Measurement of Interfacial Profiles of Wavy Film Flow on Inclined Wall

N Rosli[1] and K Amagai[2]

[1]Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Malaysia

[2]Department of Mechanical Science and Technology, Gunma University, Kiryu 376-0053, Japan

E-mail: nurrinarosli@ump.edu.my

Abstract. Falling liquid films on inclined wall present in many industrial processes such as in food processing, seawater desalination and electronic devices manufacturing industries. In order to ensure an optimal efficiency of the operation in these industries, a fundamental study on the interfacial flow profiles of the liquid film is of great importance. However, it is generally difficult to experimentally predict the interfacial profiles of liquid film flow on inclined wall due to the instable wavy flow that usually formed on the liquid film surface. In this paper, the liquid film surface velocity was measured by using a non-intrusive technique called as photochromic dye marking method. This technique utilizes the color change of liquid containing the photochromic dye when exposed to the UV light source. The movement of liquid film surface marked by the UV light was analyzed together with the wave passing over the liquid. As a result, the liquid film surface was found to slightly shrink its gradual movement when approached by the wave before gradually move again after the intersection with the wave.

1. Introduction

Falling liquid films on inclined wall present in many industrial processes, such as in food processing, seawater desalination and electronic devices manufacturing industries. The behavior of liquid films, such as the variations in coating thickness or uneven delivery of liquid during the manufacturing process are often caused by the wavy film flow presents in the film surface. This leads to the need in better understanding the liquid film surface characteristics, in order to ensure the successive generation of high quality products.

Over a century ago, the investigation on falling liquid films whether with employment of vertical or inclined flat plates, in numerical or experimental studies has been extensively carried through by many researchers. The pioneering study lies in the works achieved by e.g. Kapitza[1], Benjamin[2], and Yih[3] through their analysis on the stability of the falling liquid films. Yu et al. [4] have investigated the flow characteristics of water film falling on a vertical plate. Pavlenko et al. [5] studied the dynamics of laminar-wave flow of an intensively evaporating saturated liquid film on a vertical plate. Another laminar wavy motion of liquid film on a vertical wall has been discussed by Min and Park [6] from their numerical calculation method. Ito et al.[7] have used a needle contact method in their work

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[1]   To whom any correspondence should be addressed.

of liquid film flowing down a heated surface to measure the film thickness, wave number, wave height and wave velocity.

Moreover, the occurrence of wave structures in the liquid film flows has also grown as significant discussion among the study of falling liquid films. For examples, Chinnov and Kabov [8] clarified the thermocapillary effect on the rivulet structure of wave in liquid film falling down a heated inclined plate. Salque et al. [9] described the surface waves structure and its relation to the liquid film atomization in a venture. Kil et al. [10] in their integral approach clarified the wave characteristics of falling liquid film on a vertical circular tube. Duprat et al. [11] discussed the phenomena of bound-state formation in a viscous film coating a vertical fiber. This matter then has been further discussed by Wehinger et al. [12] in their numerical simulations of liquid film also in a vertical fiber. Karimi and Kawaji [13] reported circulatory motions in their work to describe turbulence characteristics of wavy film falling down a vertical tube. Moran et al. [14] then extended the investigation to describe wavy film characteristics falling down an inclined plate. Their works proved that the circulatory motion occurred merely in the waves with very small thickness from substrate to peak.

Lel et al.[15] in their work have presented two different methods to measure wavy films thickness. The first one was a chromatic confocal imaging method, which using the effect of chromatic aberration from a lens that split the white light from a halogen lamp into a continuum of monochromatic images. While another one was a fluorescence intensity method, which allowed the simultaneous measurements of film thickness and wave velocity. In order to investigate the behavior of multiphase flow on inclined plates, Hoffmann et al.[16] have used a particle image velocimetry (PIV) method to measure the flow surface velocity. They used a stroboscope that allowed double exposures of the pictures of the tracers.

When liquid film travels along a vertical or inclined wall, the liquid surface flow is particularly influenced by the wavy flow structure on the liquid film surface. This probably leads the liquid surface to flow differently than before wave passing over it. Therefore, a better understanding that provides information on relations between liquid surface and wave characteristics are of important. However, conducting an experimental study considering such information with appropriate method is not surprisingly difficult.

Here, a study on wavy film flow on inclined wall through simultaneous measurement of liquid film surface velocity, wave velocity and liquid film thickness fluctuation has been aimed in this paper work. The liquid film surface velocity was measured using a non-intrusive technique called as laser tagging method by photochromic dye. It is a simple tracer technique, in which a dye trace was tagged onto the liquid films using ultraviolet (UV) light irradiation of Nd: YAG laser (λ= 355nm). The movement of the dye trace was then analyzed together with the movement of wave passing the dye trace by image analysis. Velocity difference between the liquid film and wave was then investigated. Furthermore, a cross-correlation method was also used to measure the average wave velocity, based on irradiation of two parallel diode laser beams (λ= 407nm) perpendicular to the liquid films flow. From one of the diode laser beams irradiation, liquid film thickness fluctuation was measured using a light absorption method.

2. Experimental apparatus and methodology
In this study, kerosene oil dissolved with photochromic dye and coumarin153 was used as the test liquid, respectively to achieve the purpose of liquid film velocity and thickness measurement. The type of photochromic dye was TNSB type, dissolved in the kerosene oil with concentration of about 0.12wt%. This concentration was sufficient to yield a vivid colored state of working fluid when irradiated by UV light.

Figure 1 illustrates the overview of experimental setup. The inclined wall was made of acrylic plate with reservoir area composed at the end of the wall for liquid accumulation. A metallic mesh was placed in the reservoir area in order to control the flow of liquid film upon falling to the flat wall after accumulation. The size of the flat wall that allows full delivery of liquid film was 300mm in length and

120mm in width. The inclined wall was mounted on aluminium extrusions installed with free-angle brackets to allow alteration of the wall inclination angle, θ from horizontal to vertical direction. The test liquid from a liquid storage basin passed through a pump, valve and flow meter before entering the reservoir area. As we attached a semi circular cylinder at the flat wall entrance, the test liquid fell down the wall as wavy film flow and then came back to the liquid storage basin.
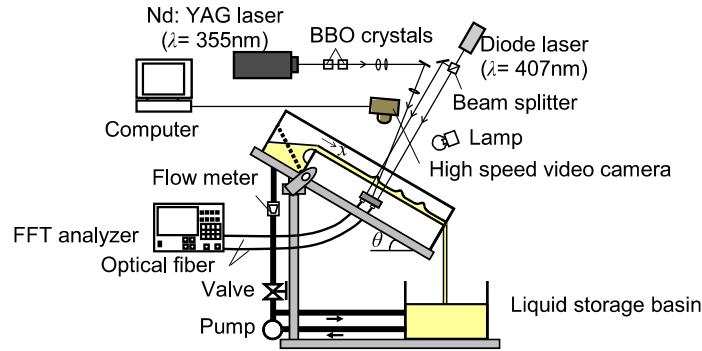

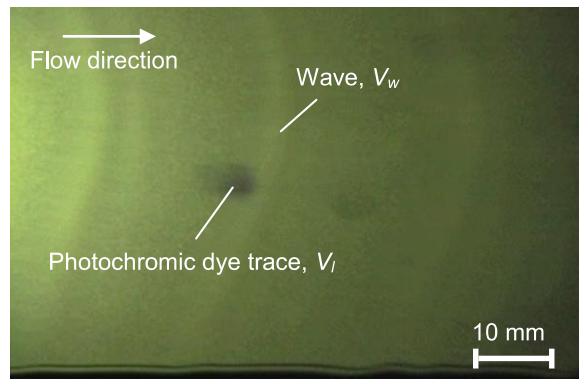**Figure 1.** Overview of experimental apparatus.

Figure 2. Sample image of liquid film flow on inclined wall
upon measurement of liquid film and wave velocities.

Upon the wavy film falling down the wall, pulses of UV light (third harmonic light, λ=355nm) from Nd: YAG laser was irradiated to the test liquid in order to mark a dark color point of photochromic dye trace in order to measure the liquid film surface velocity. Beta barium borate (BBO) crystals were used to obtain the third harmonic light. Combination of lens and mirror were used to lead the UV light to the liquid film. A convex lens was placed on the light path to ensure a concentrated dye trace for best analysis results. Simultaneously, the flow patterns and the movement of wave and dye trace formed in the liquid film were recorded by a high speed video camera. Figure 2 shows the sample image of liquid film with photochromic dye trace appearance which was seen as a dark color point. The motion picture was transferred to a still image data. Images with wave passing over the dye trace were selected for analysis process. The position of the dye trace and the wave were then determined by digitizing their coordinates. A halogen lamp was used to provide lighting for visualization.

In this study, the experiment was conducted wall inclination angle, θ= 30°, 60°, 90° at various measuring position which defined as distance from the liquid inlet, x= 60mm, 100mm, 140mm, 180mm. The Reynolds number was fixed at Re= 81.3. The Reynolds number was defined by the following equation:

$$Re= \rho Q/\eta b \tag{1}$$

where, ρ is the density, Q is the flow rate, η is the viscosity of the test liquid and b is the width of the inclined wall. The liquid film surface velocity, V_l was obtained from the displacement of the dye trace, Δx_l over consecutive frames during a time interval, Δt as shown in the following equation:

$$V_l=\Delta x_l/\Delta t \tag{2}$$

The instantaneous velocity of wave, V_w can be obtained in the same way as shown in the following equation:

$$V_w=\Delta x_w/\Delta t \tag{3}$$

where, Δx_w is the displacement of the wave.

Figure 3 shows the schematic view of optical arrangement for the average wave velocity and liquid film thickness measurement. A pulse of diode laser light ($\lambda= 407nm$) was directed to the liquid film in perpendicular to the inclined wall. For the average wave velocity measurement, a beam splitter was placed on the beam path in order to divide the original beam as shown in the figure. The two beams with a known-spacing, $S= 12mm$ between them thus appeared on the liquid film flow with a parallel direction to the film flow.
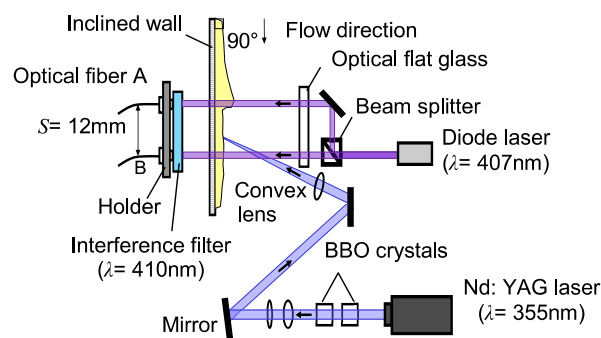

Figure 3. Schematic view of optical arrangement for average wave velocity and liquid film thickness measurement.

A pair of optical fiber was attached behind the inclined wall with their surfaces covering the region of total incident light of the two beams. The optical fibers were relatively large in diameter, i.e. about 6.4mm compared to the diameter of total incident light, i.e. about 2mm. Therefore, the error from light refraction can be reduced. The light intensity was then converted into voltage signals by two photomultipliers connected to the other tip of the optical fibers. The two signals were then cross-correlated by using a Fast Fourier transforms analyzer, giving the time delay between the two signals, $\Delta\tau$. The average wave velocity can be derived as the following equation:

$$\overline{U_w} = S/\Delta\tau \tag{4}$$

where, S is the known spacing between the two beams and $\Delta\tau$ is the time delay between the two signals from cross-correlation operated by the FFT analyzer. The results were than compared with the average velocity of wave passing the dye trace, $\overline{V_w}$ as mentioned in above for results validity determination.

The liquid film thickness was measured based on the light absorption method. The absorption is actually caused by the diode laser excitation to the test liquid dissolved with 0.5g/l of coumarin153. This method is referred from the well-known theory of Beer-Lambert law, which exhibits a proportional relationship of absorbed diode laser light intensity and liquid film thickness. In other words, the liquid film thickness was determined by the attenuation of light intensity after it passes through the liquid film. A blue interference filter (λ= 410nm) was placed between the inclined wall and the optical fibers in order to merely allow the diode laser transmission through the liquid film.

3. Results and discussion

3.1. Visualization of wave patterns

Figure 4 shows the images of wave patterns on liquid film flow down the wall at inclination angle, θ= 30°, 60° and 90°. In the case of θ= 30°, there were imperfections of waves formation in the beginning of liquid film flow. This can be attributed to the reduced influence of gravitation at smaller inclination angle that caused the delay in wave inception, as described by previous reported work [17]. The waves then became visible with the increasing distance from liquid inlet. Furthermore, the waves apparently evolved into slant lines. This can be attributed to the non-uniform distribution of film flow on the test wall surface due to the imbalance side inclination. In other words, the inclined wall might be inclined heavier on the right side which leads the liquid film to accumulate on the heavier side and forced to travel faster than other side.

In the case of θ= 60°, the waves patterns were clearer than that of θ= 30°. The wavelength became larger with increasing distance from liquid inlet. In the beginning, the waves smoothly travelled like solitary-type pattern. It then grew up into large tear-drop humps in U or W-shape. A closer look to the wave patterns also reveals the presence of short forerunner wave right in front of the main wave. In the case of θ= 90°, the waves patterns were found in irregular U and W-shape. This can be described by the strong influence of gravitation which dominates the liquid film dynamics and thus amplifies the liquid drop in gravitation direction [18].
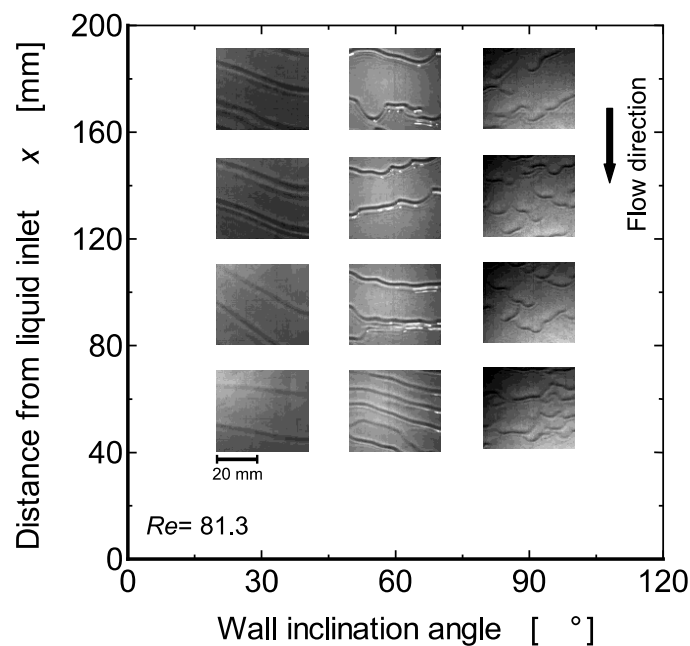

Figure 4. Sample images of wave patterns formed on the liquid film flow surface.

3.2. Liquid film surface and wave velocities

Figures 5 to 7 show the time series movement of liquid film and wave at Reynolds number, Re= 81.3 and wall inclination angle θ= 30°, 60° and 90°. In each figure, (a) represents the positional relation between the liquid film and wave, while (b) represents the velocity profile.

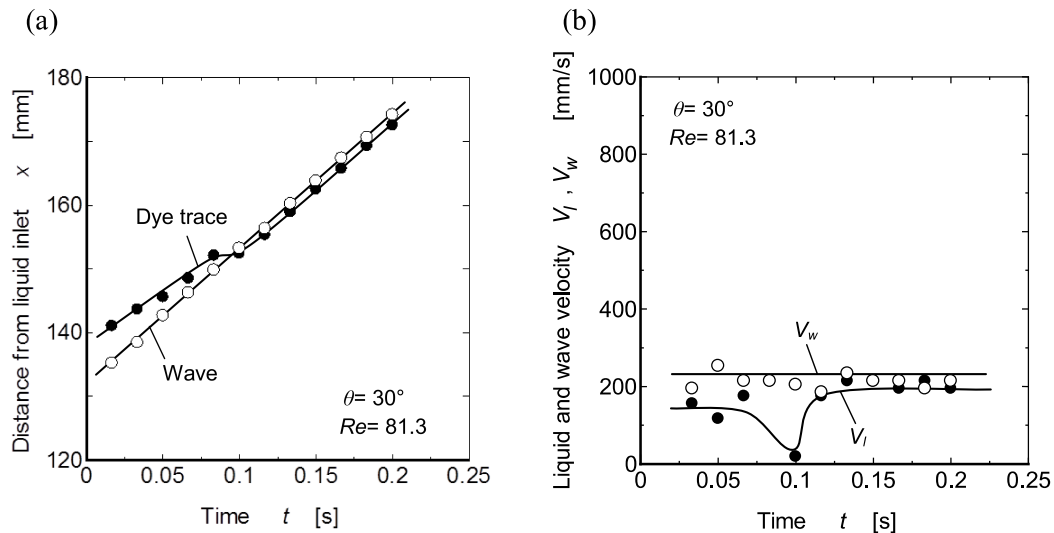(a)   (b)

Figure 5. Time series movement of liquid film and wave in (a) positional relation and (b) velocity profile at Reynolds number, Re= 81.3 and wall inclination angle θ= 30°.

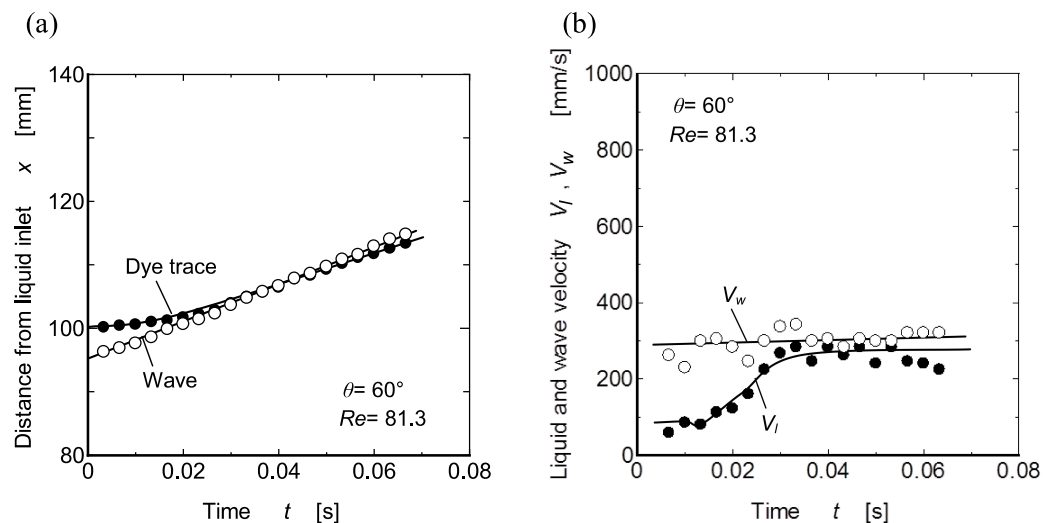(a)   (b)

Figure 6. Time series movement of liquid film and wave in (a) positional relation and (b) velocity profile at Reynolds number, Re= 81.3 and wall inclination angle θ= 60°.

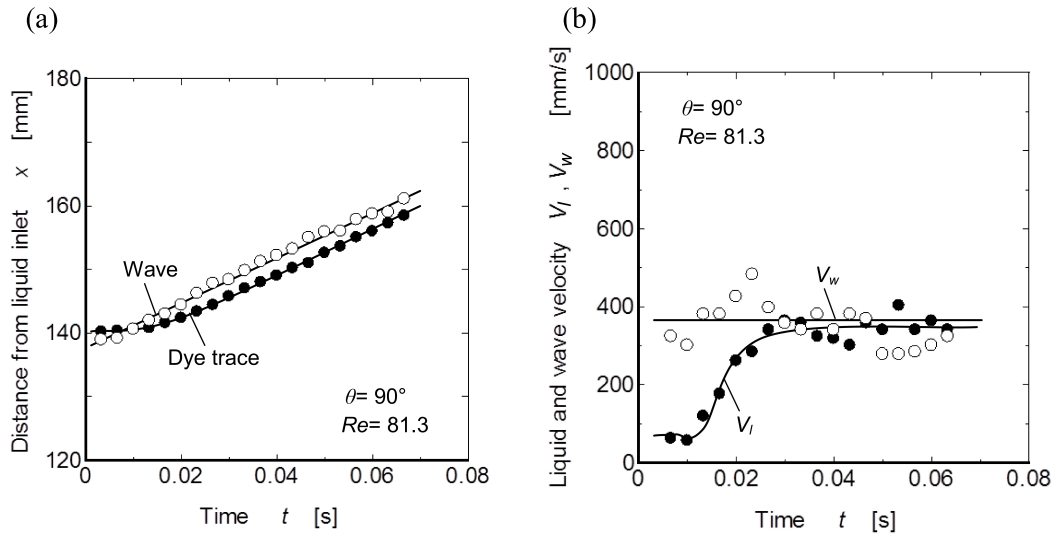(a)   (b)

Figure 7. Time series movement of liquid film and wave in (a) positional relation and (b) velocity profile at Reynolds number, Re= 81.3 and wall inclination angle θ= 90°.

The crossing point between the plotted data points of (a) in each figure represents the intersection between wave and dye trace during the liquid film flows along the inclined wall. As can be seen, the wave was found to gradually move downstream. However, the liquid film which represented by the dye trace movement seemed to slightly shrink its gradual movement when approached by the wave, and then gradually move again after the intersection.

This movement trend was confirmed by the velocity profile as shown in (b) in each figure. As it can be observed, the wave apparently tried to remain unaffected and moved in almost constant velocity even after passing by the liquid film. On the other hand, the liquid film was found to move in almost constant velocity, but then slightly decrease nearly same timing of the intersection. Thereafter, the liquid film velocity showed a rapid increase till reaching a constant rate.

The slight decrease of velocity represents the moment when the wave approaching the liquid film. In specifically, the local thickness of liquid film in the front part of the wave became thinner due to the pulling effect of liquid film in further region for another wave formation. Therefore, the local velocity decreased probably due to the fewer influence of the thin liquid film. On the other hand, the rapid increase represents the acceleration of the liquid film dragged by the wave that was moving in higher velocity.

3.3. Liquid film thickness fluctuation
The liquid film thickness fluctuation at different positions on inclined wall at inclination angle, θ= 60° and 90° are depicted in figure 8 and figure 9, respectively. In both figures, (a) represents the time series, while (b) represents the distance series. The wavy film motions observed in the figure 8 was found to agree well with the previously noted wave patterns as seen in figure 4, especially the short forerunner wave that appeared in front of the main wave.

Specifically in figure 8, liquid film distributed in the upper stream region (x< 100 mm) was found to have a relatively flat film flow. The flat film flow suddenly evolved into larger amplitude of fluctuation and maintained the intensity of wavy motions up to the next downstream region. This phenomenon probably occurred due to the wave inception point that moved into further downstream [18]. Thus, the wavy film was formed started from the downstream region (x> 100 mm).

On the other hand, there is no significant change of thickness fluctuation seen in the liquid film at inclination angle, θ= 90° as seen in figure 9. According to our literature review [17], the larger gravitation influence caused by the increasing inclination angle increased the liquid film flow velocity at stream wise direction. Thus, the wave amplitude normal to the gravitation direction became thinner.
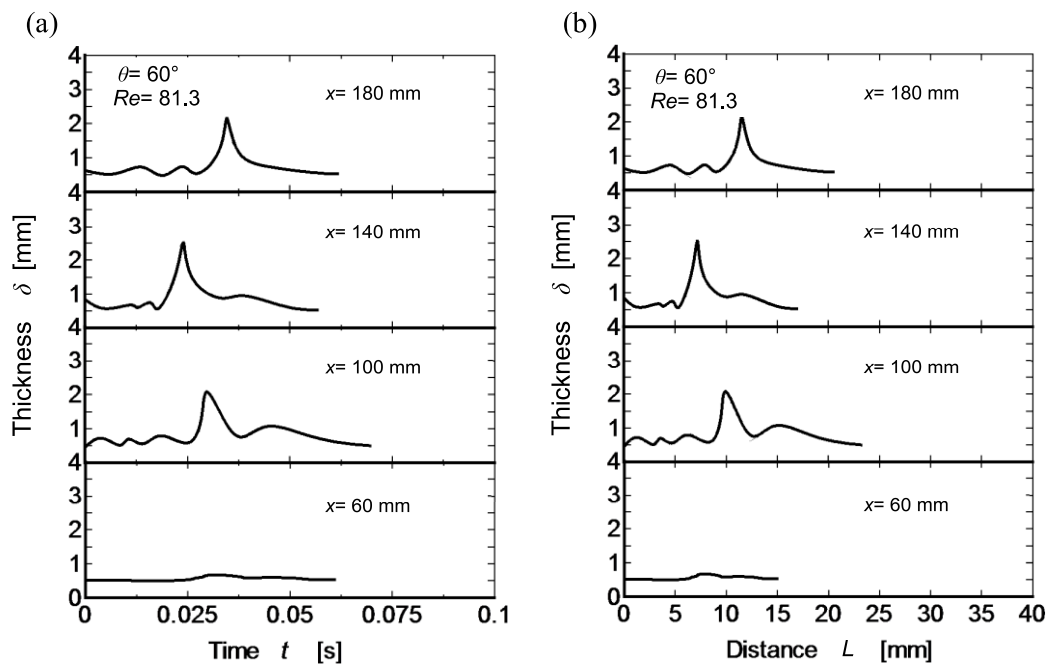
(a)   (b)

Figure 8. Liquid film thickness fluctuation in (a) time and (b) distance series at different positions on inclined wall upon Reynolds number, *Re*= 81.3 and wall inclination angle *θ*= 60°.

(a)   (b)
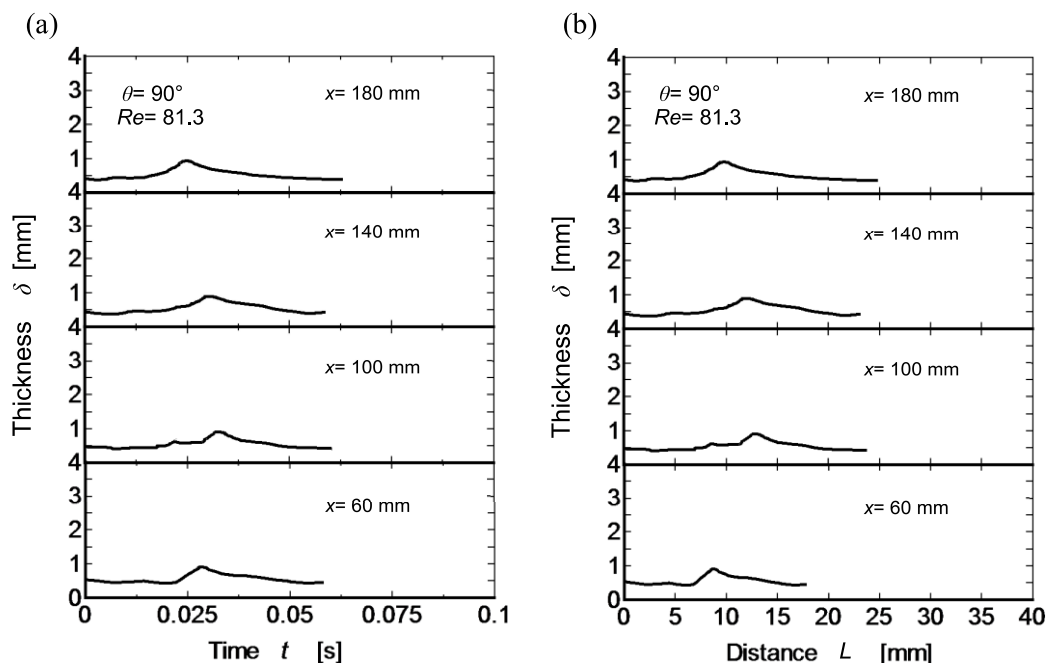

Figure 9. Liquid film thickness fluctuation in (a) time and (b) distance series at different positions on inclined wall upon Reynolds number, *Re*= 81.3 and wall inclination angle *θ*= 90°.

Figure 10 shows the average wave amplitude at different wall inclination angle versus to distance from liquid inlet. Overall, the average wave amplitude was found to become larger with decreasing

inclination angle. Furthermore, the average wave amplitude at wall at inclination angle, $\theta= 30°$ and $60°$ seemed to rapidly increase at upper stream region ($60mm< x< 100mm$) before reaching a tendency to remain constant thereafter ($x> 100$ mm). The wave amplitude at $90°$ angle shows a weak increasing with increasing distance from liquid inlet. This trend is corresponding to the low amplitude of thickness fluctuation observed in figure 9.
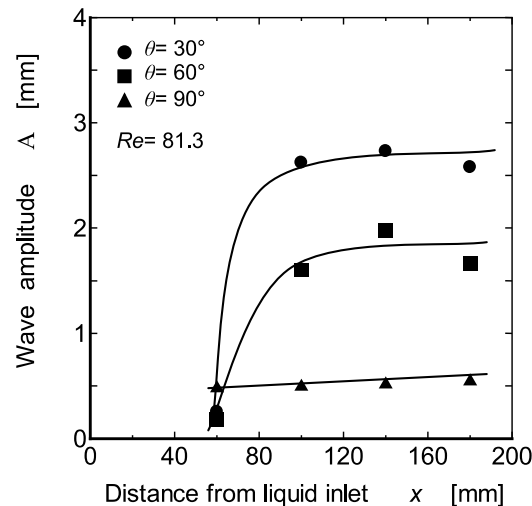

Figure 10. Average wave amplitude at different positions on inclined wall upon Reynolds number, $Re= 81.3$.

4. Conclusions

This paper presents a study on wavy film flow on inclined wall through simultaneous measurement of liquid film surface velocity, wave velocity and liquid film thickness fluctuation. The main finding lies in the phenomenon occurred to the liquid film surface upon the presence of wave. The liquid film surface was found to slightly shrink its gradual movement when approached by a wave. It then gradually moved again with increasing velocity right after the wave passing by. The velocity then remained constant until approaching by another wave. The wave movement on the other hand was found as nearly unaffected from the beginning until after approaching the liquid film surface.

Furthermore, different types of wave pattern were found with variations of wall inclination angle. Inclination with imbalance side also hindered a uniform distribution of liquid film down the entire wall. Moreover, the wave patterns that were well observed by a high speed video camera were also successfully validated through the results of liquid film thickness fluctuation measured by the light absorption method. Moreover, the liquid film thickness was found to decrease with increasing wall inclination angle. In vertical wall, almost no significant change of thickness fluctuation was found.

5. References

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