observe the fuel-spray profiles and structures [29]. The single-droplet aerodynamic calculations were repeated to understand the spray droplet movements [30].

2. Experimental setup

A pressure wind tunnel was introduced in the previous study [31]. The pressure wind tunnel consists of a diffusion section, rectification section, contraction section, observation section, and throttling section (Fig. 1). The experimental cross-flow with a proper velocity and pressure can be captured in the observation section by controlling the throttle. A mini-sac-type single-hole nozzle with 0.15-mm hole diameter was mounted on the top wall of the observation section. The angle between the central line of nozzle and vertical direction was 25° to meet the axial hole direction and maintain the vertical injection of spray. A pressure sensor and hot-wire anemometer were fixed in the rear of the observation section. When the pressure and velocity satisfy the experimental conditions, the control system triggers the spray and measuring systems.

A high-speed camera HX-3 (NAC Image Technology Inc.) was used to record the spray with a frame rate of 10,000 fps and 1280*720 resolution. A xenon lamp (USHIO, SX-UID501XAMQ) was used for illumination with a constant current of 25 A (See Table 1). During the photography, the camera and illumination were arranged in different sides of the observation section with an angle, confirming that the imaging is caused by Mie scattering. When observing the horizontal section of the spray, the camera was moved to the bottom of the observation section, and a continuous 532-nm wavelength laser sheet (DPGL-2W, Japan Laser) illuminated the horizontal section.

The experiments were carried out under two major conditions: a constant cross-flow velocity ($U_x = 5$ m/s) and constant air-fuel momentum flux ratio ($q = 506{,}000$). The cross-flow pressure (or ambient pressure) under the constant cross-flow velocity varied from 0.1 MPa to 0.4 MPa, whereas the pressure and velocity under constant q are (a) $U_x = 10$ m/s, $P_a = 0.1$ MPa; (b) $U_x = 7$ m/s, $P_a = 0.2$ MPa; (c) $U_x = 5$ m/s, $P_a = 0.3$ MPa; and (d) $U_x = 4.4$ m/s, $P_a = 0.4$ MPa [32].

Gasoline was replaced with a dry solvent in this experiment, because the dry solvent has the same physical properties as gasoline expect a higher initial boiling point. The fuel was injected into the observation section with 10-MPa injection pressure and 4-ms injection duration. The experimental temperature was controlled at 283 K.

3. Results

3.1. Spray profiles

The spray is bended, and some droplets are entrained into the downstream flow when fuel is injected into the cross-flow field, as discussed in the previous study [17]. The distortions become more obvious in the lower part of the spray when the cross-flow