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Experimental investigation on velocity inside a diesel spray after impingement on a wall

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ABSTRACT

Recently, a combustion chamber of a high speed diesel engine has been downsized in order to improve fuel economy. Moreover, injection pressure of the diesel fuel tends to increase due to promotion of fuel atomization. Therefore, the diesel spray flame impinges on a cavity wall of a combustion chamber in recent diesel engines. It results that promotion of heat loss from the engine occurred due to the heat transfer between the impingement spray flame and the cavity wall. Therefore, it is necessary to understand the impingement phenomenon of the diesel spray flame for improvement of the thermal efficiency. In order to understand the impingement mechanism between the spray flame and the wall, velocity measurement of an impingement diesel spray flame is required. Moreover, the heat transfer strongly depends on the flow characteristics of the impingement spray flame. Velocity information of the impingement spray might provide heat transfer mechanism between the spray and the wall although the diesel spray was not a flame. In this study, velocity field of an impingement diesel spray was measured with time-resolved PIV. Effect of ambient gas density, injection pressure and impingement angle on flow characteristics of the impingement diesel spray was investigated. Moreover, velocity of the diesel spray just before impingement on the wall was measured in order to investigate dependence of the impinging spray velocity on the post-impingement spray velocity. As the result, averaged radial peak velocities of the post-impingement diesel spray decreased with an increase of ambient gas density. Moreover, dependence of the impinging spray velocity on the averaged peak velocities of the post-impingement spray was clarified.

1. Introduction

A High pressure fuel injection system have been applied to recent high speed diesel engines to promote atomization of diesel fuel, and it resulted in an improvement for efficiency of diesel combustion. In a recent research, the combustion characteristics of a diesel spray ejected from the micro-hole nozzle (0.08 mm) of the diesel injector with ultra-high injection pressure (300 MPa) was investigated [1]. Under the high pressure fuel injection condition, the spray ejected from the nozzle penetrated into ambient gas of combustion chamber with high speed, and then the spray or the spray flame impinged on the cavity wall of the combustion chamber in the engine. Especially, in the case of downsized engine concept, the impingement of the spray or the spray flame on the wall frequently occurred due to short distance between the nozzle and the wall. Borman and Nishiwaki [2] reported that heat loss from 20% to 30% or more occurred by impingement of the diesel flame on the cavity wall. Their report suggests that the impingement disturbs the further improvement of the thermal efficiency of the engine. Therefore, there might be negative effect for heat loss in the engine due to the heat transfer between the impingement flame and the cavity wall.

In the past, heat transfer characteristics by interaction of a diesel spray flame and a wall were investigated by experimental approaches. Senda et al. [3] discussed the heat transfer characteristics by a wall impingement spray. They pointed out that heat flux between the spray and the wall at impingement point was varied by changes of impingement distance and ambient gas temperature. Kuboyama and Kosaka [4] discussed heat loss from a wall of a combustion chamber by impingement of a diesel spray flame. They measured heat flux of the wall by using a rapid compression expansion machine (RCEM). They reported that the heat flux was strongly influenced by temperature of the spray flame. Moreover, they suggested that gas flow induced by a fuel spray and impingement of the spray contributed to a raise of the heat flux in the flame impingement region. Yoshizaki et al. [5] investigated the behavior of the diesel flame impinging on a cavity wall and

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reported that a liquid film was formed on the impingement wall in the case of short impingement distance due to the unevaporated diesel spray.

As for investigation on characteristics of an impingement diesel spray, macroscopic behavior of the impingement diesel spray was investigated by many researchers (Fujimoto et al. [6], Saito et al. [7], Ko et al. [8], Andreassi et al. [9]). On the other hand, Arcoumanis and Chang [10] discussed heat transfer between a heated plate and an impinging transient diesel spray. They measured velocity inside the impingement diesel spray by using a phase doppler anemometry (PDA) and established the relationship between *Nu* number and *We* number regarding an unevaporated diesel spray under atmospheric ambient condition. There are many fundamental investigations for behavior of the impingement diesel spray and heat flax from a spray flame to a wall.

Here, as for heat loss by the impingement, the heat loss Q can be described with following equation (Eq. (1)) based on Newton's law of cooling.

$$Q = hA(T_H - T_L)\tau \quad (1)$$

h is heat transfer coefficient of combustion gas, A is heat transfer area, and T means temperatures of higher and lower sides. τ means contact time of the flame to the wall. In order to consider the heat loss Q from the combustion chamber, heat transfer coefficient h should be controlled, and reduction of the coefficient h results in the improvement of the thermal efficiency of the engine. The coefficient h is strongly related to flow characteristics of an impingement diesel flame. However, there was a few investigation regarding flow characteristic of an impingement flame even though the characteristics might provide the heat transfer process between the spray flame and the impingement wall.

Research group of authors [11] reported flow characteristics of the diesel spray impinging on a wall under high ambient gas density conditions with basis of assumption which flow characteristics of an impingement spray flame was similar to that of an impingement spray. Its concept corresponded to the experimental approach by Arcoumanis and Chang [10]. Authors [11] clarified self-similarity of velocity distribution in the post-impingement diesel spray and investigated effect of ambient gas density on turbulent kinetic energy of the spray by using time-resolved PIV technique. Here, flow field of the post-impingement diesel spray was strongly related to that of the spray before impingement. However, its relationship has not been investigated sufficiently in the previous work of authors. Therefore, it is necessary to investigate dependence of the post-impingement spray on the spray impinging on the wall.

In this study, flow characteristics of the post-impingement diesel spray on the wall were investigated for various ambient gas densities and injection pressures by using time-resolved PIV. Moreover, the effect of the impingement angle of the spray on the flow characteristics was also investigated. From those results, the relationship of the spray velocities between the post-impingement spray and the spray impinging on the wall was discussed.

2. Experiment set-up

Schematic view of experimental apparatus for velocity measurement inside an impingement diesel spray is shown in Fig. 1. The experimental apparatus consisted of a fuel injection system, a high pressure vessel, an impingement wall and an optical system for visualization of a diesel spray. Diesel fuel was injected into the pressure vessel by using a common-rail system, and the impingement wall was placed in the vessel. In this study, time-resolved PIV was applied to measurement of velocity field in the impingement diesel spray. As for visualization of the spray, a continuous wave (CW) laser was used as light source, and a laser light sheet was formed by a cylindrical lens. Its thickness was around 1 mm. The impingement spray was illuminated by the laser-light sheet. It means that any tracer particles for PIV was not seeded into the spray, and the spray droplets were used as tracer particles for PIV measurement. A digital high speed video camera (Vision Research, PhantomV2511) was arranged in the perpendicular position to the laser light sheet, and sequential tomographic images of the spray were captured. Frame rate was set at 270,833 f.p.s. and 140,086 f.p.s. to capture the spray image with the narrow interval for PIV analysis. In PIV analysis, velocity data were obtained from the sequential tomographic images of the spray by using direct-cross correlation method. Impingement distance was constant at 40 mm. Inclination angles of the impingement wall were selected at 0 deg. and 20 deg. At 0 deg. of the angle, namely, the spray impinged on the wall normally at its angle, and 20 deg. was the oblique impingement.

Table 1 shows experimental condition in this study. A single-hole diesel nozzle was used. The velocity measurement of the post-impingement diesel spray was carried out under several ambient gas density conditions. The ambient gas density of ρ_a = 11.6 kg/m^3 on table 1 corresponded to the density in a combustion chamber at ignition timing of a natural aspirated (NA) diesel engine, and the ambient gas density condition of ρ_a = 46.5 kg/m^3 corresponded to high boosted diesel engine condition.

When a diesel spray impinged on a flat wall, a rolled-up spray around the spray tip masked the impingement spray illuminated with a laser light sheet as shown in Fig. 2(A). Therefore, it was difficult to capture tomographic images of an impingement diesel spray clearly. In this study, a slender bar was adapted as an impingement wall instead of the flat wall in order to reduce the mask effect of the rolled-up spray on the tomographic image. Research group of authors [12] also applied the slender bar as the impingement wall, and they already have checked difference of the impingement diesel spray behavior between the bar case and flat wall case for the spray tip penetrations and the flow pattern inside the spray. Consequently, they reported that there was no much difference of the behavior between the bar and the flat wall. It means that it was possible to adapt the bar instead of the flat wall as the impingement wall.

3. Experiment results and discussions

3.1. Mean velocity distributions of impingement diesel spray

Fig. 3 shows the mean velocity fields for various ambient gas densities and injection pressures at normal impingement of the spray. Horizontal axis R shows radial distance from its origin, and the origin of the axis was defined as the point at the intersection of the center axis of the nozzle hole with the wall. Vertical axis H shows height distance from the wall surface. Radial component of the velocity was u, and vertical component of the velocity was v in this study. Spray periphery was shown with a dotted line. Its periphery was obtained from tomographic images of the impingement spray. In the analysis of the mean velocity field, the instantaneous velocity fields in steady state period were averaged, because the spray behavior around the tip was unsteady flow such as the rolled-up motion. The velocity data before the tip reaching at R = 7.9 mm (ρ_a = 11.6, 23.2 kg/m^3) and R = 10.3 mm (ρ_a = 34.8, 46.5 kg/m^3) in radial direction were neglected in the analysis in order to average spray velocity data in steady state period. Those positions (R = 7.9 mm and 10.3 mm) were determined in order to guarantee enough number of instantaneous velocity data for obtaining ensemble mean velocity of the spray. In the later stage