# Experimental Investigation on Behavior of an Impingement Diesel Spray on a Wall with Adhering Liquid Fuel

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**Abstract**

In modern diesel engines, injection pressure of diesel fuel tends to increase in order to promote atomization of the liquid fuel, and the downsizing concept has been applied as compared with the conventional engines to improve thermal efficiency of the engine. The impingement distance between the spray and a piston cavity become short, and the impingement of the fuel spray frequently occurs. Under cold start of the engine especially, a liquid film of the fuel is formed on the wall by the impingement of the spray, and pollutant matters such as HC and soot are emitted from the engine due to fuel adhesion on the wall. Therefore, it is important to understand behavior of the spray on the wall with adhering liquid fuel. In this study, in order to investigate the behavior of the spray after impingement on the wall, a relationship between the jet velocities before and after the impingement was evaluated by using the PIV technique. This experiment was conducted by using a nitrogen gas jet that does not cause liquid fuel adhesion. As the result, it seems that fuel liquid film formed on the wall contributed to the velocity of the spray after impingement on the wall.

**Keywords**

spray, liquid film, jet velocities, PIV, gas jet

**Introduction**

Recently, diesel fuel has been atomized by high-pressure injection of fuel for the purpose of improving combustion in diesel engines. Currently, the injection pressure of commercial diesel engines exceeded 250MPa, and the injection pressure in experimental studies have reached 400MPa [1]. Wang et al. [2] and Kuti et al. [3] experimentally investigated the effects of ultra-high injection pressure and micro-hole nozzles on spray characteristics. From these studies, it was found that the spray penetration increased with an increase of the injection pressure, and effective penetration and higher air entrainment promoted atomization. In addition, for the purpose of improving fuel consumption, the downsizing concept of the engines has been applied. As a result, in a downsized diesel engine, the diesel spray or flame likely impinge on a cavity wall due to the short distance between the nozzle and the wall. Borman and Nishiwaki [4] reported that heat loss increase of 20% to 30% occurred by impingement of the diesel flame on the cavity wall. They suggested that impingement disturbs further improvement of the thermal efficiency of the engine. Therefore, heat transfer between the impinging flame and the cavity wall is considered in order to reduce the heat loss. On the other hand, it can be said that the improvement of thermal efficiency can be expected by suppressing heat loss the wall surface. Several methods have been proposed to suppress wall heat loss. Thermo-swing wall insulation technology[5] is a method of coating the wall surface of the combustion chamber with a material with low thermal conductivity and low heat capacity, and the wall surface temperature during the combustion period follows the combustion gas temperature. Thus, the heat loss was reduced due to a decrease of temperature difference between the combustion gas and the wall. Andruskiewicz et al. [6] also verified the effect of this technology on the reduction of heat loss with practical engines. Arato et al. [7] proposed a method to optimize the shape of the cavity for improvement of the thermal efficiency by simulation.

In order to consider a strategy to supress heat loss, it is important to understand flow characteristics of the spray flame, because heat transfer strongly depends on the flow characteristics of impinging flame. Many studies have been done on the impingement of the diesel spray and flame on the wall. Tatsumi et al. [8] measured the heat flux of the impinging spray frame using a wall insertion type constant volume vessel. They reported that there is a trade-off relationship between flame velocity and flame contact area or contact time for the heat loss. Kuboyama et al. [9] measured the local heat flux and the local radiant heat flux on the piston wall surface using a rapid compression expansion machine. They reported that the wall heat flux is strongly affected by the flame temperature that impinges on the wall. It was also reported that the gas flow induced by the injection of fuel spray and the wall impingement significantly increased heat flux in the impingement region of the spray flame. Chen et al. [10] investigated the combustion characteristics of an impinging diesel spray on a wall under several wall temperatures and ambient pressure conditions. They reported that the ignition delay becomes shorter and the generation of soot increases with an increase of wall temperature.

However, there were few reports on the flow characteristics inside an impingement flame. A group of authors [12] investigated flow characteristics of a non-evaporative spray impinging on a wall by using a time-resolved PIV technique, assuming that flow of a diesel spray flame impinging on a wall was the same as the flow of a spray. They reported that effect of fuel liquid film formed on a wall on flow characteristics of a spray. When the spray flame impinges on a wall inside the engine, a fuel liquid film is not formed, but fuel liquid film may be formed on a wall of the piston due to the low temperature inside the engine cylinder such as the cold start condition. Yoshizaki et al. [13] investigated the behavior of diesel flames impinging on a wall and reported that a fuel liquid film formed on a wall in the case of short impingement distance due to the unevaporated diesel spray. Jesus et al. [14] reported that fuel liquid films were a factor in the discharge of HC and soot. Therefore, it is necessary to investigate the effect of the formation of liquid film on spray flow after impingement.

In this study, the gas jet instead of diesel spray impinged on the wall adhering liquid film, and the velocity inside the gas jet after impingement of the wall was measured with time-resolved PIV. The velocity before the impingement wall was set to be similar to the diesel spray conditions. The effect of liquid film on velocity of gas jet flowing on the liquid film was investigated with basis of results of non-evaporated diesel spray.

## Experimental Setup and Methods

A schematic view of experimental setup for velocity measurement of impinging gas jet is shown in Figure 1. The experimental setup consisted of a pressure vessel, gas injection system, an impingement wall and an optical system for visualization of the nitrogen gas jet. The gas jet was injected into the pressure vessel only once and an impingement wall was placed in the vessel to form an impingement. The high-speed camera and gas injection were synchronized by the signal of the pulse generator. A slender bar was used as the impingement wall to capture high quality PIV images of the impinging gas jet. The width of the impingement wall was 10mm. In order to form the liquid film, the slot with 0.1mm of depth was installed on the surface of the impingement wall. Before impingement of gas jet, liquid fuel was filled in the slot. In this study, time-resolved PIV was applied to measurement of the velocity field in the gas jet. As for visualization of the jet, a continuous wave (CW) laser (wavelength : 532 nm, output : 4000 mW) was used as light source, and a laser light sheet was formed by a cylindrical lens and a spherical achromatic lens. Its thickness was 1 mm or less, and width of the laser light sheet was 5 mm. In order to measure the gas flowing on the wall surface, the laser light sheet was emitted so that it was parallel to the impingement wall surface and along the wall surface. A high-speed digital video camera (HPV-X2) was used to capture the gas jet. The spatial resolution was 0.03 mm/pix. The frame rate of the camera was set from 125,000 to 239,808 f.p.s., and the exposure time was from 3500 to 4500 ns. The impingement distance was constant at 25 mm. The impingement angle was 0 deg., namely, the jet impinged on the wall vertically at its angle. The analysis area of the jet velocity field was 4 mm from the impingement wall surface in the vertical direction and 12mm apart from jet axis in the horizontal direction. Moreover, a schematic view of the experimental setup for observation of fuel liquid film behavior when the nitrogen gas jet impinges on the wall is shown in Figure 2. The experimental set up consisted of a pressure vessel, gas injection system, an impingement wall and an optical system for visualization of fuel liquid film behavior.

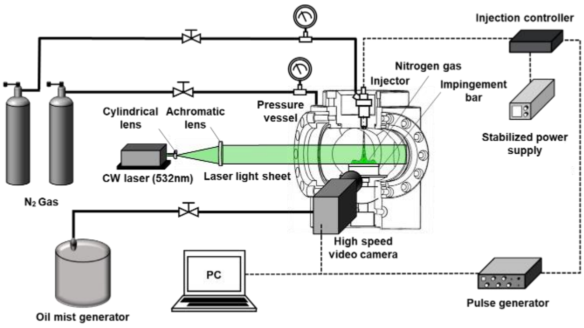


**Figure 1** Experimental setup for velocity measurement of impingement gas jet

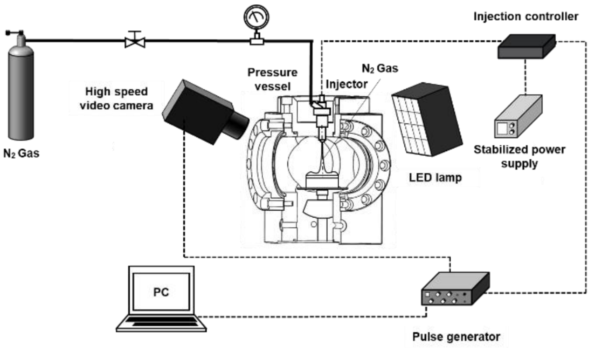


**Figure 2** Experimental set up for observation of fuel liquid film behavior

Table 1 shows the experimental conditions for the impinging nitrogen gas jet on a wall. A nozzle that changed multiple-hole into single-hole was used, and diameter of the nozzle was $d_o$ = 0.130 mm. The ambient gas density was changed from 1.2 kg/m$^3$ to 12.3 kg/m$^3$. The impingement distance was constant at 25mm. Injection pressures were selected at 5MPa to 13MPa. The test gas was Nitrogen. Incense smoke or oil mist were used as tracer particles for PIV measurement.

**Table 1** Experimental conditions for impingement nitrogen gas jet on the wall

| | | | | |
|---|---|---|---|---|
| Nozzle hole diameter $d_0$ [mm] | 0.130 | | | |
| Ambient gas temperature $T_a$ [K] | 300 | | | |
| Ambient gas density $\rho_a$ [kg/m$^3$] | 1.2, 2.2, 3.4, 4.5, 5.8, 6.9, 9.2, 11.6, 12.8 | | | |
| Injection pressure $P_{inj}$ [MPa] | 5, 6, 9, 11,13 | | | |
| Injection period $t_{inj}$ [ms] | 3.2 | | | |
| Test gas | Nitrogen gas | | | |
| Impingement distance $L_w$ [mm] | 25 | | | |
| Impingement wall angle $\theta_d$ [deg.] | 0 | | | |
| Tracer particles | Incense smoke, Oil mist | | | |
| Wall type | w. slot wall | | | Glass wall |
| Wall roughness $Ra$ [μm] | 31 | | | 2 |
| Liquid film | w.o film | Diesel fuel | Silicone oil | w.o film |
| Kinematic viscosity $v$ [m$^2$/s] | | $6 \times 10^{-6}$ | $50 \times 10^{-6}$ | |

## Results and Discussion

Mean velocity distributions of an impinging gas jet

Figure 3 shows the mean velocity distributions of an impinging gas jet on a wall under the condition of injection pressure $P_{\text{inj}}$ = 13 MPa and ambient density $\rho_{\text{a}}$ = 12.3 kg/ m$^3$. The horizontal axis shows radial distance from the injection hole axis, and the Vertical axis shows distance from the wall surface. The radial component of the velocity was $u$, and vertical component of the velocity was *v*. In the analysis of the mean velocity field, the instantaneous velocity fields of the jet in steady state were averaged, because the jet behavior around the tip was unsteady flow such as the rolled-up motion. In Figure 3, a solid line shows the height distribution for radial component of the averaged velocity. The maximum velocity obtained from this distribution was defined as $U_{peak}$, and the average of these was defined as $\overline{U_{peak}}$. In addition, the height indicating $U_{peak/2}$, which is half the value of $U_{peak}$, was defined as $H_{Upeak/2}$. Approximating the location of $H_{Upeak/2}$ with two straight lines causes an intersection as shown in this figure. In this study, the velocity field of the impingement gas jet was separated into two regions which were named "impingement region" and "wall jet flow region ". In the discussion of the present report, flow characteristics of an impingement gas jet in the wall jet flow region were focused on.

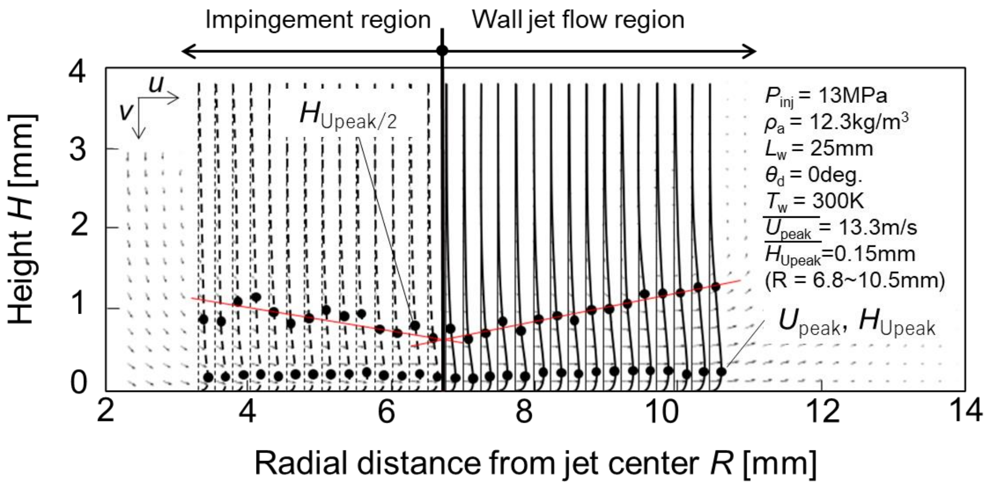


**Figure 3** Definition of impingement region and wall jet flow region in mean velocity field

<u>Relationship of velocity before and after impingement on the wall about diesel spray and nitrogen gas jet</u>

Figure 4 shows the relationship between the velocity before and after the impingement on the wall in diesel spray and gas jet. Averaged peak velocity in vertical axis of the figure means the spatial average of the peak velocity in wall jet flow region. Tip velocity was obtained by spray or jet tip penetration.

In the previous work of our research group, the relationship of velocity before and after the impingement diesel spray on the wall was investigated as shown in the figure [15]. As a result, the spray velocity after the impingement on the wall increased in proportion to spray velocity before the impingement on the wall as shown by the dotted line in Figure 4, and the rate of increase decreased in the region where the velocity before the impingement exceeded 50 m/s. Here, the influence of liquid film formed on the wall was suggested as a factor for reducing

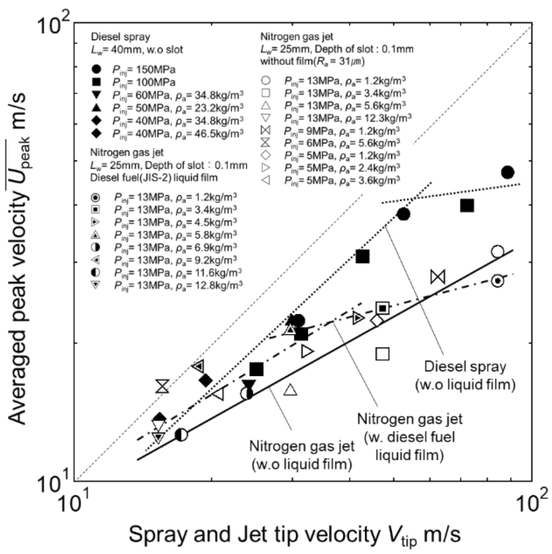


**Figure 4** Relationship between the velocity before and after the impingement on the wall in diesel spray and gas jet

the rate of increase in the spray velocity of the impingement spray on the wall. Therefore, in this study, relationship between the jet velocity before and after the impingement on the wall by using nitrogen gas jet, which does not cause the formation of liquid film on the wall by injection, was investigated. The jet velocity before the impingement was calculated by the sequential shadow image of free gas jet, and the gas jet was visualized by entraining tracer particles into the jet.

The relation of gas jet velocities before and after impingement on the wall was shown with solid line in Figure 4. The velocity after the impingement increased with an increase of velocity before the impingement in contrast of impingement of diesel spray. In the case of diesel spray, the fuel liquid film was formed on the wall surface during period of fuel injection. However, there was no liquid film on the wall in the case of gas jet impingement. Therefore, it seems that the reduction of increase rate of the velocity after the impingement as for diesel spray was caused by the formation of liquid film on the wall. Here, in order to verify the influence of the liquid film on the reduction of increase rate of the velocity, the gas jet impinged on the wall with adhering diesel fuel. The dashed line in Figure 4 shows the relation of gas jet velocities before and after impingement on the wall with fuel liquid film. The increase rate of the velocity after impingement was weak over 30m/s of the velocity before the impingement even though the gas jet impinged on the wall, and its trend was similar to that of diesel fuel. It means that the reduction of increase rate of the velocity was affected by the liquid film on the wall. Thus, it seems that the increase rate of the velocity was reduced by liquid film movement induced by the flow of gas jet on the liquid film. However, when comparing of velocities of the impinging gas jet with and without a liquid film on the wall, there was discrepancy. The velocity after the impingement on the wall with the liquid film was higher than that on the wall without liquid film, although the velocity after the impingement decreased by the movement of liquid film. Next, the effect of liquid film on the velocity of the gas jet on the liquid film was investigated by changing the kinematic viscosity of liquid film on the wall.

<u>Effect of kinematic viscosity of the liquid film on the relationship of velocity before and after the impingement of the nitrogen gas jet</u>

Figure 5 shows the relationship of velocity before and after the gas jet impinged on the wall with a liquid film with different kinematic viscosity. Liquid film was formed on the wall surface using silicone oil with kinematic viscosity $\upsilon = 50\times10^{-6}$ m/s$^2$, and the jet velocity before and after the impingement on the wall was investigated by conducting the impinging jet experiment. In addition, this result was compared with the result of diesel fuel liquid film (kinematic viscosity $\upsilon = 6\times10^{-6}$ m/s$^2$). The alternate long and short dash line in the Figure 5 shows the tendency of increasing jet velocity after the impingement under the condition that a silicone oil liquid film was formed on the wall. From the Figure 5, the increasing tendency of the jet velocity after the impingement on the wall with silicone oil liquid film was the same as that of no liquid film condition. From this result, it is

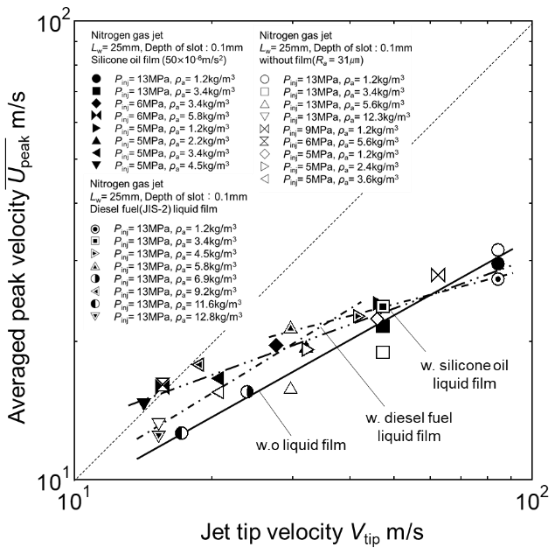


**Figure 5** Relationship between averaged peak velocity and jet tip velocity for gas jet impinging on a wall adhering liquid film with different kinematic viscosity

considered that liquid film of high kinetic viscosity did not affect the decrease in the increasing tendency of the jet velocity after the impingement. It can be also seen that the jet velocity after the impingement on the wall with silicone oil liquid film is also faster than the jet velocity after the impingement on the wall without liquid film. Here, it was predicted that changing liquid film from diesel fuel to silicone oil would increase shear force at the gas-liquid interface due to increasing kinematic viscosity of liquid film, which would slow down the jet velocity after the impingement more than that after the impingement on the wall without liquid film. However, the velocity of the gas jet on liquid film of higher kinetic viscosity was higher. In order to clarify the factor of the discrepancy, interface of the liquid film was observed with a high speed camera.

Figure 6 shows behavior of liquid film during the impingement of gas jet.

The respective velocities in Figure 6 (a) and 6 (b) are the regions before and after the increasing tendency of the jet velocity after the impingement on the wall with diesel fuel liquid film. As shown in Figure 6 (a), the liquid film was wavy due to the impingement of the gas jet. On the other hand, in the case of high velocity of the impingement gas jet, the liquid film was wavy intensely as compared with low velocity of the impingement gas jet. From this observation, it seems that the resistance of wavy interface of liquid film to the gas jet flow increased, and the velocity of the jet after the impingement on the wall became low in the case of high velocity of the impingement gas jet. Furthermore, interfaces of liquid film with different kinetic viscosity at the same impingement velocity of the jet, which was 25.0m/s, were shown in Figure 6(c) and (d).

It was found that interface of liquid film with high kinetic viscosity was hardly wavy as compared with that with low kinetic viscosity. It means that the resistance of wavy interface of liquid film to the gas jet flow reduced in the case of liquid film with high kinetic viscosity. Therefore, the velocity after the impingement on the wall with liquid film with high kinetic viscosity was higher than that on the wall with liquid film with low kinetic viscosity. From the above, it can be

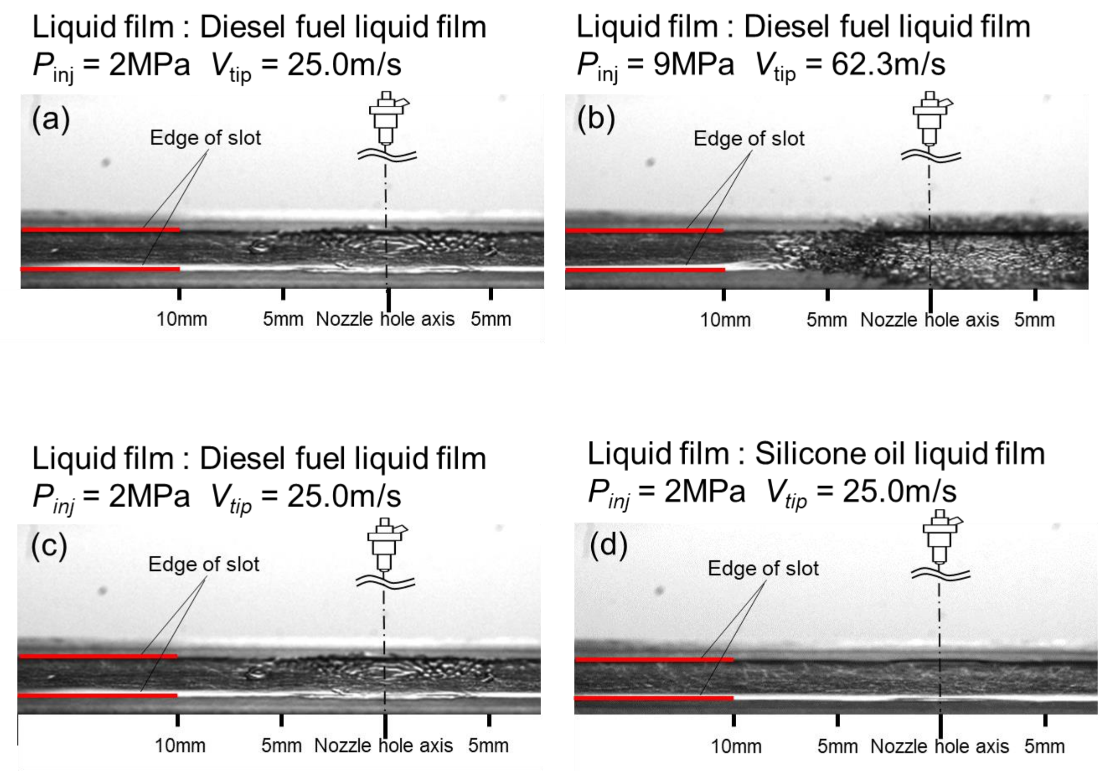


**Figure 6** Interface of liquid film in different injection pressure

inferred that the jet velocity after the impingement is faster on a smoother surface, and the relationship of velocity before and after the impingement of the gas jet that impinged on the low roughness wall was investigated.

Figure 7 shows the relationship of velocity before and after the impingement of the gas jet that impinged on the wall due to the difference in the properties of the jet impingement surface. As a low roughness wall, the glass wall with a surface roughness *Ra* = 2 µm was investigated. The relationship of velocity before and after the impingement of the gas jet that impinged on the low roughness wall was shown with dotted line. As comparing the velocity after the impingement on the low roughness wall with the impingement without liquid film as shown with solid line (ex. high roughness wall: *Ra* = 31 µm), the velocity of the low roughness wall was higher than that of the high roughness wall. It was reasonable result in terms of fluid dynamics. On the other hand, the velocity of the gas jet on liquid film of high kinetic viscosity was lower than that of the low roughness wall. It was caused by an increase of the resistance of liquid film with slight wavy as shown in Figure 6(d). Therefore, it was found that wavy interface of liquid film by causing gas flow on the liquid film contributed the velocity of gas flow on the liquid film.

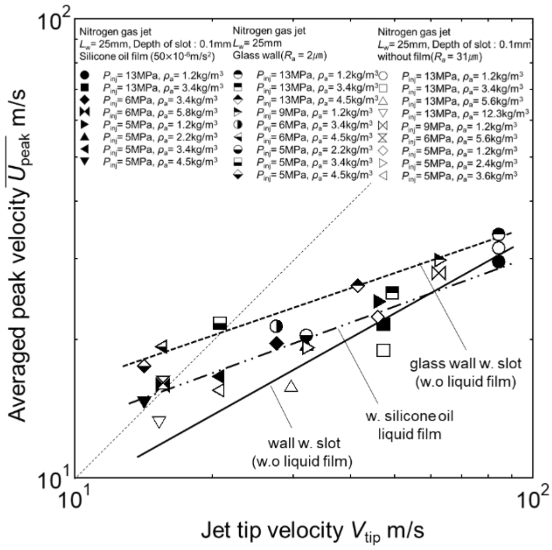

**Figure 7** Relationship between averaged peak velocity and jet tip velocity in different surface roughness of wall

## Conclusions

In this study, behavior of an impingement diesel spray on a wall with adhering liquid fuel were investigated. The results obtained in this study are as follows;

(1) The velocity of the diesel spray after the impingement on a wall increased with an increase of the impingement velocity of the spray, and the increase rate of the velocity became weak in high impingement velocity of the spray due to contribution of fuel liquid film.
(2) The velocity of the impingement gas jet after the impingement on a wall increased with an increase of the impingement velocity of the jet.
(3) Wavy interface of liquid film was formed by the impingement of gas jet, and the velocity after the impingement on the wall became low by formation of wavy interface of liquid film. It was caused by an increase of the flow resistance of gas flow by wavy interface of liquid film.

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