CHARACTERISTICS OF IMPINGEMENT DIESEL SPRAY ADHESION ON A FLAT WALL

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ABSTRACT: Many researchers since last decade have been looking forward to improving diesel engine performance through keeping low harmful emission. The aim of this study was to clarify the fundamental characteristics of non-evaporated impinging spray and adhesion behavior of fuel by measuring the adhering fuel mass on a wall. In this study, a fuel injection system, a high pressure vessel and an image processing unit for impingement spray were used. Experimental investigations were carried out with various injection pressures from 40 MPa to 170 MPa and ambient pressures from 0.1 MPa to 4.0 MPa. The impingement distances were set from 30 mm to 90 mm. The results showed the adhered fuel mass was affected by impingement distances. The adhered mass ratio was inversely proportional to injection pressure. At higher ambient pressure and higher the injection pressure, adhered mass fuel tended to decrease. Adhered fuel mass ratio had the potential to decline after reaching its peak when impingement velocity decreased beyond a critical velocity.

KEYWORDS: *Diesel spray, impingement disk, adhered fuel, impingement distance, injection pressure.*

1.0 INTRODUCTION

Over the last decade, study and research on diesel spray have progressed significantly. Many research works have been performed by automotive engineers to improve the performance of diesel engines and to reduce the exhaust emissions as well as fuel consumption.

In a high-speed DI diesel engine, behavior, structure and characteristics of diesel spray have been investigated by many researchers [1-14, 33]. From the viewpoint of spray combustion in the piston cavity, spray impingement on a cavity wall and fuel film adhering to its wall surface have a strong influence on combustion processes, engine performance and also characteristics of diesel exhaust harmful emissions. However, there are a few studies on impinging diesel spray with regard of adhering fuel on the cavity wall. Then it is necessary to understand the effect of fuel adhering when the spray impinges on the cavity wall.

Various aspects of impinging diesel spray available in current literatures are reviewed in order to have a better understanding of the impinging diesel spray on the wall. In addition, the adhering fuel which is formed when the spray impinges to a wall, is discussed as an important factor in wall impingement spray. Furthermore, an understanding of the impinging diesel spray mechanisms is crucial for finding the best way on improving engine performance as well as reducing emissions which occur in the combustion process.

Wall impingement of fuel spray is known as the main contributor to direct injection high-speed diesel combustion, so it becomes an important factor in reducing diesel exhaust emissions. In small type high speed DI diesel engine, the injected fuel spray impinges on a wall of the combustion chamber because of short distance between an injection nozzle and a cavity wall. From the viewpoint of Boot et al. [15] and Han et al. [16], the fuel impingement on a cylinder wall or a piston surface occurs and causes the hydrocarbon emission. Recently, Arai [17] pointed out the importance of diesel spray handling and that the task of diesel spray injection was fuel preparation at desired timing and desired space in the combustion cavity.

The vaporization and combustion of diesel spray are strongly affected by the characteristics of non-evaporating spray. For understanding the mechanism of non-evaporated diesel spray condition on adhering fuel, spray-wall interaction, spray modeling, and further the development of the advanced combustion system, the behavior of impingement spray should be clarified experimentally and theoretically. Adhering fuel mass on the piston/cavity wall seems to be an important factor in non-evaporated impinging diesel spray. The adhesion behavior influences the combustion process and results in harmful emissions. As the spray impinged on piston cavity wall, liquid film of diesel fuel is formed. Consequently, the smoke level increases due to evaporation of heated liquid film together with surrounding gas [18].

Therefore, it is necessary to investigate the impingement spray behaviour under different injection pressure condition. In this study, due to the importance of injection pressure and impingement distance, effects of injection pressure and impingement distance on adhering fuel were experimentally investigated.

2.0 EXPERIMENT

2.1 Methodology of adhered fuel mass measurement

Figure 1 shows the general method of impinging diesel spray investigation in this study. However, only effect of injection pressure and impingement distance will be covered in this paper. In practical direct injection diesel engine, multi-hole nozzle injector was used. Then spray-to-spray interaction might affect the combustion process. However, when interaction between spray-to-wall was investigated, spray-to-wall interaction of a single spray was fundamental and also important for multi-spray behavior including spray-to-spray interaction. Then, this investigation only involved a single hole injector system for the whole experiment. Because impinging spray on the wall is complex phenomena, using single hole injector system could simplify the experimental analysis [19-21]. The diesel spray would impinge on the dry surface of the wall. Similar to the phenomena occurred in real engine, when the fuel remained on the surface of the wall it would be burned by the following combustion phase, and then the next spray would be impinged again on the dry surface. Although the wetted surface was also important in diesel spray impingement, the impinging spray effect on the dry surface of the wall could not be avoided as many researchers also focused on the dry wall surface [22-26]. As the spray impinged on the dry surface wall, the adhered fuel mass was measured as the main parameter in this study. Then adhered mass ratio was analyzed.

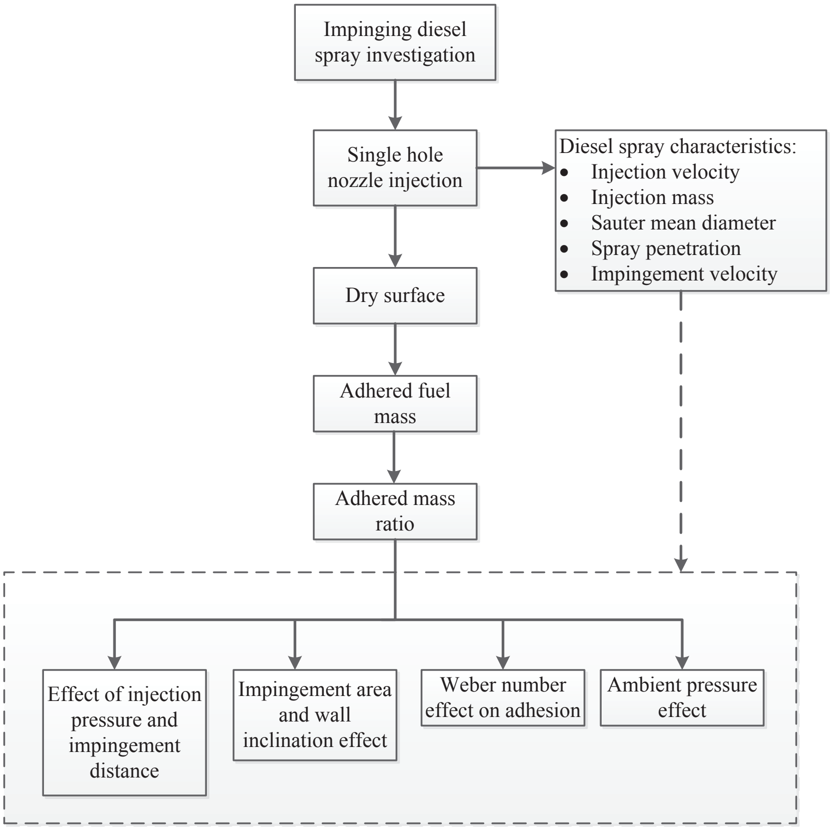

Figure 1: General method of impinging diesel spray investigation

2.2 Experimental apparatus and setup

2.2.1 Experimental apparatus for normal wall experiments

In this study, a normal wall impinging spray was conducted. The purpose of the experiments was to measure the adhering fuel mass on the wall. A real photograph for both experimental apparatus is shown in Figure 2. It consisted of a fuel injection system, a high pressure vessel and an image processing unit for impingement spray. The high pressure vessel with a size of 220 mm × 200 mm × 280 mm was used. The high pressure vessel was filled with N_2 gas of room temperature in which to control the ambient density inside the pressure vessel. Diesel fuel of JIS No.2 was used as a test fuel. The test fuel was injected into the vessel with a single shot fuel injection system, and a spray impinged on an impingement disk placed in a vessel. In order to observe the behavior of an impingement spray, a shadow imaging technique was applied. A metal halide lamp was used as the light source, and sequential shadow images of diesel spray were captured with a high speed digital camera (Phantom, PCI-512).

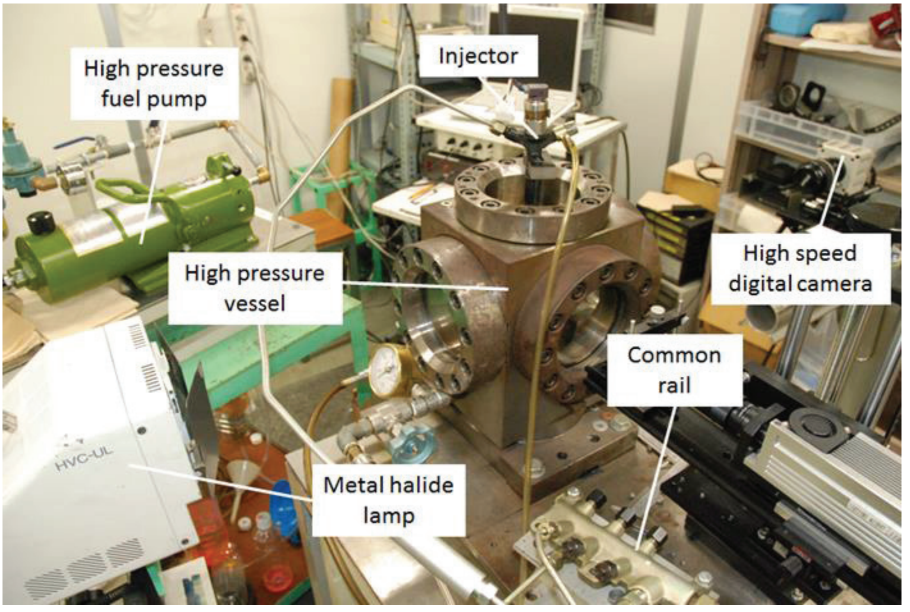

Figure 2: Photograph of impinging diesel spray test bench

2.3 Experimental condition and procedure

(1) Main experimental conditions

Table 1 shows the main experimental conditions for both types of experiments. The diameter of the nozzle hole was 0.17 mm. Its diameter was in a range of multi-hole injector which was around 1 liter per cylinder. The injection period of 3.2 msec was adopted in this research. Injection pressures were 40, 80, 100, 120, 130, 150 and 170 MPa with injection mass of 18.2, 24.5, 26.8, 28.7, 29.6, 31.5 and 32.8 mg respectively for each injection pressure. Recently, high injection pressure was applied in the diesel engine in order to atomize the liquid fuel into small droplets and enable rapid vaporization in the combustion chamber [31]. Thus, it is good to have the high injection pressure condition such as 170 MPa in order to observe the behavior of the adhering fuel due to fully atomization of the injection spray.

The ambient gas temperature in the high pressure vessel was 300 K (i.e. room temperature). The ambient pressure in the vessel was set from 11 MPa to 4 MPa. Here, at Pa = 1 MPa and 300 K, ambient gas density of 11.6 kg/m^3 was equivalent to a compressed gas density of 3 MPa at 800 K. These pressure and temperature were similar to a combustion chamber condition at ignition timing of conventional natural aspirated (NA) diesel engine. In an ultra-high boost engine, compressed gas density in combustion chamber became 4 or 5 times higher than that of NA engine. Therefore, in order to clarify the impingement behavior of a diesel spray in ultra-high boost engine, high ambient pressure conditions such as 2 MPa and 4 MPa were included in the test conditions. The impingement distances Lw from the nozzle tip to the wall varied from 30mm to 90mm. The impingement distance of L_w = 30 mm and 50 mm were set to clarify impingement behavior of small size conventional diesel engine. At these distances for small size of diesel engine, the spray penetration might impinge on the cylinder wall and piston cavity. Impingement distances of L_w = 70 mm and 90 mm were set to examine impingement behavior of medium size diesel engine and early injection of PCCI condition. As early injection timing of PCCI condition, the in-cylinder temperature and surrounding pressure were low. In other words, the fuel vaporization rate would reduce and the liquid penetration length would increase, and the adhering fuel mass on the wall might increase. Thus, longer impingement distance in this study could be presented for this condition.

The fundamental behavior of adhering fuel is related to the nature of the affinity and it is greatly affected by the surface material. Then, in this study, the aluminum which corresponded to the material of the small type engine piston was used as the impingement wall surface material. The surface roughness of the wall was approximately 1.6 μm. The diameters D_d of impingement disk was 30 mm. There was no flat disk impingement in a practical cavity of diesel engine, however, flat wall impingement could be considered to appear as the fundamental behavior of wall impingement, and it was also a simple case for phenomenological analysis.

Table 1: Main experimental conditions

Injector	Nozzle type	Single hole nozzle / common rail injection						
	Diameter of nozzle hole D_n mm	0.17						
Injection liquid	Fuel oil	Diesel fuel (JIS No.2)						
	Density at 300K ρ_l kg/m^3	828						
	Surface tension σ kg/s^2	0.0278						
	Viscosity μ_l g/mm-s	3.1×10^{-3}						
Injection condition	Injection period τ_{inj} msec	3.2						
	Injection pressure P_{inj} MPa	40	80	100	120	130	150	170
	Injection mass m_{inj} mg (P_a = 0.1 MPa)	18.2	24.5	26.8	28.7	29.6	31.5	32.8
Ambient condition	Temperature T_a K	300						
	Pressure P_a MPa	1			2		4	
	Density ρ_a kg/m^3	11.6			23.2		46.4	
	Viscosity μ_a g/mm-s	1.8×10^{-5}						
Impingement condition	Impingement distance L_w mm	30, 50, 70, 90						
	Impingement disk diameter D_d mm	30						
	Impingement disk area A_d mm^2	707						
	Impingement disk surface roughness RA µm	Approx. 1.6						
	Impingement disk material	A 5056						

2.4 Experimental Procedure

The measurement procedure of adhering fuel mass is illustrated in Figure 3. The mass of dry impingement disk was measured before fuel injection. Then, the impingement disk was set normally to the injector. After spray was impinged on the disk, the disk was removed from the high pressure vessel and adhered fuel mass was measured together with the mass of disk by using a precision balance with sensitivity of 0.01 mg.

Adhered fuel mass m_{adh} was derived by the difference of the disk masses before and after impingement as shown in Equation (1). Adhering mass ratio αadh was defined as Equation (2). Adhered fuel mass was sampled three times or more in each experimental condition, and then an average of them was taken. The total mass of injected fuel was measured using the small bottle with tissues inside it in order to capture the injected fuel. It was measured with a little effect of ambient density. Similar measurement procedure is as shown in Fig. 4 but was replaced by the small bottle. The total mass of injected fuel was measured for each injection pressure condition and was sampled more than 5 times, and then the average of them was taken. The data error range for both measurements were observed less than 8%.

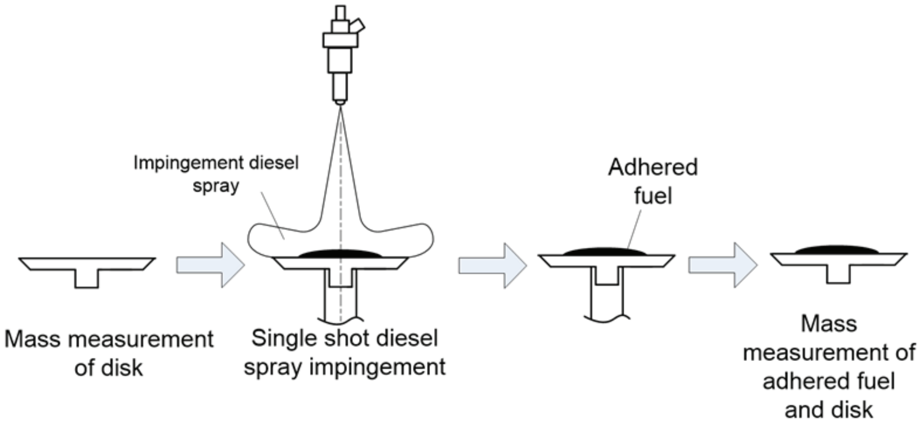

Figure 3: Measurement procedure

m_{adh} =
[Mass of the disk after spray impingement] – [Mass of the dry disk] (1)

$\alpha_{adh} = m_{adh}$ / [Total mass of injected fuel] (2)

3.0 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Basic performance of the single hole injector

(1) Injection mass of fuel

Figure 4 shows the relationship of injection mass of fuel and the injection pressure under injection period of 1.5 msec and 3.2 msec [33]. For both injection periods, the injection fuel mass increased by an increase of injection pressure. The injection fuel mass of 3.2 msec-spray increased steeper than 1.5 msec-spray. However, the same trend of increment of injection fuel mass which was proportional to square root of pressure difference ($〖(P_{inj}-P_a)〗$ ^0.5) between injection pressure and ambient pressure was maintained. Owing to the high ambient pressure, the injection fuel mass in high ambient pressure condition (P_a = 4 MPa) was slightly lower than that in 1 MPa condition. Injection mass was proportional to the period of injection duration.

Hence, the other evidence of steady state injection was continued and injection rate did not change. The total mass of injected fuel changed with injection and surrounding pressures.

As for fuel adhering phenomena in a real engine, only a single shot impingement occurred at every engine cycle. Sometimes, two and three injections happened when a pilot or a split injection was adopted. In this study, as a fundamental study of adhering fuel research, the single shot case was used for the main study of fuel adherance.

(2) Spray tip velocity and D_{SMD} from injection rate

Figure 5 shows the spray tip velocity at various injection pressure from 40 MPa to 170 MPa and ambient pressure of 1 MPa. The spray tip velocity was calculated based on the spray penetration of the free spray which was measured from the shadow graph images. The results showed the spray velocity decreased with the increase of axis distance which was the distance from the nozzle tip to the impingement wall. Moreover, the spray velocity decreased with the decrease of injection pressure. In this study, this kind of result was used to estimate the impingement velocities at various impingement distances.

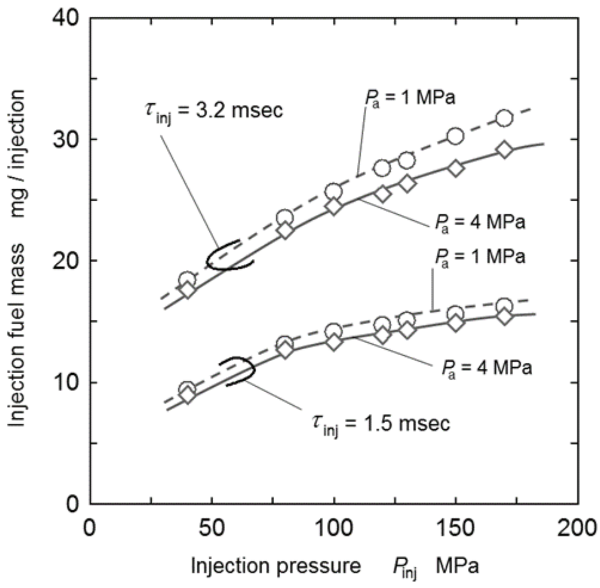

Figure 4: Injection mass of fuel [32]

Figure 6 shows the calculated Sauter mean diameter at various ambient pressures and injection pressures. Almost all the obtained D_{SMD} was the under high speed regime. The Sauter mean diameter (D_{SMD}) of spray was derived from the typical empirical equations of diesel spray [2], except low injection pressure with low ambient pressure.

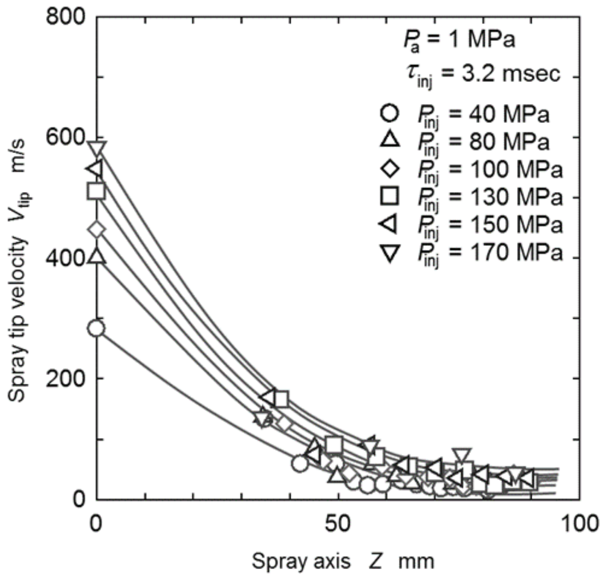

Figure 5: Spray tip velocity

The results showed the D_{SMD} decreased with the increase of injection pressure regardless of ambient pressure. The decreasing trends were almost similar for all ambient pressures cases. The D_{SMD} obtained larger value at ambient pressure of 4 MPa, while lower at ambient pressure of 0.1 MPa. As the ambient pressure increased, the spray velocity decreased and resulted in the increase of droplet size. In addition, when at high ambient pressure, coalescence of droplets due to small penetration of spray resulted in large droplet size. The similar results were also obtained by Hiroyasu et al. [4].

3.2 Impingement distance and adhered mass ratio

Akop et al. [32] showed two different trends on the fuel adherence namely as 'A' and 'B' trends. The 'A' trend shows the tendency for adhered mass ratio to increase with an increase of impingement distance regardless of injection pressure. In other words, fuel adhering by 'A' mechanism was not significantly dependent on injection pressure. Re-bound of spray droplets and splash of adhered fuel were considered as the main mechanism of less adhering fuel. Furthermore, short impingement distances such as L_w = 30 mm have stronger influences on less adherence than injection pressure. In the 'B' trend, adhered mass ratio tended to decrease with an increase of impingement distance. Owing to the slow velocity of long spray penetration, spray droplets moved with the entrained gas stream and less adherence was formed with a greater increase of impingement distance. Furthermore, these results could be discussed by impingement velocity effect.

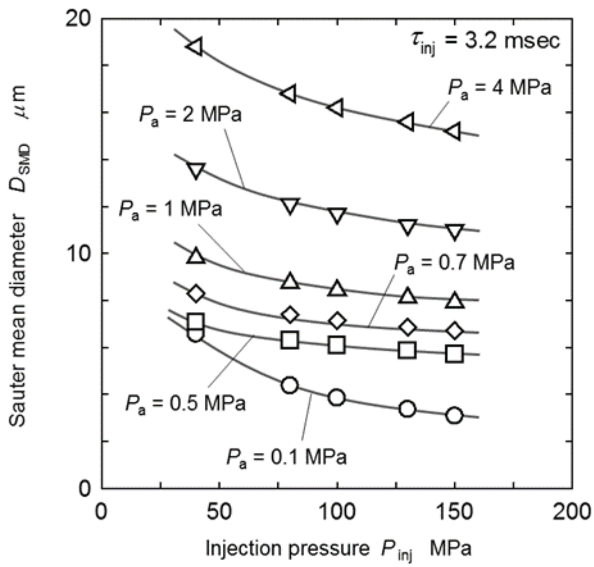

Figure 6: Calculated Sauter mean diameter

3.3 Impingement velocity effect

From the results of Akop et al. [32], it might be suggested that the 'A' trend shows a velocity domain dependence, while the 'B' trend might depend on the lower value than a critical velocity of velocity dependance domain. Figure 7 shows another expression of the results shown from Akop et al. [32]. Impingement velocity was selected as the main parameter of the phenomena. Injection velocity was set by injection pressure whereas impingement velocity was dominated by injection pressure and impingement distance. Then, this velocity had direct effect on impingement phenomena and it was the reason why it was selected as the main parameter. This classification is clearly shown in Figure 7. Critical velocity which divided ‘A’ and ‘B’ trends was at around 40 m/s. Even though critical velocity was one of the dominant parameters that affected adhered fuel mass, it was insufficient to explain the overall phenomena. There are some complicated trend as shown in Figure 7. For example, at the velocity of 40 m/s, trends of ‘A’ and ‘B’ were weird. Even though same impingement velocities were used, adhered mass ratios showed different behavior according to injection pressure and impingement distance. The complicated trend was with regard to another controlling factor of changing of adhered mass ratio. The factor of critical velocity alone was not enough to justify the mechanism change of adhered mass ratio. It might be the effect of droplet diameter and others.

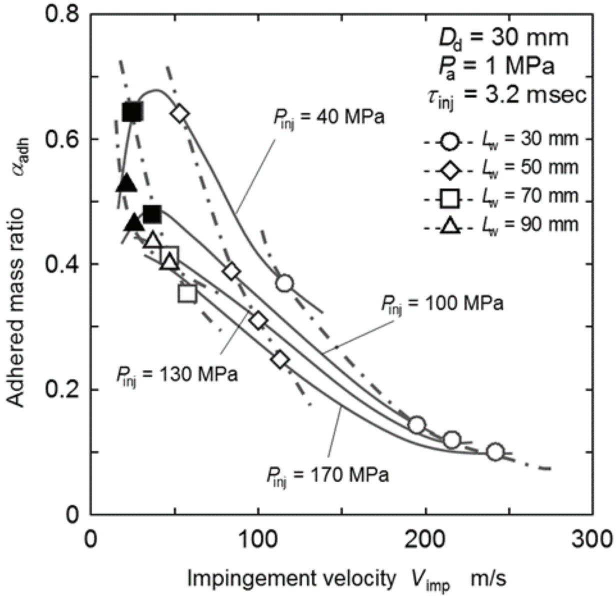

Figure 7: Relationship between adhered mass ratio and impingement velocity

4.0 CONCLUSIONS

The impinging diesel spray for non-evaporation condition is analyzed for the fundamental study of adhering fuel on the wall. The investigation in this study involves a single hole injection system for the whole experiment as to simplify the measurement works. Many parameters have been considered in this study such as impingement distance, injection pressure and also the ambient pressure. As the spray impinges on the dry surface wall, the adhered fuel mass is measured as the main parameter in this study. Then adhered mass ratio is analyzed.

In order to clarify the fundamental of spray impingement, the effect of injection pressure and impingement distance on the adhering mass ratio are analyzed quantitatively. Various injection pressures and impingement distances are considered. The effect of injection pressure and impingement distance on the wall area are also discussed.

As the results, at a low injection pressure such as 40 MPa, the adhered fuel mass obviously obtained higher in all impingement distances. The adhered mass ratio was inversely proportional to injection pressure. Also, at a short impingement distance such as 30 mm, the adhered fuel mass was unaffected by ambient pressure, because spray impinging at this distance has sufficient velocity to splash fuel film and to reduce adherance. While, at a long impingement distance such as 70 mm, a decrease of adhered fuel mass was clearly observed. Adhered fuel mass ratio has the potential to decline after reaching its peak when impingement velocity decreased beyond a critical velocity.

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