Effect of Wavy Structure of Liquid Film on Flow Characteristics of Impingement Jet Flowing on Fuel Liquid Film

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ABSTRACT

In recent years, diesel engines have been downsized in order to improve combustion efficiency by using high-pressure injection to atomize the fuel and to increase fuel economy. As a result, the diesel spray flame inevitably impinges on the combustion chamber wall, resulting in heat loss due to heat transfer between the flame and the wall. According to Newton's cooling law, the heat transferred from the flame to the wall is proportional to the heat transfer coefficient, which is closely related to the flow of the spray flame. However, there are few reports on the flow of a spray flame impinging on a wall. The flow characteristics of a non-vaporized spray impinging on a wall surface, assuming that the flow of a spray flame impinging on a wall surface is equivalent to that of a non-vaporized spray. The fuel film formed on the wall affected on the flow characteristics of the spray. When the spray flame impinges on the wall in the engine cylinder, no liquid film is formed on the wall, but during cold start, a liquid fuel film may form on the piston wall due to the low temperature in the engine cylinder, resulting in HC and soot emissions. As a result, the spray may flow over the formed film. Therefore, it is necessary to investigate the flow characteristics of the spray flowing over the fuel film.

In this study, the experiments using an impingement gas jet were conducted on a wall surface with a fuel film, and the velocity field of the jet after impingement of the wall surface was measured by the time-series PIV. In addition, the thickness of the wavy liquid film formed by the gas jet impingement was measured by using the laser induced fluorescence (LIF) method, and discussed the relationship between the velocity of the jet after wall impingement and the characteristics of the wavy liquid film.

1. 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 increases of 20% to 30% occurred by impingement of the diesel flame on the cavity wall. They suggested that its 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 suppress 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.

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. [11] 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. Benajes et al. [12] 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. A group of authors [13] investigated flow characteristics of a non-evaporated 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. In this report, the relation between the velocities of the spray before and after impingement on a wall was investigated. It was found that the spray velocity after the impingement increased with an increase of the velocity of the spray impinging on the wall, and the its increase rate was not constant and changed. However, the reason why its increase rate of the spray velocity after impingement was changed with the respect to the velocity of the impinging spray was not clarified.

In this study, in order to clarify the factor for change of its increase rate of the spray velocity after impingement, 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.

2. Experimental set-up

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

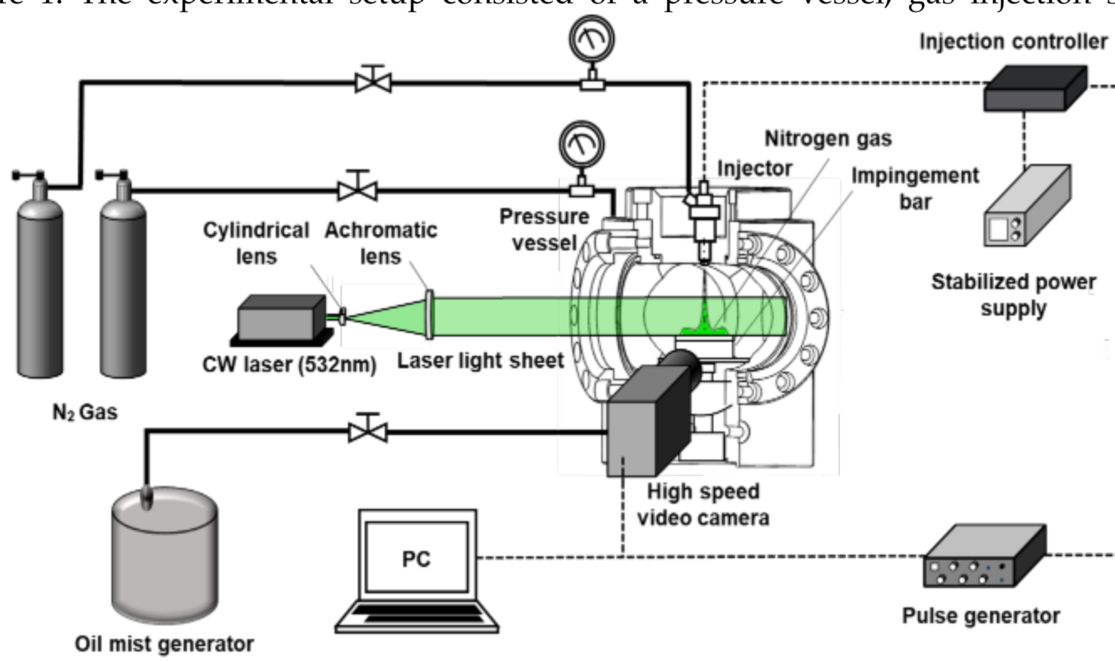

Figure. 1 Experimental set-up for velocity measurement of impingement gas jet

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

Nozzle hole diameter d_0 [mm]	0.130
Ambient gas temperature T_a [K]	300
Ambient gas density ρ_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 θ_d [deg.]	0
Tracer particles	Incense smoke, Oil mist

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 instead of a flat wall 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.

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 do = 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, and Incense smoke or oil mist were used as tracer particles for PIV measurement.

3. Experimental results and discussions

3-1 The effect of the liquid film on a wall on the velocity of gas jet after impingement on a wall

Figure 2 shows the mean velocity distributions of an impinging gas jet on a wall under the condition of injection pressure P_{inj} = 13 MPa and ambient density ρ_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 quasi-steady state were averaged, because the jet behavior around the tip was unsteady flow such as the rolled-up motion. In Figure 2, a solid line shows the height distribution for radial component of the averaged velocity. The maximum velocity obtained from this distribution was defined as $\overline{Upeak}$ and the average of these was defined as $\overline{Upeak}$. In addition, the height indicating $U_{peak/2}$, which is half the value of $\overline{Upeak}$ 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.

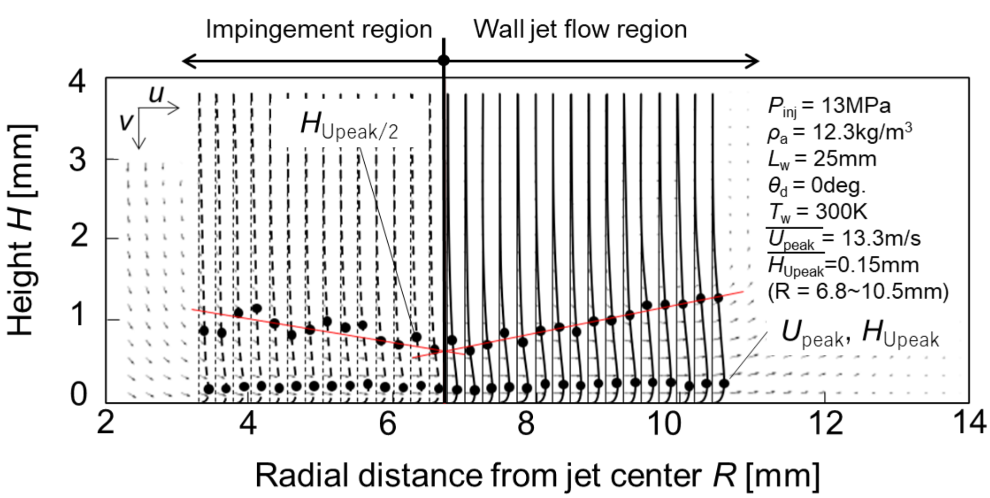

Figure. 2 Averaged velocity field of the gas jet after impingement on a wall

Figure 3 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 tip penetration of the diesel spray or the gas jet.

The spray velocity after the impingement on the wall increased in proportional to the spray velocity before the impingement on the wall as shown by the dotted line in Figure 3, and its increase rate 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 the increase rate in the spray velocity of the impingement spray on the wall, because, the liquid film of diesel fuel was formed by wall impingement during injection of the spray. 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 gas jet was visualized by entraining the tracer particles in the jet in order to measurement of velocity before the impingement on the wall, and the tip velocity of the gas jet was calculated by the sequential shadow image of free gas jet.

The relation of gas jet velocities before and after impingement on the wall was shown with solid line in Figure 3. The gas jet velocity after the impingement increased with an increase of velocity before the impingement even though the increase rate of the diesel spray was not constant. 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

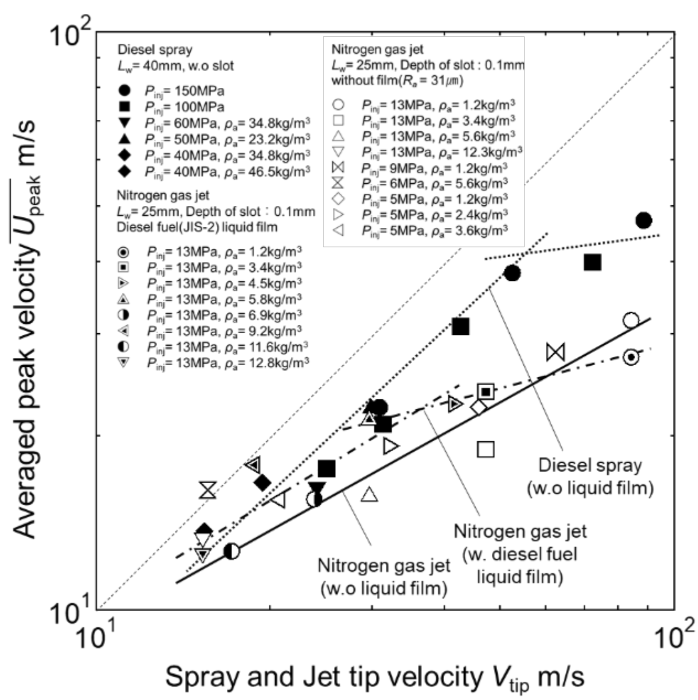

Figure. 3 Relationship between the velocity before and after the impingement on the wall in diesel spray and gas jet

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 advection induced by the flow of gas jet on the liquid film.

3-2 The effect of the surface of liquid film on a wall on the velocity of gas jet after impingement on a wall

In order to clarify the reason why the increase rate of the jet velocity after the impingement on the wall changed, the interface of the liquid film impinging the gas jet was observed as shown in figure 4.

As shown in figure 4 (a), the liquid film was wavy due to impingement of the jet on the liquid film before the change of the increase rate of the jet velocity. On the other hand, after the change of the increase rate of the jet velocity, the wavy of its film surface was more intense as compared with figure 4 (a). In other words, as the velocity of the jet before the impingement on the liquid film increases, the rippling of the liquid film becomes more intense. This result suggests that the jet flow over the liquid film increased resistance from the wavy liquid film interface, and the increase rate of the jet velocity decreased as shown in figure 3.

Based on this result, it is necessary to clarify the wavy structure of the liquid film formed by the jet impingement in order to the effect of the fuel film on the flow characteristics of the jet after wall impingement. Therefore, structure of the wavey surface of the liquid film formed by the jet impingement was investigated by measurement of the liquid film thickness using LIF method.

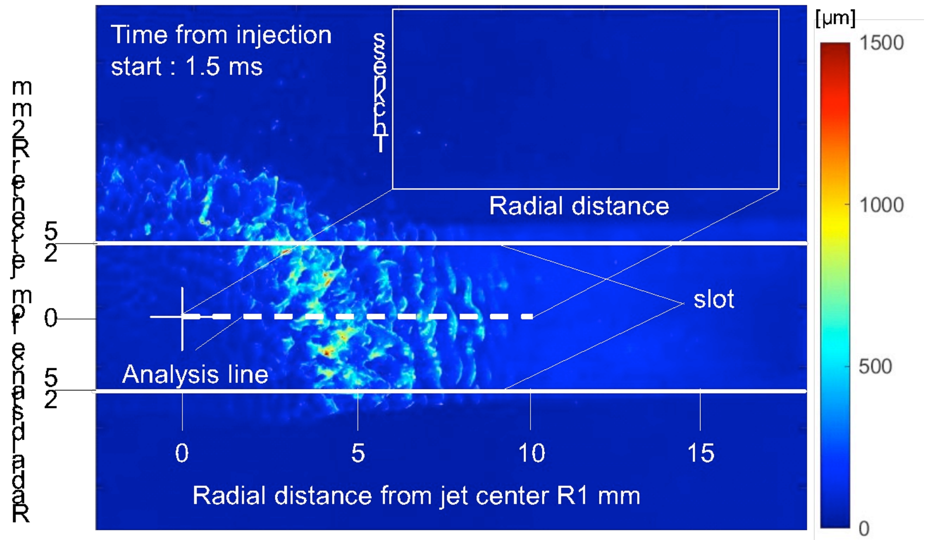

Figure. 5 The thickness distribution of liquid film that the gas jet impinges on

Figure 5 shows the thickness distribution of the liquid film in the slot of the impingement wall. In the LIF measurement, Nile red was used as fluorescent substance, and its substance was solved in diesel fuel directly. Its substance could be excited by light source of 532nm and emitted fluorescent light of 585nm. The excited light was blocked with the optical notch filter in order to detect the fluorescent light.

According to the thickness distribution of the liquid film, the its thickness at the impingement of the jet was thin due to the advection of liquid film by impact of jet flow, because the thickness of the liquid film was thicker away from the impingement point. Moreover, wavy surface of the liquid film appeared at the thicker liquid film.

Here, the thickness distribution of the liquid film along the center axis of the slot are shown in figure 5. Form this distribution, the effects of the amplitude and spatial frequency of the wavy surface on the jet velocity on the liquid film was investigated.

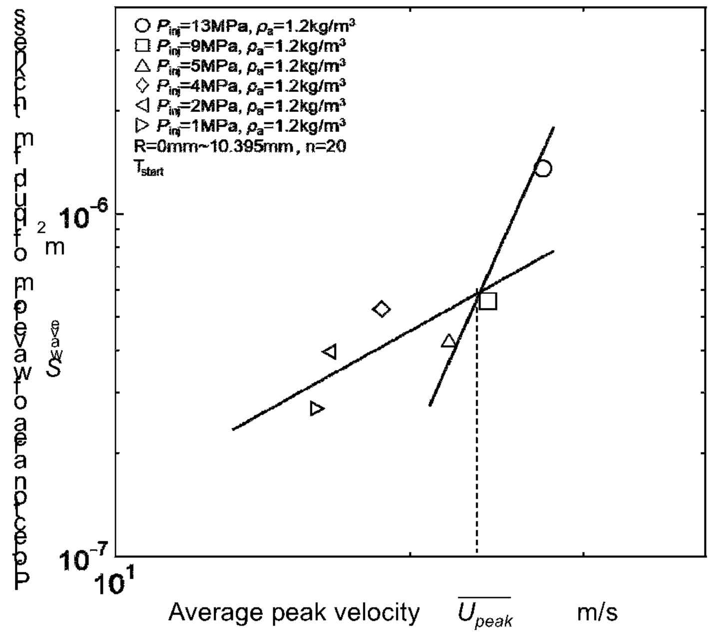

Figure.7 Procedure on evaluation of the liquid film amplitude

As for evaluation of the amplitude of liquid film, the projection area of the wave form was obtained. In this experiment, the test liquid, which is diesel fuel, was filled in the slot of 100μm depth. The absolute displacement from the reference line located at 100μm from the bottom of the slot was measured, and the projection area of the wave form was obtained with the procedure as shown in figure 6.

Figure 7 shows the relationship between the jet velocity on the liquid film and the projection area of the amplitude. The projection area of the waveform of the liquid film thickness increased with an increase of the jet velocity on the liquid film. It means that the movement of liquid film in height direction increased with the jet velocity. Moreover, over 20m/s of the jet velocity, the projection area dramatically increased. With considering figure 3, its velocity was almost the same as the velocity at the inflection point changing the increase rate of the jet velocity on the liquid film. It means that the displacement of the liquid film in height direction became large, and the momentum of the gas jet was exchanged to its displacement. Thus, it seems that the increase rate of the jet velocity became weak, because the momentum of the jet was consumed to the movement of the liquid film in the height direction.

Next, the spatial frequency of the waveform of the liquid film thickness was evaluated with FFT analysis. Figure 8 shows the spatial frequency of the waveform of the liquid film thickness for liquid film before and after change of increase rate of jet velocity on the liquid film as shown in figure 4.

Before the change of the increase rate of the jet velocity showing in figure 8 (a), the waveform of the liquid film was constructed with the low frequency range. On the other hand, after the change of the increase rate of the jet velocity showing in figure 8 (b), the waveform in high frequency range included in the wave of the liquid film as compared with the spatial frequency of figure 8 (a). Therefore, there was the possibility for increase of drag force from high frequency waveform of the liquid film to the gas jet flow on the liquid film due to increase of its surface area. Thus, it seems that the increase rate of the jet velocity became weak, because the shear stress between the liquid film surface and the gas jet increased.

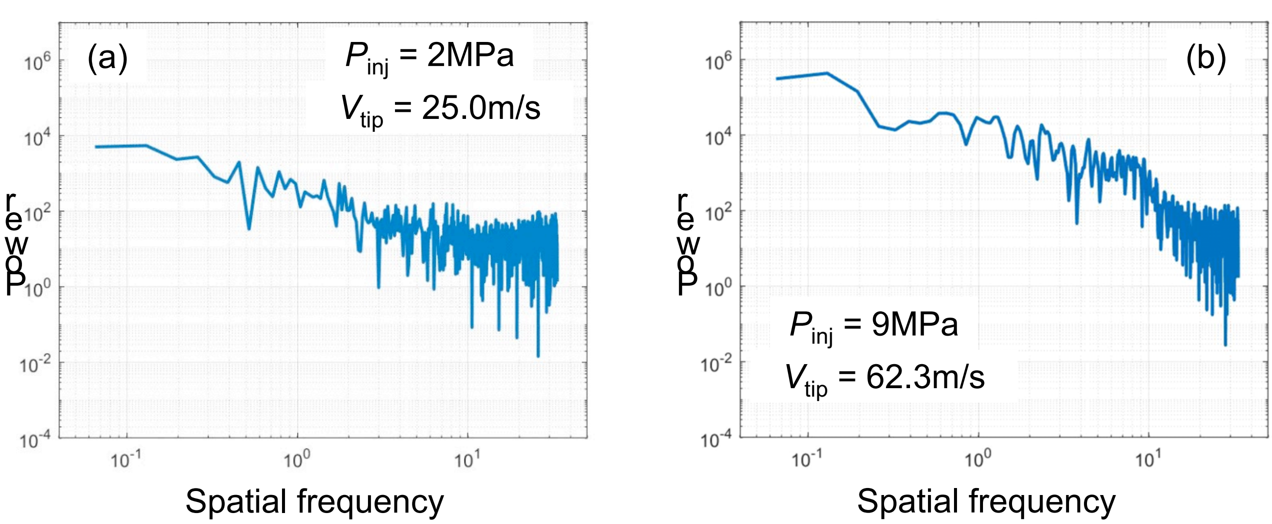

Figure.8 Spatial frequency of the thickness distribution of the liquid film

4. Conclusions

In this paper, the effect of liquid film on velocity of gas jet flowing on the liquid film was investigated with PIV and LIF techniques. The results obtained in this study are as follows;

1. The velocity of the gas jet after impingement on the wall increased with an increase of the velocity of the jet impinging on the wall. The increase rate of its velocity changed with liquid film formed on the impingement wall.
2. The wavy of the liquid film surface that the gas jet impinged was more intense with an increase of the jet velocity Impinging on the wall.
3. The total amplitude of the liquid film in height direction increased with an increase of the jet velocity on the liquid surface.
4. The amplitude of the liquid film dramatically increased over the velocity at inflection point of the velocity of the gas jet after impingement with respect to the velocity of the jet impinging on the wall. It seems that the increase rate of the jet velocity became weak, because the momentum of the jet was consumed to the movement of the liquid film in the height direction.
5. After the change of the increase rate of the jet velocity after impingement on the wall, the waveform of high frequency range included in the wave of the liquid film as compared with before the change of the increase rate.

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