

Optical Diagnostics for Splash Behavior of Fuel Liquid Film on a Wall with Induction by Airflow

R. Kobayashi¹, R. Kushida¹, Y. Zama^{1,*}

1: Division of Mechanical Science and Technology, Gunma University, Japan

* Correspondent author: yzama@gunma-u.ac.jp

Keywords: Liquid film, Droplets, LIF, PIV, PFI engine

ABSTRACT

Reducing particulate number (PN) and unburned hydrocarbon (HC) emissions in port fuel injection (PFI) engines is an urgent priority. In these engines, fuel spray impacts the intake valve and forms a liquid film. During the intake stroke, fuel droplets shed from the fuel film is generated and goes into the combustion chamber. There is a possibility that the entry of shed droplets into the combustion chamber leads to the formation of locally fuel-rich zone, thereby affecting exhaust emission. Therefore, it is necessary to understand the droplet shedding mechanism of the liquid film on the intake valve in order to consider the strategy for the reducing exhaust emissions. Test channel simulating an intake port of PFI engine was utilized in this study, and a quartz glass plate simulated intake valve was installed in the channel to provide optical access. The test fuel ejected from a PFI injector impinged on the glass plate, and the behavior of the liquid film formed on the plate was observed. The various optical diagnostics techniques, including shadow imaging, laser-induced fluorescence (LIF) and particle image velocimetry (PIV), were applied to capture the droplet shedding process from the liquid film on the glass plate. Consequently, the effect of intake airflow velocity in the valve gap on the shedding process was investigated in this study, and the airflow velocities in the valve gap (V_g) were set to 40, 60, and 80 m/s. As the results obtained in this study, airflow separation occurred at the boundary between the valve face and the contact surface on the simulating intake valve, and the liquid film stagnated within separation zone formed on the contact surface. The maximum thickness of the fuel film formed on the contact surface of valve seat increased with increasing the airflow velocity in the valve gap. Moreover, it was found that the generation of the coarse droplets more than 100 μm , and the maximum diameter of droplets shed from the liquid film decreased with increasing the airflow velocity. However, the observed droplet diameter was more than twice as large as the spray droplet diameter generated by PFI injector, suggesting that the droplet shed from the liquid film on the intake valve could have a detrimental effect on exhaust emissions.

1. Introduction

Reducing particulate number (PN) and unburned hydrocarbon (HC) emissions in spark-ignition engines has become an urgent priority. PN emissions were primarily considered a major issue for direct-injection (DI) engines. However, as highlighted by Bonatesta et al., PFI engines also generate significant particulate matter. Because fuel wall-wetting leads to the entry of large sized droplets

into the cylinder. These droplets create locally fuel-rich zones that cause incomplete combustion. Emission regulations, such as the Euro 6/7 standards and Real Driving Emissions (RDE) testing frameworks, are becoming increasingly strict. Consequently, reduction of these emissions has emerged as a critical issue.

Currently, PFI systems are widely adopted in engines such as mini-sized vehicles due to their cost-effectiveness, high fuel consumption efficiency and ability to form a homogeneous air-fuel mixture. During the intake stroke, the injected fuel spray impacts on the intake port walls and the back of the intake valve, forming a liquid fuel film. Subsequently, droplets were detached from the liquid film formed on the valve by the high-velocity intake airflow. The large fuel droplets are generated by this process, and these droplets enter the combustion chamber, resulting in a negative effect on fuel atomization. Consequently, HC and PN emissions increase.

To reduce these emissions, it is important to understand the behavior of liquid fuel in the vicinity of the intake valve. As mentioned above, Shin et al. investigated the complex fuel flow around the intake valve and categorized the mechanisms into direct inflow, backflow, and wall adhesion. They revealed that closed-valve injection resulted in substantial fuel accumulation on the valve surface, whereas open-valve injection increased direct inflow of fuel but also led to significant wall impingement depending on the spray angle. Consequently, the liquid fuel film is formed on the intake valve by the impingement, and the liquid film is atomized by interaction of the intake airflow.

Koederitz et al. investigated the break-up mechanism of liquid films on the intake port and valve surface. Their study demonstrated that aerodynamic stripping was the dominant factor determining the size of droplets entering the cylinder. They found that at high intake port air velocities, the shear forces overcome the surface tension of the fuel film. The interaction between the air flow and the liquid film generates secondary droplets, typically ranging from 20 to 50 μm , which are strongly dependent on the instantaneous valve lift.

An optical diagnostic method is the promising way to clarify droplet formation from the liquid film. Winklhofer et al. developed the application of the laser-induced fluorescence (LIF) method to establish a non-intrusive technique for measuring fuel film thickness in the intake port. They demonstrated that the liquid film behavior is highly sensitive to wall temperature and intake flow conditions. Moreover, they reported that shear force induced by intake airflow enhances the instability of the film surface and generates the interfacial wave. As a result, the advection of the liquid film is driven by the shear force, and most of the fuel is carried into the combustion chamber. Also, Almkvist et al. employed the LIF method to visualize the spatial distribution of the film on the intake port wall and provided quantitative data on how the liquid film is dynamically sheared by the intake airflow. Their results captured the transient accumulation of the liquid film near the

valve seat region during the intake stroke. The localized film thickness drastically fluctuates within a single engine cycle in response to the instantaneous intake air velocity. Furthermore, to evaluate fuel behavior in more practical environments, Hentschel et al. developed a compact spectroscopic probe to directly measure the wall film thickness in the intake manifold of a standard production SI engine. Their real-time probe data explicitly demonstrated that during transient engine operations, such as rapid acceleration, the wall film thickness increases significantly and causes severe fuel pooling. As a result, this leads to temporary air-fuel ratio excursions and delayed fuel transport compared to steady-state conditions.

In our previous studies, Furuta et al. elucidated the fundamental characteristics of fuel film on intake port and valve face, where the fuel film was visualized using a simplified rectangular channel equipped with a quartz glass wall to simulate the intake valve. The results revealed that a fuel film was formed on the valve contact surface, and large droplets shed from the film subsequently flowed into the combustion chamber. However, as so far, few studies focus on the contact surface of the intake valve seat. And the mechanism governing the droplet shedding and the influence of airflow velocity through the valve clearance has not yet been fully stated.

Therefore, the purpose of this study is to experimentally investigate the effect of airflow velocity on the advection and shedding behavior of the fuel liquid film deposited on the valve face of intake valve. An optical test channel simulating the geometry of the intake port was utilized in this study. To clarify the fundamental mechanisms of fuel film advection and droplet shedding, the various techniques of the optical diagnostics, including shadow imaging, LIF and PIV, were applied. The droplet shedding mechanism of the liquid film is discussed based on the observations of the liquid film behavior, measurements of the film thickness and analysis of flow field around the valve.

2. Experimental setup and condition

The test channel shown in Fig. 1(a) simulates intake pipe and valve of PFI gasoline engine for mini-sized vehicle. The channel has square cross-section with dimensions of 30 mm $\times$ 30 mm. Figure 1(b) shows the layout of a quartz glass plate simulating the shape of an intake valve. It is 3 mm thick and has a 45° seat angle. The valve is placed inside channel at an inclination angle of 60° with respect to horizontal direction, and the valve gap between the bottom wall and the contact surface is 5 mm. To provide optical access for visualization, the channel is enclosed using transparent acrylic for the side and top walls and quartz glass for the bottom wall. A honeycomb straightener is installed at the inlet of the test channel to generate a uniform inlet flow. The intake airflow is generated by a suction pump, which is regulated to maintain a constant differential pressure between the upstream and downstream sections of the channel. The fuel injector is

mounted at an angle of 20° relative to the horizontal direction, at a distance of 70 mm from the valve wall. The test fuel is pressurized with nitrogen gas and injected into the test section.

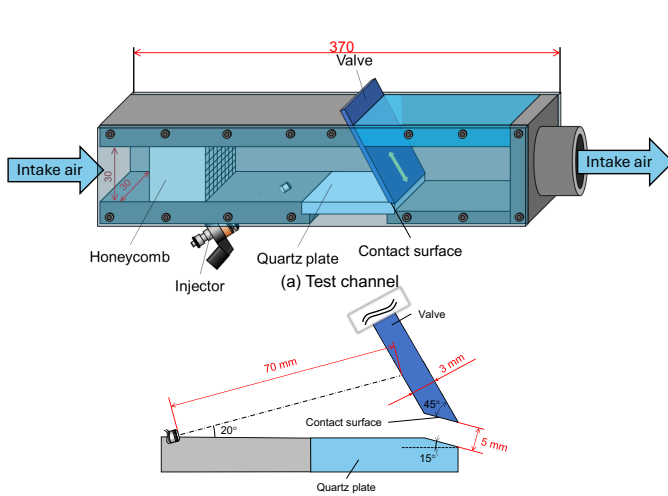


Figure.1 Test channel and test valve of intake port

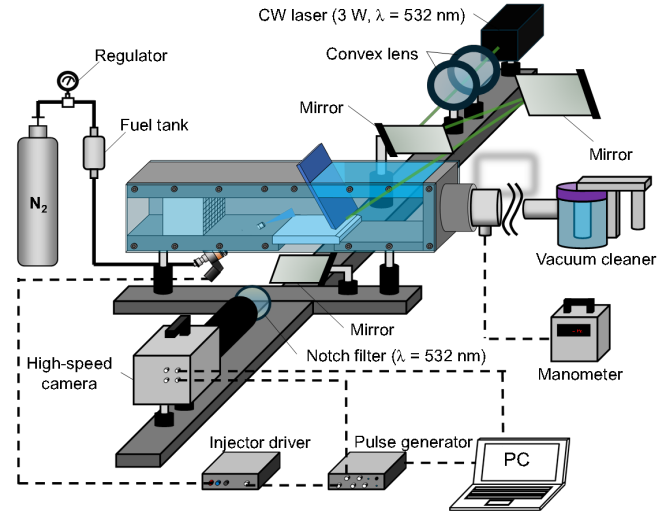


Figure.2 Experimental apparatus for measurement of liquid film thickness

As finding previous our study, droplets shed from the liquid film formed on the contact surface of valve seat. The generation of droplets from liquid film seems to be related to thickness of the liquid film, and liquid film thickness on the contact surface was measured using the LIF technique. Figure 2 shows the schematic of the experimental setup for the liquid film thickness measurement. It consists of the test channel, fuel injection system, and optical imaging system. A high-speed camera (MEMRICAM ACS-1 M60) captured the liquid film from bottom of the channel via an optical mirror. A CW laser (wavelength: 532 nm, output: 3W) was used as the light source. The laser beam was expanded to a diameter of 5 mm via a convex lens and incident normal to the contact surface from the top of the channel. The test fuel was mixture of iso-octane with an ethanol solution containing 80 mg/L of Rhodamine B at the volume ratio of 9:1 in order to apply LIF technique. Ethanol was used as a solvent of Rhodamine B. The frame rate of the camera was set to 10,000 f.p.s. and the exposure time was $99.5 \mu\text{s}$. Airflow velocity through the valve gap V_g was set to 40, 60 and 80 m/s (corresponding to differential pressure between the upstream and downstream sides of the test channel $\Delta P = 2.1, 4.8$, and 8.4 kPa). The injection pressure was $P_{\text{inj}} = 300 \text{ kPa}$, and the injection duration was determined as $\tau_{\text{inj}} = 10 \text{ ms}$. The experiments were conducted at room temperature based on the assumption of a cold start engine operation status.

Since the droplet shedding is predominantly driven by aerodynamic shear forces at the valve gap, understanding the detailed flow structure is crucial. Therefore, particle image velocimetry (PIV) was employed to measure the velocity field around the intake valve. Figure 3 shows the experimental setup for measuring the velocity field of the airflow around the intake valve. Particle images around the valve were captured from side of the test channel using a CCD camera with

frame-straddling function (pixelfly usb, PCO). The camera was synchronized with a double-pulsed Nd:YAG laser (wavelength: 532 nm) via a pulse generator. A laser light sheet with a width of 30 mm was formed by a cylindrical lens, and its thickness was less than 1 mm. The measurement area was illuminated by the laser-light sheet from top of the channel. Oil mists were introduced from upstream of the channel as tracer particles.

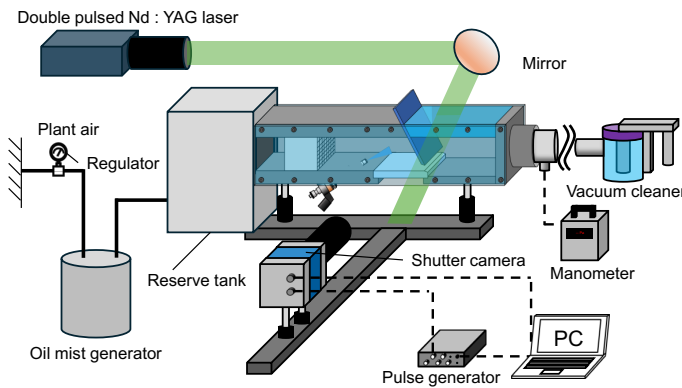


Figure.3 Experimental apparatus for measurement of flow velocity in valve lift gap

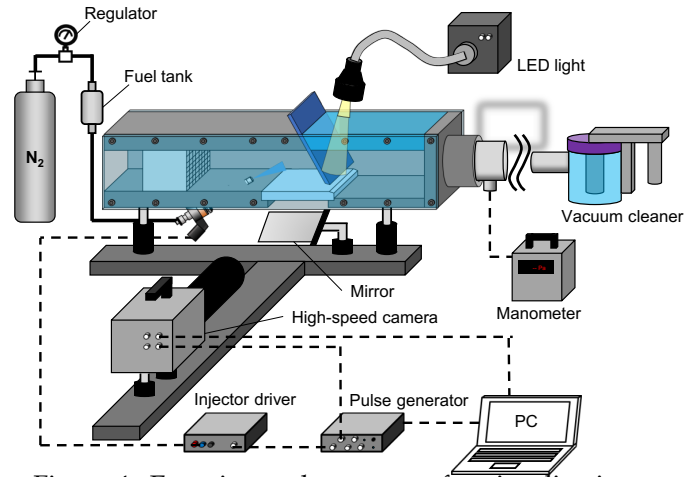


Figure.4 Experimental apparatus for visualization of contact surface liquid film and measurement of droplet diameter

The shadow imaging technique was employed to visualize the liquid film behavior on the contact surface of valve seat and to measure the diameters of the shedding droplets. Figure 4 shows the experimental apparatus for the shadow imaging. The apparatus was the same as that used for the LIF measurement except for the imaging optical system. A high-bright LED (UFLS-751-08W-UT, U-Technology Co. Ltd.) was utilized as the light source, and the liquid film was illuminated by the LED from the top side of the channel. The frame rate of the camera for liquid film visualization was 50,000 f.p.s., and the frame rate of 100,000 f.p.s. was adapted for droplets size measurement. The exposure time was fixed at $0.4 \mu\text{s}$.

3. Experimental Result and discussion

Liquid Film Thickness on Contact Surface of Valve Seat

As observed in the shadow imaging from our previous study, the fuel film on a valve face was advected by the intake air flow and accumulated on the contact surface of valve seat. Based on this finding, the observation area in the present study was specifically targeted at this contact surface to investigate the accumulation and shedding processes.

Figure 5 shows the LIF measurement results at the instant when the maximum liquid film thickness was observed for each airflow velocity. Here, the liquid film thickness was evaluated

within a localized central area of the valve seat contact surface due to the limited illumination area of the light source. Figure 6 shows the time evolution of the maximum liquid film thickness within the localized central area for various airflow velocities. The maximum thickness at each instant was obtained from the peak value of the film thickness averaged over five experiments.

The maximum film thickness increases with the increase of airflow velocity, and higher velocities lead to a thicker film accumulated on the contact surface as shown in Fig.6. This is because the higher intake flow velocity accelerates the advection of the fuel film from the upstream valve face, resulting in an increase of fuel mass flow rate. This increase in flow rate contributes to the rate of increase in the liquid film thickness. Moreover, the time required to reach the peak thickness decreases as airflow velocity increases. This is because the increased airflow accelerates the rate of fuel transport from the valve face to the contact surface of the the valve seat. After, after reaching its peak, the maximum thickness of liquid film decreased regardless of airflow velocity, and the decreased thickness became more pronounced as the airflow velocity increased. Here, in our previous study, the liquid film accumulated on the contact surface of the valve seat, and the droplets were generated from the liquid film. Therefore, the droplet generation is considered to be one of the primary factors contributing to the decrease in film thickness. Moreover, shear force between the airflow and the liquid surface increases with increasing the velocity of the airflow, and the rate of film thickness reduction is accelerated by the increase of the amount of fuel blown-off by the airflow.

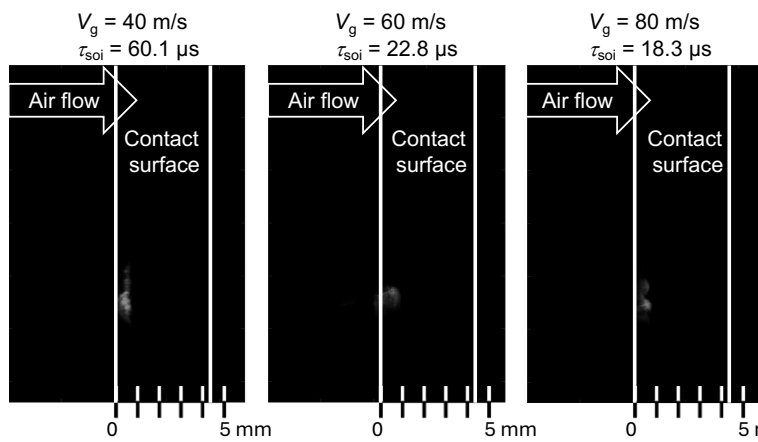


Figure.5 Liquid film thickness at contact surface for each flow velocity

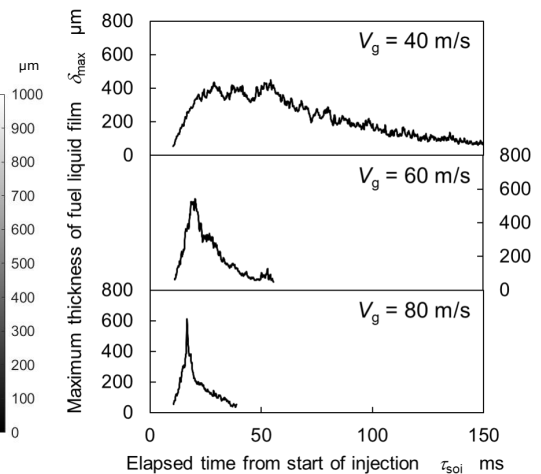


Figure.6 Time history of maximum thickness of liquid film on adhesion area

Airflow Velocity Field Around the Valve

The differences in film thickness on the contact surface among airflow velocities seem to be caused by changes in the flow field around the valve. Therefore, PIV measurements were conducted to measure the velocity field at various airflow velocities in the valve gap. The mean

velocity fields in the gap at $V_g = 40$ m/s and 80 m/s are shown in Fig. 7(a) and (b), respectively. In the figures there are no velocity vectors near the valve tip and below the valve surface due to insufficient laser illumination. Therefore, these regions were not considered in the present study because the focus of the study is the fuel films formed on the upstream of the contact surface.

Within the measurement region, the velocity fields under all airflow velocities show that flow separation occurs near the edge between the valve face and the contact surface of the valve seat (hereinafter referred to "the edge"), and separation zone upstream of the contact surface is formed as shown with hatched area of Fig. 7. Here, the streamline closest to the contact surface is defined as boundary between the main flow and the separation zone, and the maximum distance from the contact surface to main flow was measured to determine the height of the separation zone.

As shown in Figure 8, the distances from the contact surface of the valve seat to the boundary increases with increasing airflow velocity. This is because the inertia of the airflow increases with increasing the airflow velocity, resulting in an increase in the distance between separation and reattachment points and expansion of the separation zone.

Therefore, fuel advected from the valve face accumulates within the separation zone on the contact surface. Because a higher airflow velocity expands the separation zone, a larger volume of liquid can accumulate, leading to a greater film thickness before it reaches into the main airflow. Moreover, continuous fuel inflow to the contact surface increases the film thickness, and its surface contacts the main flow of the intake air. Then the fuel film is shed by shear force between liquid film and air flow, forming droplets.

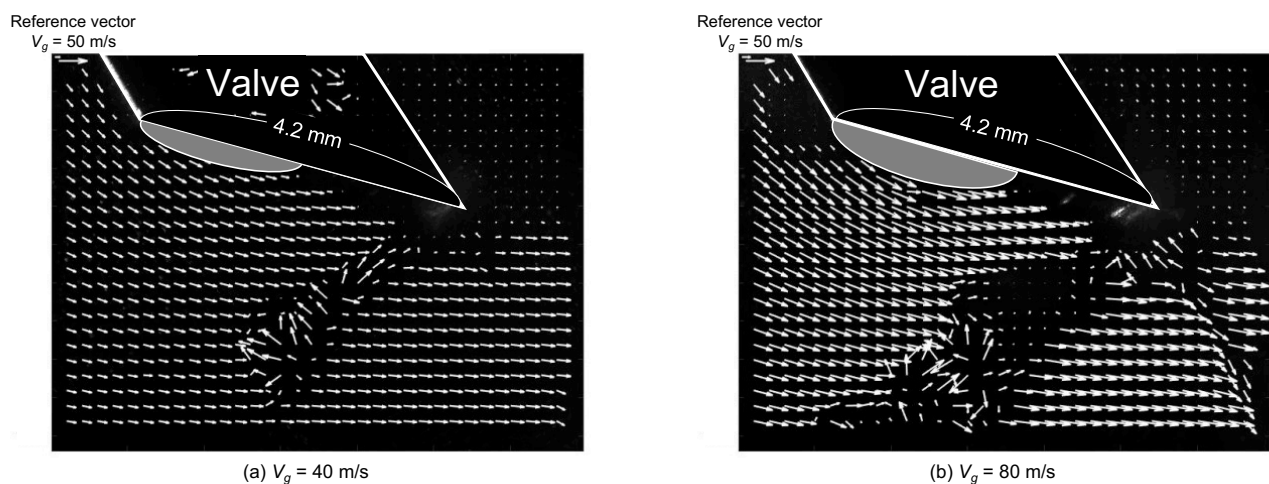


Figure. 7 Velocity distributions of airflow in the valve lift gap

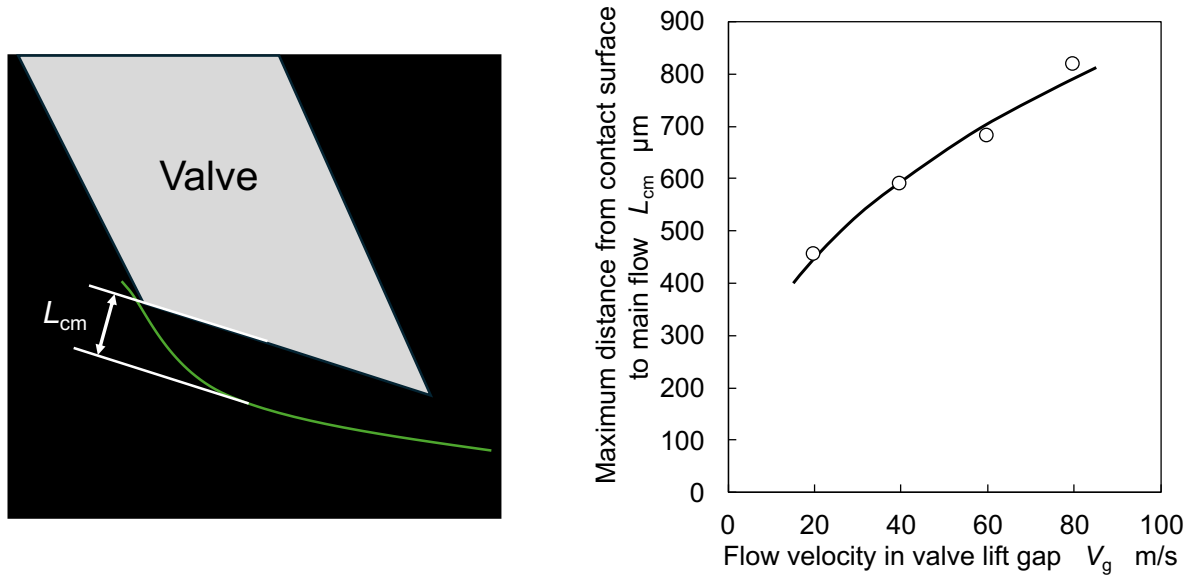


Figure.8 Relationship between flow velocity in valve lift gap and maximum distance from contact surface to main flow

Visualization of Liquid Film on Contact Surface of Valve Seat

To visually confirm the influence of the airflow velocity field on the liquid film dynamics, visualization of the liquid film on the contact surface of valve seat is conducted to compare its temporal thickness variation with its mechanism of liquid film formation. The upper part of Fig. 9 shows the time evolution of maximum film thickness at $V_g = 80 \text{ m/s}$, and the film appearance at three essential instants, which are Fig.9 (a) peak thickness formation, Fig.9 (b) thickness decreases and Fig.9 (c) droplet shedding. The horizontal axis on the image is the distance from the edge.

In Fig. 9 (a), an accumulation of the liquid film is observed near the edge. In Fig.9 (b), the film spreads further downstream than in Fig.9 (a), likely driven by fuel advected from the valve face. In Fig.9 (c), the film extends even further downstream, and droplets are shed from the film tip. This was caused by the interaction between the airflow and the liquid film. As the liquid film tip extends beyond the flow separation zone and directly touches the high-speed main airflow, the sudden increase in shear stress destabilizes the film tip and promotes the droplets formation.

Figure 10 shows the distance from the edge to the liquid film tip versus the velocity of the airflow in the gap. This distance is at the moment of the shedding of the liquid film tip. The distance decreases with increasing airflow velocity. This trend seems to be attributed to the increased shear stress between the airflow and the liquid film at higher airflow velocities, which causes droplet shedding from the leading edge of liquid film before the film can significantly extend downstream.

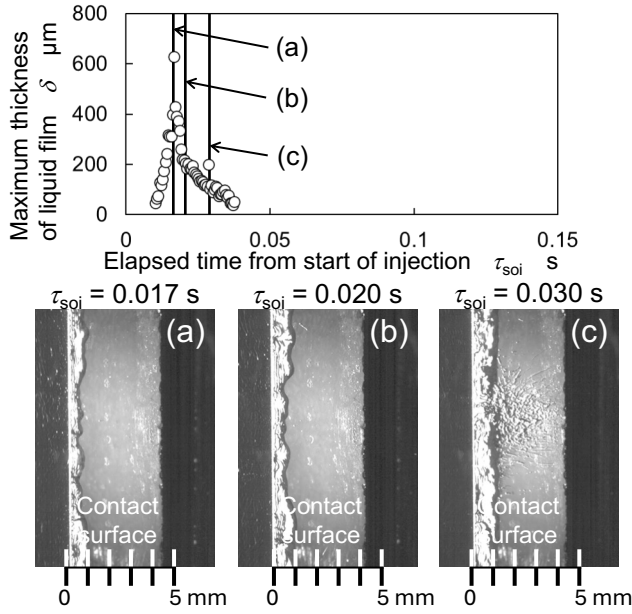


Figure.9 Behavior of adhere liquid film on a contact surface of a valve seat $V_g = 80$ m/s

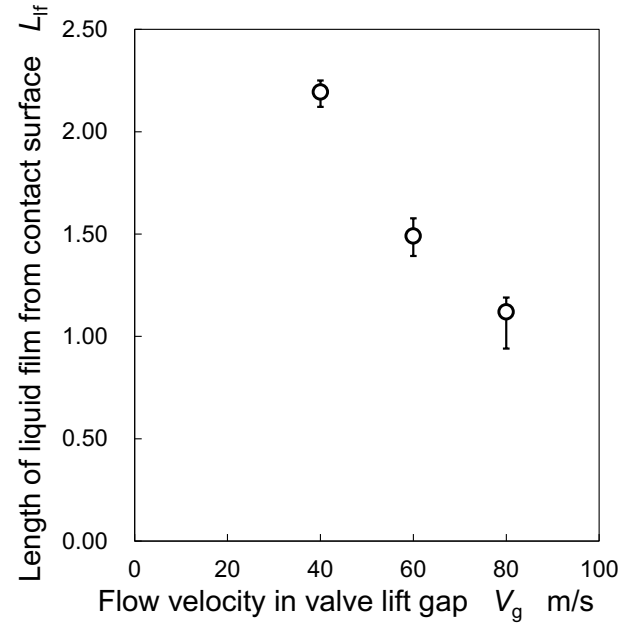


Figure.10 Relationship between flow velocity in valve lift gap and length of liquid film from contact surface

Measurement of Droplet Diameter Shed from Liquid Film

In the previous section, it was confirmed that droplets shed from the liquid film formed on the contact surface of valve seat. The diameters of the droplets shed from the liquid film on the contact surface of valve seat were evaluated by using shadow image of the droplets. Figure 11 shows the observation area of droplet size measurement and the image of individual droplet-shed from the contact surface. Regardless of the airflow velocity in the gap, 2,000 droplets were randomly sampled from the captured images by using image processing, and the area-equivalent diameter of individual droplet was evaluated.

Since larger droplet affects combustion by causing local rich zones and soot formation, the maximum droplet diameter d_{max} was extracted from droplet size data obtained from the shadow images.

Figure 12 shows the maximum droplet diameter d_{max} with respect to velocity on intake air in the gap. The maximum droplet diameter d_{max} decreases due to the promotion of liquid atomization as the airflow velocity increases. Nevertheless, even at high airflow velocity $V_g = 80$ m/s, the maximum droplet diameter remained as large as $d_{max} = 138$ μ m. Considering that the Sauter mean diameter (SMD) of the fuel spray droplets for PFI was 60 μ m, the maximum diameter of the shaded droplets observed in this study are more than twice as large. These results indicate that droplets generated from the liquid film on the contact surface were significantly larger than the fuel spray ejected from the injector under the tested airflow conditions. Consequently, the entry of such large fuel droplets into the combustion chamber is considered to deteriorate combustion.

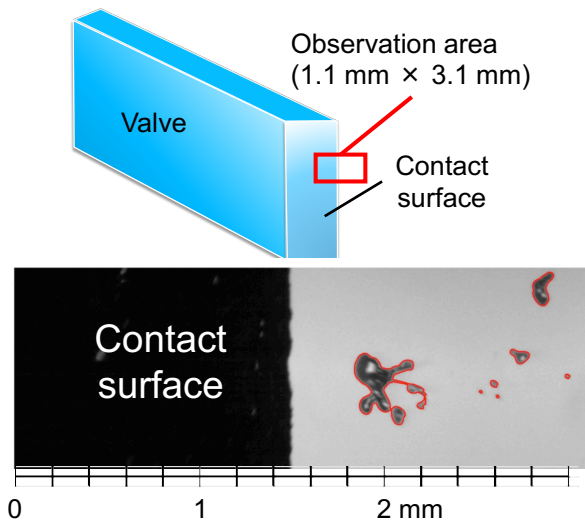


Figure.11 Observation area for droplet diameter measurement and image of droplets-shed from the liquid film $V_g = 80$ m/s

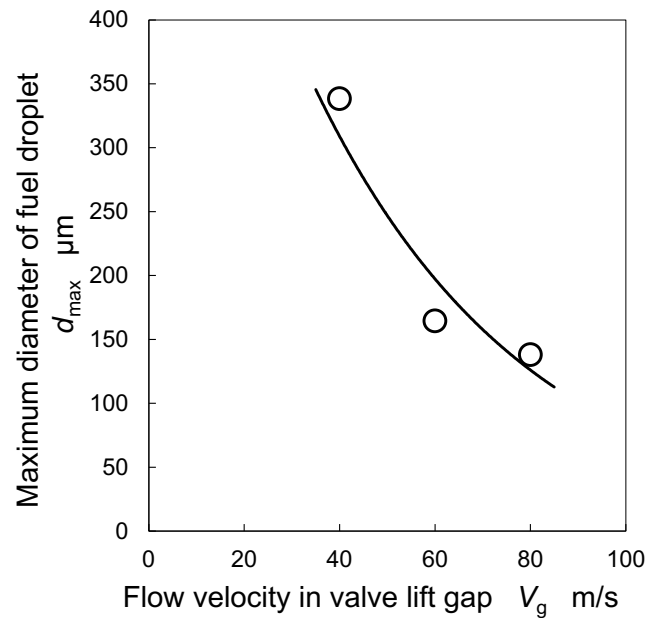


Figure.12 Relationship between flow velocity in valve lift gap and maximum diameter of fuel droplet

4. Conclusions

In this study, the effects of airflow velocity on the behavior of the fuel film adhered on the contact surface of valve seat is investigated. Insights of this study are as follows.

- (1) As the airflow velocity through the valve clearance increases, the maximum thickness of the fuel film formed on the contact surface of valve seat increases, and the time required to reach this maximum thickness reduced.
- (2) Airflow separation occurred at the boundary between the valve face and the contact surface, and the liquid film stagnates within separation zone formed on the contact surface.
- (3) As the air velocity increases, the maximum diameter of droplets shed from the liquid film decreases. However, the observed droplet diameter was more than twice as large as the spray droplet diameter generated by PFI injector, suggesting that the droplet shed from the liquid film on the intake valve could have a detrimental effect on exhaust emissions.

Acknowledgments

This paper is obtained as a result of a grant project (JPNP21014) conducted by The Research association of Automotive Internal Combustion Engines (AICE) with support from the New Energy and Industrial Technology Development Organization (NEDO).

References

Almkvist, G., Denbratt, I., Josefsson, G., and Magnusson, I., "Measurements of Fuel Film Thickness in the Inlet Port of an S.I. Engine by Laser Induced Fluorescence," SAE Technical Paper 952483, 1995.

Bonatesta, F., Chiappetta, E., and La Villetta, M., "Particulate Matter Emissions from a Port Fuel Injection Spark Ignition Engine," SAE International Journal of Fuels and Lubricants, 7(1):15-26, 2014.

Furuta, K. and Zama, Y., "Blow-off behavior of fuel liquid film adhering on an intake valve by port injection," 21st ILASS-Asia 2023, Jeju, Korea, 2023.

Hentschel, W., Grote, A., and Langer, O., "Measurement of wall film thickness in the intake manifold of standard production SI engine by spectroscopic technique," SAE Technical Paper 972832, 1997.

Koederitz, K. R., Evers, M. R., Wilkinson, G. B., and Drallmeier, J. A., "Break-up of liquid fuel films from the surfaces of the intake port and valve in port-fuel-injected engines," International Journal of Engine Research, 3(1):37-58, 2002.

Shin, Y., Cheng, W. K., and Heywood, J. B., "Liquid Fuel Transport Mechanisms Into the Cylinder of a Firing Port-Injected SI Engine During Warm Up," SAE Technical Paper 941876, 1994.

Winklhofer, E., Plimon, A., Fraidl, G. K., and Winklhofer, E., "Measurement of fuel film thickness in the intake port of an S.I. engine by laser induced fluorescence," SAE Technical Paper 922231, 1992.

Yasukawa, Y., Okamoto, Y., Kobayashi, N., and Saito, T., "Multi-Swirl Type Injector for Port Fuel Injection Gasoline Engines," SAE Technical Paper 2014-01-1436, 2014.