

Thickness Measurement of Film Flow Discharged from a Rectangular Nozzle using light absorption

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ABSTRACT

Space separation using a liquid film instead of the firewall can be considered as a method to prevent such accidents and to block heat and toxic substances. However, few research has been conducted from the viewpoint of the formation of a stable liquid film. In this study, we investigated the flow characteristics of the liquid film discharged from a nozzle with a high aspect ratio. The liquid film thickness was measured by measuring light absorption by fluorescence dye dissolved in the liquid, and the film width was measured from the image of the liquid film. As a result, we found that (1) the film thickness in the edge region becomes thicker toward the downstream, (2) the cross-sectional area of the liquid film decreases downward due to the acceleration of the flow, which is greater than the gravitational acceleration, and (3) the presence of side walls suppresses the decrease in the film width due to the Coanda effect.

1. Introduction

Fire protection zones separated by firewalls are of importance to prevent the spread and damage of fires. On the other hand, accidents have occurred where people have been trapped inside the protected zones. Space separation using a liquid film instead of the firewall can be considered as a method to prevent such accidents and to block heat and toxic substances. Most of the research on liquid film discharged from a nozzle aims to atomize the liquid [1][2], and few research has been conducted from the viewpoint of the formation of stable liquid film. In this study, we investigated the flow characteristics of the liquid film discharged from a nozzle with a high aspect ratio. The liquid film thickness was measured by measuring light absorption by fluorescence dye dissolved in the liquid, and the film width was measured from the image of the liquid film. The liquid velocity and acceleration were evaluated from the measured film thickness and width.

2. Experimental Apparatus and Method

Figure 1 shows the schematic of the experimental apparatus, which consists of a water reserve tank, a nozzle, and a pump that supplies water from the tank to the nozzle. The width, thickness and length of the nozzle are listed in Table 1. Nozzle 2, width and thickness of which are 100 mm and 1 mm, respectively, is used for the film thickness measurement. The water is discharged from the nozzle and forms a liquid film flow. The average liquid film velocity V_0 at the nozzle exit was changed from 1.2 to 12.0 m/s. The measurement area is from the nozzle exit to 120 mm downstream of the nozzle exit.

To measure the thickness of a liquid film, we utilized the light absorption by a fluorescent dye (Rhodamine B). Figure 2 shows the schematic of the measurement system. The LED flat light source (Shinkosha, FL-470A4) emits blue light at a constant intensity in space. The emitted light passes through the liquid film in which the fluorescent dye is dissolved. The blue light is absorbed by the fluorescent dye. The absorption rate is proportional to the number of fluorescence molecules on the light path. Since the fluorescent dye is dissolved at a constant concentration, C , in the water, the change in the light intensity, dI , is proportional to the light intensity I and the path length $d\delta$ of the light in the liquid film:

$$dI = -\varepsilon C I d\delta \quad (1)$$

where ε is the absorption coefficient. This equation yields;

$$\log I - \log I_0 = -\varepsilon C \delta \quad (2)$$

$$\frac{I}{I_0} = e^{-\varepsilon C \delta} \quad (3)$$

Where I_0 is the intensity of the initial light intensity and δ the film thickness. This is the Lambert-Beer's law.

The light intensity I is recorded by the high-speed camera (Photron, FASTCAM SA-X2) with the optical filter. An example of the recorded image is shown in Figure 3. At the exit of the nozzle, the film thickness δ_0 is the same as the nozzle thickness δ_{ini} . So, the light intensity I_{ini} at the nozzle exit indicates the intensity corresponding to the film thickness of δ_{ini} .

$$\frac{I_{int}}{I_0} = e^{-\varepsilon C \delta_{int}} \quad (4)$$

Equations (3) and (4) yield

$$\frac{I}{I_{ini}} = e^{-\varepsilon C (\delta - \delta_{ini})} \quad (5)$$

$$\delta = \delta_{ini} - \frac{1}{\varepsilon C} \log \frac{I}{I_{ini}} \quad (6)$$

where εC can be calculated from Eq. 4:

$$\varepsilon C = -\frac{1}{\delta_{int}} \log \frac{I_{int}}{I_0} \quad (7)$$

Therefore, we can evaluate local liquid film thickness δ by measuring the local light intensity I passed through the liquid film. In this study, 1 000 instantaneous images are used to obtain the time-averaged image for measuring the time-averaged film thickness.

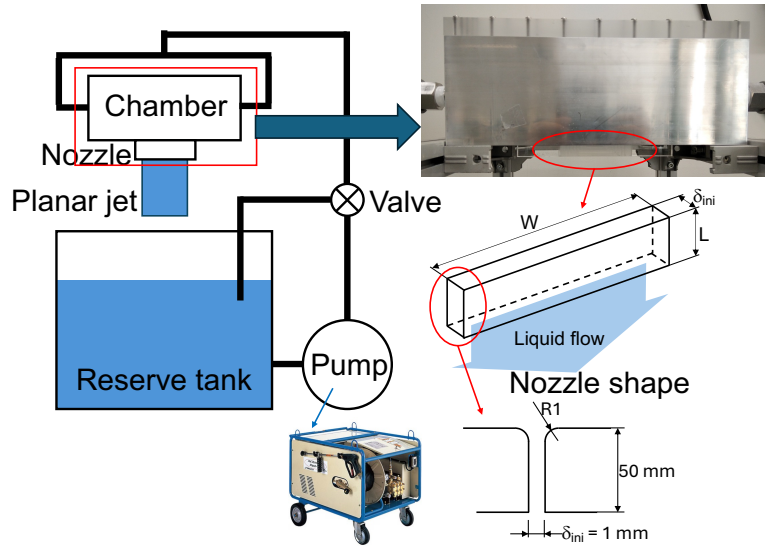


Figure. 1 Experimental apparatus.

Table. 1 Liquid properties.

Nozzle No.	1	2	3
W [mm]	50	100	200
δ_{ini} [mm]	1	1	1
L [mm]	50	50	50

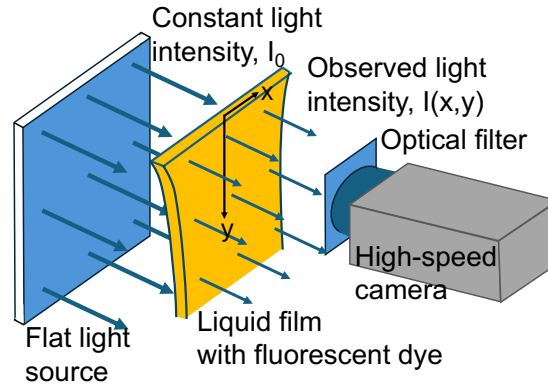
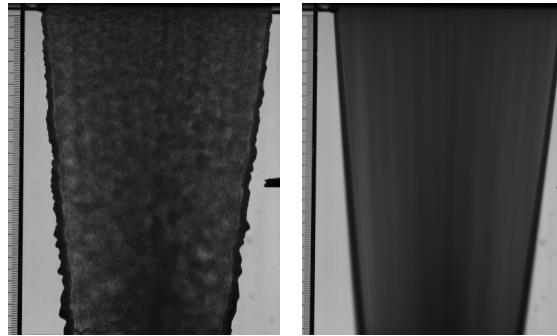


Figure. 2 Principle of measurement method.



(a) Instantaneous image (b) time-averaged image

Figure. 3 Example of image for thickness measurement.

3. Results and Discussion

Figure 4 shows the images of the liquid film in various initial velocity conditions. The film width decreases due to the acceleration of the flow as the liquid flows downstream. The lip regions, the liquid accumulation region, are formed at the edges of the liquid film. The shrinkage in the film width becomes weaker with increasing V_0 . This is because the increase in the liquid velocity leads to the relative decrease in the gravitational acceleration effect. The Reynolds number, Re , is defined by using the nozzle depth, so that Re smaller than around 2300 implies the laminar flow in the nozzle. When $Re = 1190$ and 2380 , the film flow is smooth throughout the visualized region. To the contrary, the small waves are generated just below the exit of the nozzle when $Re = 2560$ and 11900 . This is due to turbulence eddy generated in the nozzle. These small waves disappear in the downward region due to the eddy dissipation caused by the low velocity gradient at the interface. On the other hand, the large size waves are generated in the middle region in the images shown in Fig. 4. This might be due to the instability of the gas-liquid interface.

Figure 5 shows the images of liquid films generated from nozzles with different widths. There is no significant difference among the three images except for the existence of holes in the case of $W = 200$ mm. The lower figure shows the comparison in the edge regions. The structures of the films, i.e., the development of the lip regions and their developing speeds, are more or less the same among the three conditions. Hence, there is no influence of W on the development of the lip region in the edge. This implies that the liquid supply from the edge region to the inner region due to the shrinkage of the film width does not change in the three cases, and therefore, the liquid supply to the center region in $W = 200$ mm is lower than those in $W = 50$ and 100 mm. This is one of the reasons for existence of the holes in the case of $W = 200$ mm.

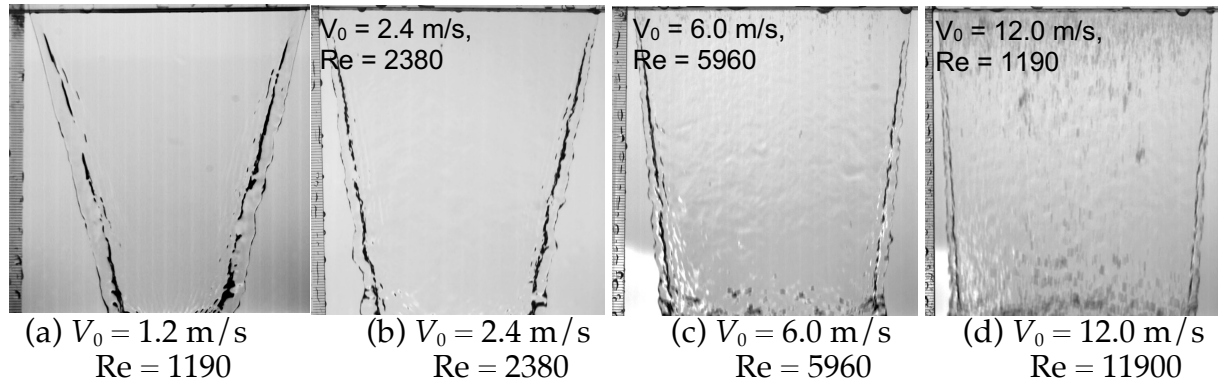


Figure. 4 Influence of liquid velocity at exit on film shape ($W = 100$ mm).

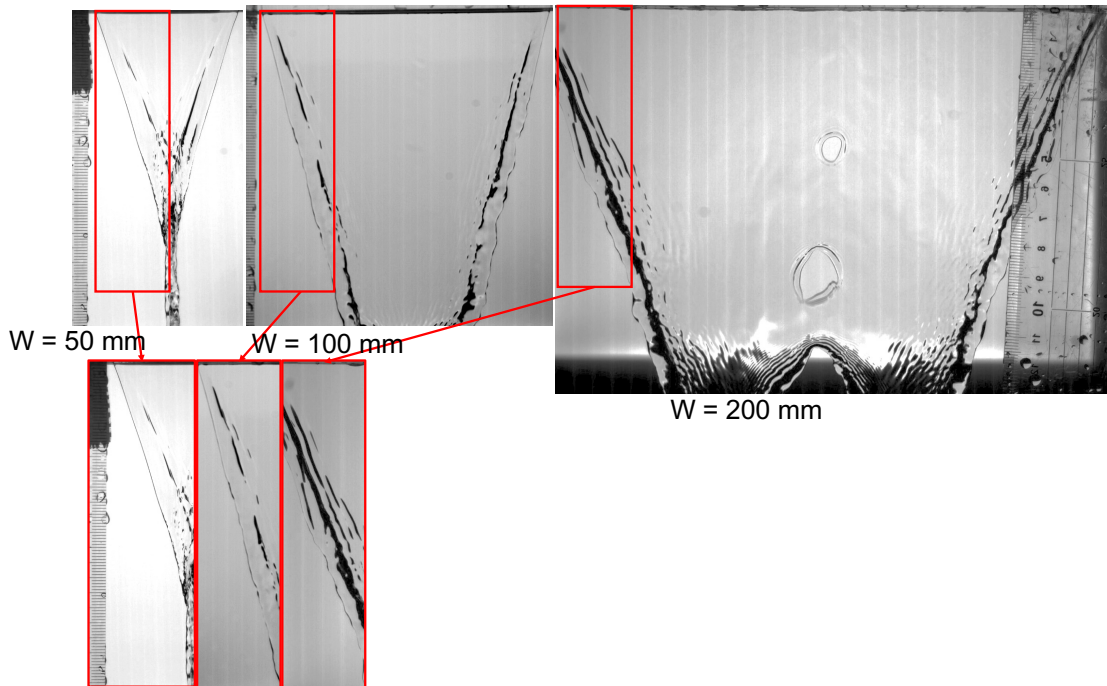


Figure. 5 Influence of liquid film width on film shape ($V_0 = 1.2$ m/s).

Figure 6 shows the distributions of the measured liquid film thickness. The measured film thickness distributions show that the center region of the liquid film is more or less uniform near the exit of the nozzle. On the other hand, it can be seen that the thickness at both edges of the liquid film increases as the liquid film flows downstream. The initial film thickness is smaller than the capillary length (2.7 mm), and therefore, the strong surface tension force, which tends to make the cross-section of the flow circular, occurs at the edge of the liquid film. This is the reason for the formation of the lip region at the edge of the liquid film. As the liquid film flows downstream, the film thickness at the edge becomes thicker. To the contrary, the film thickness in the region between both edges becomes thinner with thicker with flowing downstream in the first stage, and the decreasing rate is lower at the center than those near the edge regions. The film thickness at the center increases in the downstream region. This is also due to the surface tension effect. The change in the liquid film thickness becomes gentle with increasing V_0 , because the advection becomes larger despite constant gravity and surface tension forces.

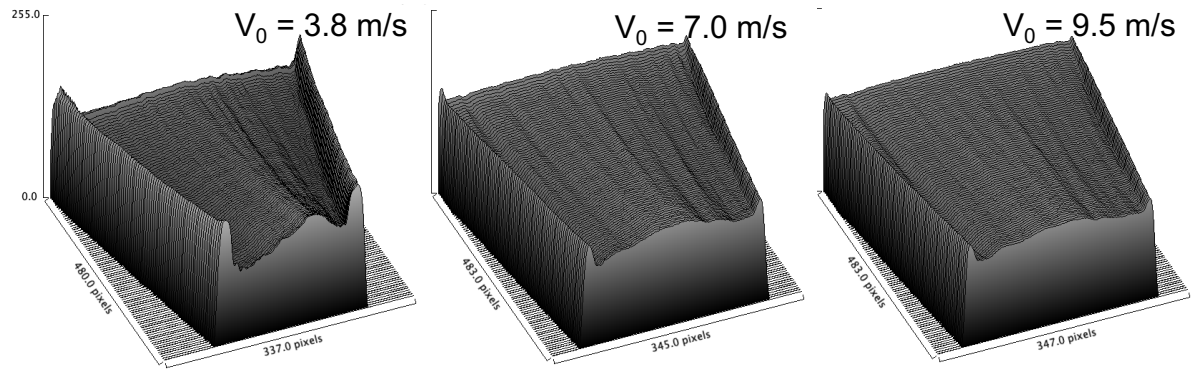


Figure. 6 Distributions of liquid film thickness.

Figures 7, 8, and 9 are the width, the average thickness, and the cross-sectional area of the liquid film. y denotes the distance from the nozzle in the vertical direction. The average thickness and the cross-sectional area were calculated from the measured film thickness distribution shown in Fig. 6. The film flow is accelerated by gravitational acceleration, and its width becomes narrower. The average thickness first decreases with increasing y , and it turns to increase around $y = 80$ mm. However, the cross-sectional area monotonically decreases with y . This indicates width reduction is larger than the increase in the average thickness. The mean velocity of the liquid was evaluated from the cross-sectional area and liquid flow rate. The results are shown in Fig. 10. The mean velocity increases in the y direction, and the gradient of the velocity, i.e., the acceleration, is higher than the gravitational acceleration. The acceleration decreases with increasing y , and it tends to reach the gravitational acceleration. This implies that the strong deformation of the liquid film

cross-section due to surface tension just below the nozzle exit induces additional acceleration in the y direction.

The reduction in film width is undesirable in the application of a liquid film to a fire wall. To prevent the reduction in film width, hydrophilic walls (aluminum plates) are placed on the side of the liquid film. The images of liquid film with and without the side wall are shown in Fig. 11. The figure clearly shows that the presence of side walls suppresses the decrease in the film width due to the Coanda effect.

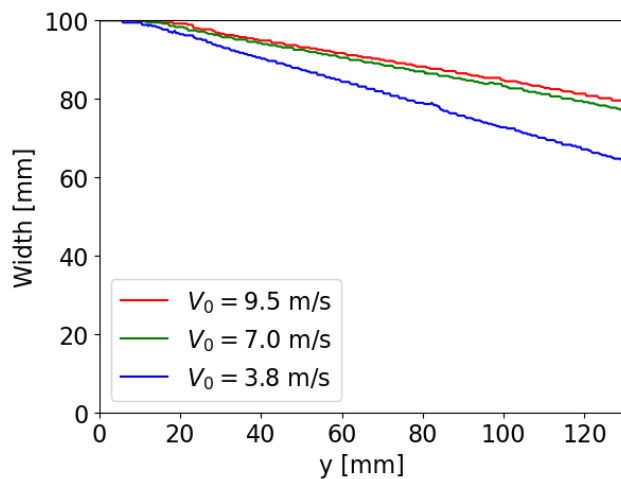


Figure. 7 Liquid film width.

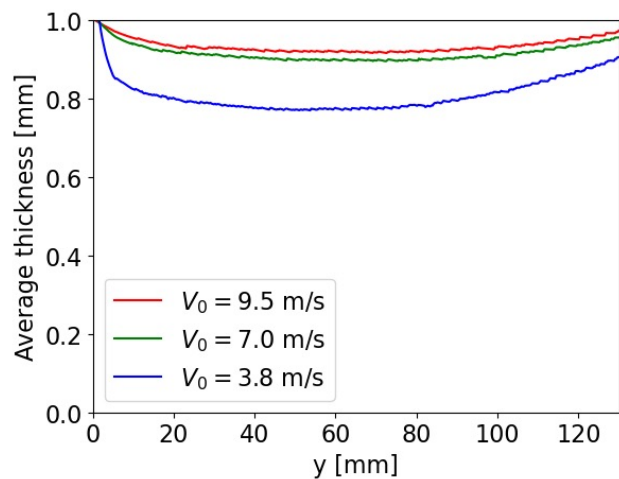


Figure. 8 Average thickness of film.

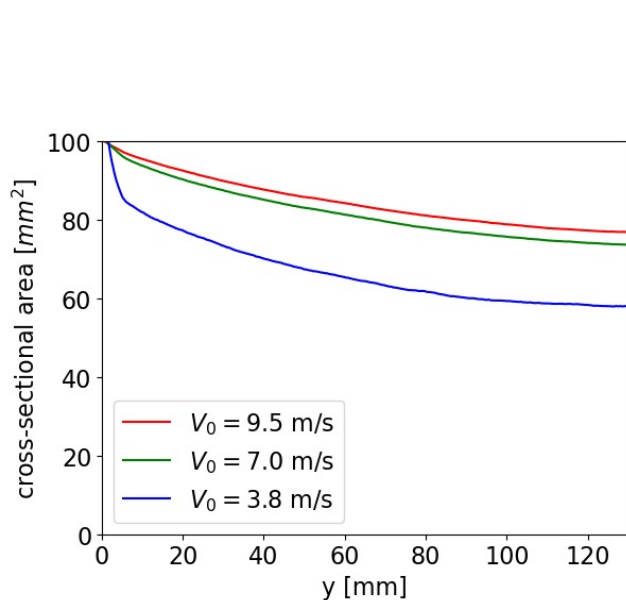


Figure. 9 Cross-sectional area of film.

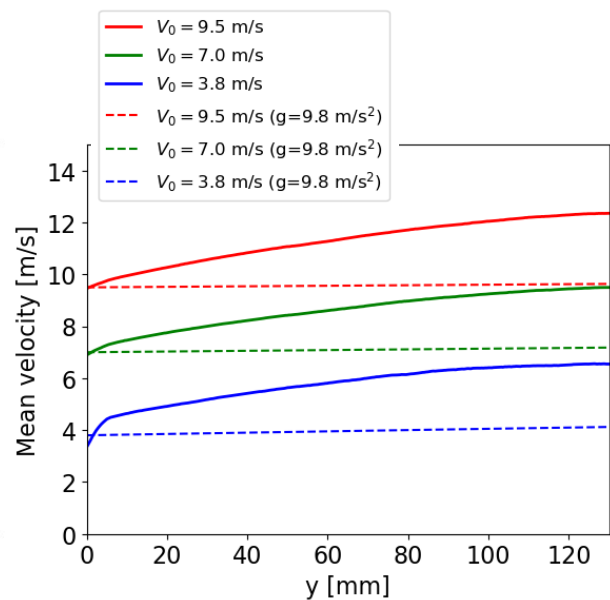


Figure. 10 Mean liquid velocity in film.

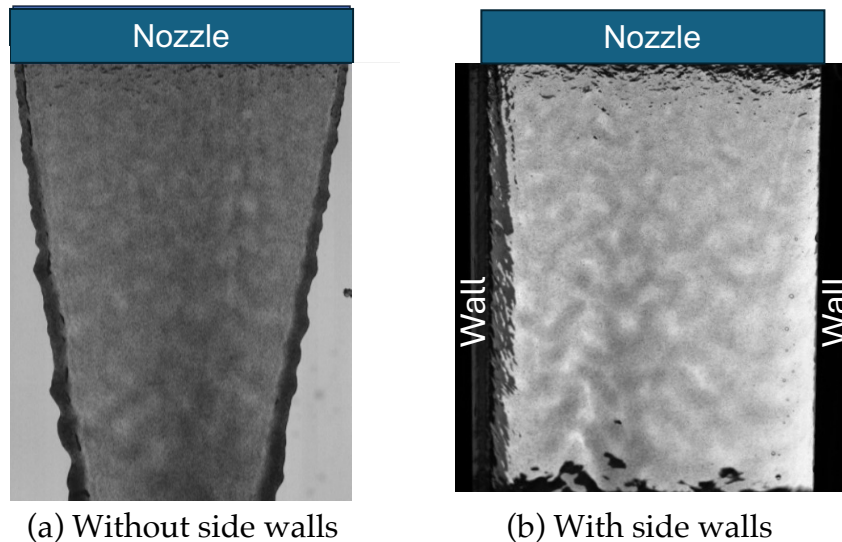


Figure. 11 Effect of side walls.

4. Conclusions

The flow characteristics of the liquid film discharged from a nozzle with a high aspect ratio were experimentally investigated. The liquid film thickness was measured by measuring the light absorption by a fluorescence dye dissolved in the liquid, and the film width was measured from the image of the liquid film.

1. The liquid film thickness can be measured by utilizing the attenuation of light by the fluorescent dye.
2. The film thickness in the edge region becomes thicker toward the downstream.
3. The cross-sectional area of the liquid film decreases downward due to the acceleration of the flow, which is greater than the gravitational acceleration.
4. The presence of side walls suppresses the decrease in the film width. This is due to the Coanda effect.

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