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Wavy water thin-film characteristics on horizontal plate using PLIF Experimental

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Abstract. Nonlinear Thin liquid film is commonly applied in numerous engineering fields, including the Passive Containment Cooling System of the nuclear power plant and steam dryer in the steam generator of nuclear power plants. The counter gas flow effect through a rectangular channel was inspected, the flow is motivated by the pressure gradient and shear gas stress while the gravity force does not influence the flow. Different flow rates of gas were set to different Reynolds numbers from 6950 to 34800 with influence on a different range of input water Reynolds number from 170 to 875 respectively. The data was collected at different sections from inlet flow until the separation section. The thickness of liquid film investigated using (PLIF) experiments. The thickness has been calculated via digital image processing and MATLAB code. Film thickness was obtained as a function of time and frequency. Results were analyzed using statistic tools such as property density function (PDF), fast Fourier transform (FFT), and power spectral density (PSD).

1. Introduction

Investigation of moving film thickness on the surface represents an important part of the numerous engineering fields. For example, the Passive Containment Cooling System (PCCS) is using water as a reactor coolant. In the aspect of safety, economical and NPP design, flow characteristics in PCCS are of immense importance. This type of research aims to get full experimental results on flow performance of the small fluid film on the surface. In the latest years, different types of research have been conducted, numerical and experimental. Different experimental designs are used to investigate and examine the thickness of water film with different properties such as the experiment's geometry, different fluid parameters, etc. The measurement system used in this research is Planar Laser-Induced Fluoresce (PLIF) method. The examination model is attached to a CCD camera and laser source. The obtained results have been treated with MATLAB software.

2. Background

On a large scale in the different industrial applications, including all sorts of equipment where the thin liquid sheet is occurring, like distillation, lubrication, heating, and cooling processes, the different thickness of liquid film is outflowing down an inclined plate, because of its comparatively minor and high mass flow. Blocken et al. [1] studied the flows water of the rain on the fronts of the buildings. One of the usages of thin liquid film is washing the dust from fixed plates of steam turbines and in the PCCS. Observation of the thin liquid film is possible over large number of the phenomena where hydrodynamic film is passing over some solid shape and we can determine contact angle between liquid and solid. Paras et al. [2] studied formation and development of the rivulets liquid film with observation of creation of cyclic waves. For many years, scholars have conducted extensive research on wall liquid membranes. Hartley et al. [3] proposed a force balance standard when investigating stable dry spots which formed via isothermal liquid film rupture. Since then, the researchers have always concluded multi aspects such as thermal effect, airflow shearing, and special-shaped slab via the force balance standard. The force factor proposes various forms of force balance models. Zuber et al. [4] considered into calculation the thermal effects as liquid film vapor pressure, thermal capillary forces and examination the liquid film thermal cracking via the force balance standard. Murgatroyd et al. [5] proposed a force balance model driven by airflow shear force considering the imbalance between liquid-gas two-phase interface shear force and liquid-solid interface wall viscous force. Joo et al. [6]investigated the minor disturbance of the flow film and established a surface wave disturbance standard, based on the long-wave model of free flow film. Ye Xuemin et al.[7] investigated the wave instability of the falling film on the inclined plate and used the equation of Orr-Sommerfeld to obtain the long-wave transmission speed. The investigation displays that the gas-liquid interface shear force and the longitudinal gravity component defined the liquid film flow state; the liquid film flow state, the direction, and gas flow size determined the liquid film variation instability. Lory et al. [8] determined a problematic situation of film split at the corner of the plate-based the surface wave disturbance standard. Usually, the flow direction of gas and liquid has three kinds of relationships: same, vertical and opposite. The most significant modification between the three statuses, the liquid film flow driving force is different, and the cracking mechanism is various. At current, wall liquid film flow research mostly focuses on the first two methods, and there is less investigation on the third case. The liquid film of the steam separator wall at the steam generator of the power station boiler and the nuclear power plant flows downward by the action of gravity and is subjected to the airflow.

3. Experiment facility

This experiment has been performed using two-phase, air-water and system as shown in Figure 1. The system is a rectangle channel with air-inlet cross-section 10 cm x 2 cm and 25 cm long with a 30-degree angle at the corner and water-inlet cross-section 0.2 cm x 10 cm. The observed segment is composed of the organic glass and steel support.

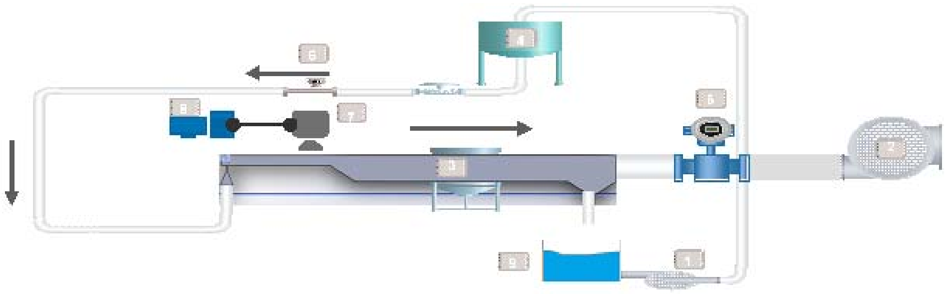

Figure 1 Sketch of the experimental system

1.	Pump	4.	Main tank	7.	High-speed camera
2.	Air-vacuum	5.	Air-flow meter	8.	Computer
3.	Rectangular Channel	6.	Water-flow meter	9.	Drain tank

Three points were selected at identified distances from the corner to study generated wave, as shown in Figure 2.

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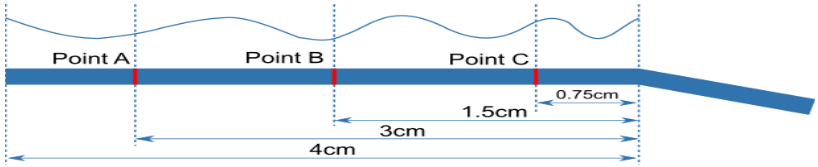

Figure 2 Position of studied points

As shown in Figure 3, the laser emits light of specific wavelength and turns the point source into a line source through a plan-convex cylindrical lens. The line source laser is irradiated onto the film in which the fluorescent dye is dissolved through the corrugated plate made of plexiglass and a flat, bright region is formed on the liquid film as shown in Figure 4.

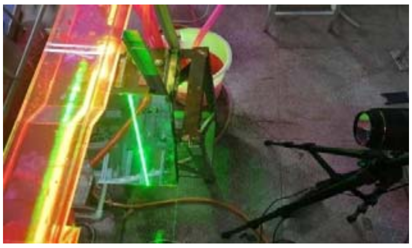

Figure 3 CCD, laser, and model

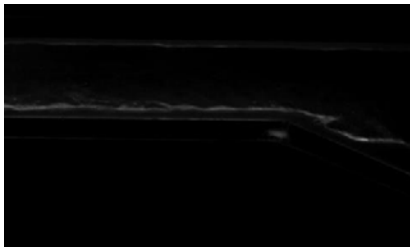

Figure 4 Film image

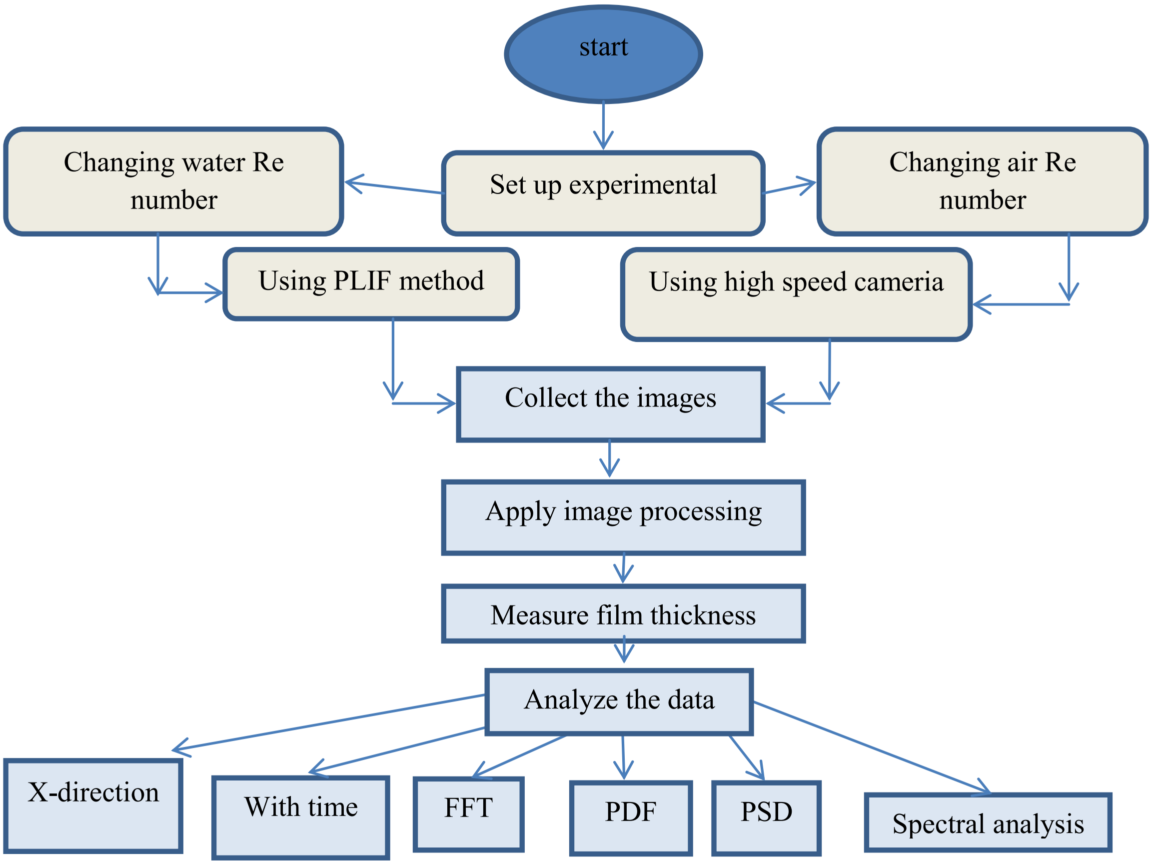

Figure 5 Experiment flow chart

4. Results and Discussion

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To investigate film characteristics, we apply a different inlet velocity for water and gas.

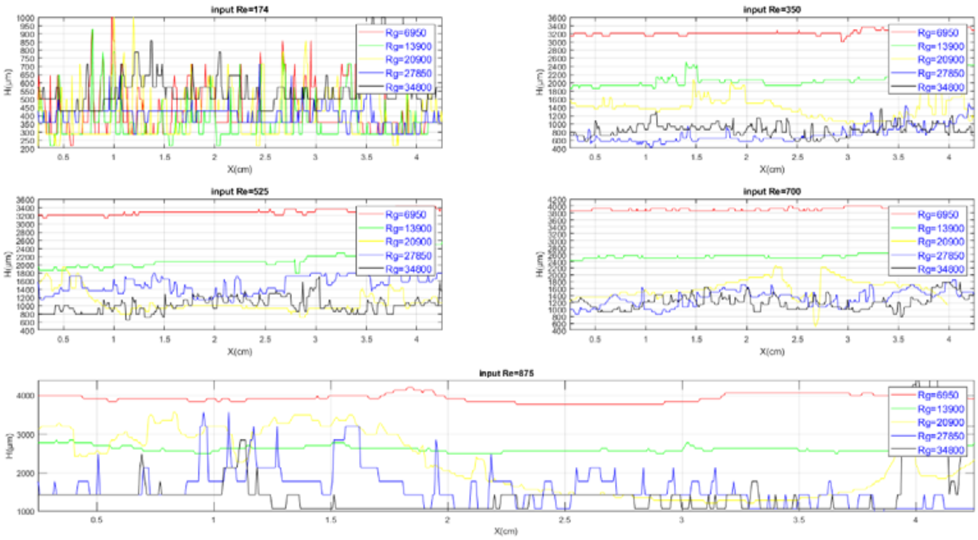

Figure 6 Water film thickness with respect to the x-direction

4.1 The behavior of the wave with the X direction

Figure 6 represents the wave shape of the film. Due to the problem of data recording, the slow-motion video has been taken in total of two seconds. After one second of the movie duration, a picture was taken. Results are recorded for five different inflow gas Reynolds (Re) number (6950, 13900, 20900, 27850 and 34800). At 174 water Re number and with a range of flow gases, solitary wave was detected for all five inflow gases; For water Re number within range of 350-700 and for 13900 and 20900 air Re number solitary wave and the capillary waves were detected and for high gas Reynolds number (27850 and 34800), capillary wave and airily waves appeared, while at 6950 air Re number, airily wave is observed. At 875 water Re number and for all five inflow air Re number airily wave is detected.

4.2 The behavior of the wave with respect to time

The evaluating points are curtained as Figure 7 for 2 seconds, where the sampling frequency is 3.2 kHz. The behavior of the wave is almost the same at all three positions (A, B and C). Wave behavior is not simple harmonic motion as presented in Figure 6. At 20900 air Re number, the behavior of capillary wave shows compressing passing with increase water Re number between two peaks. With low water Re number, the passing of the wave is direct without comprising passing wave. The film thickness fluctuation increases with increasing Re number.

4.3 The behavior of the wave with FFT analysis

FFT is demarcated as a process used to estimate a scale from a time domain to a frequency domain. The FFT spectrum analyzer input samples calculate the signal magnitude values and show the phase angle and values of that wave. It offers a decomposition of frequency in harmonics, hence can be studied individually. Therefore, it becomes more significant than the statistical analysis of a wave elevation and then is relatively essential to calculate a probability distribution function (PDF).

The water film frequency distinguishing is not precise at low Re numbers, the fluctuation of FFT is very high and the magnitude is small comparing with higher Re number.

At higher Re number, as shown in Figure 8, with a range of frequencies from 0Hz – 250Hz the fluctuation of FFT and the magnitude are very high, while with the range of frequencies from 250Hz – 2800Hz, the fluctuation of FFT is very high while the magnitude is small. So to study that curves more clearly we will apply PDF analysis.

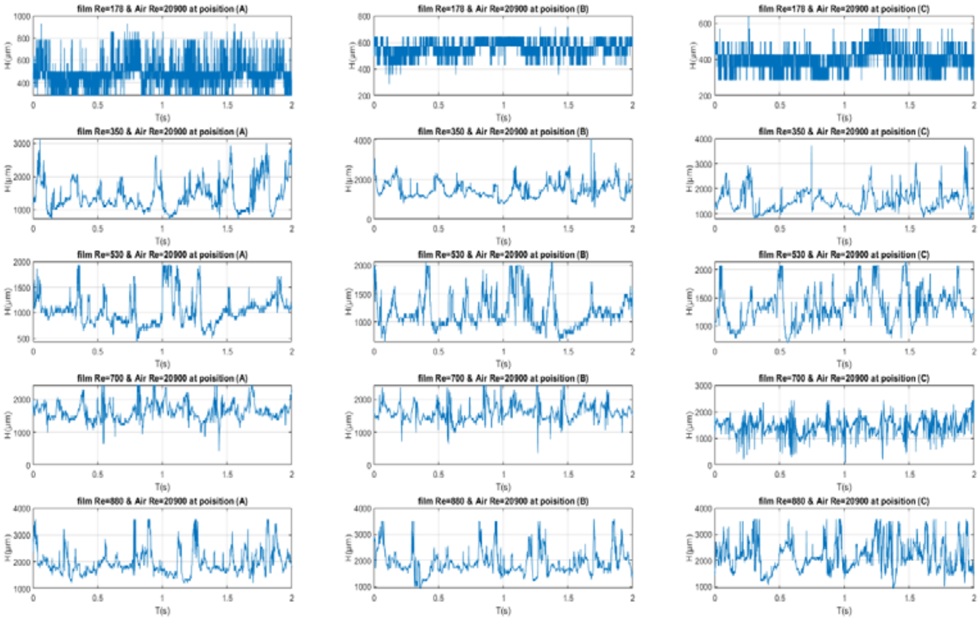

Figure 7 Film thickness with respect to time

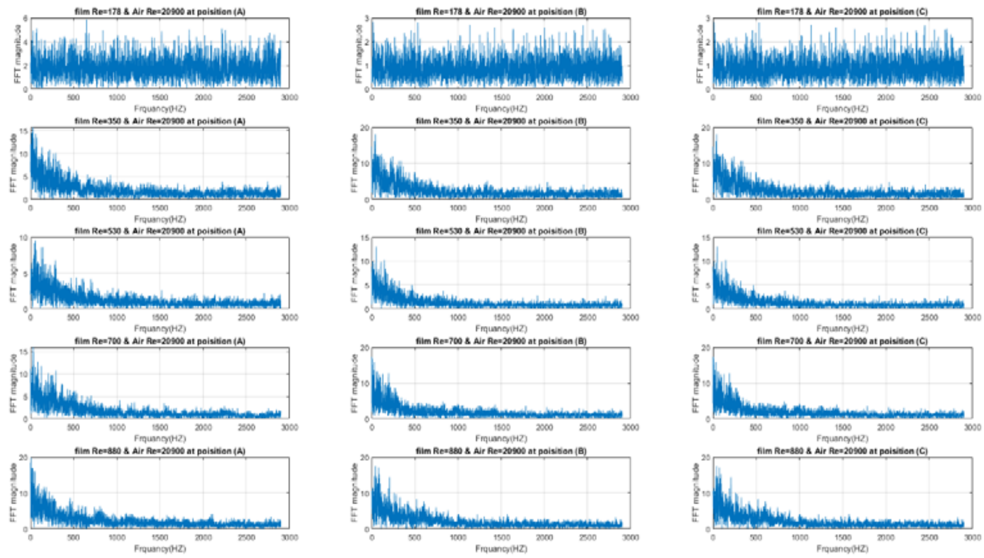

Figure 8 FFT with respect to frequency

4.4 The behavior of the wave with PDF analysis

The curves of PDF have been shown in Figure 9, with presented peak positions with the highest probability density. With low water Re number the PDF magnitude is very high, however, the density of peaks is small. At 174 water Re number we can notice peaks at two frequency values, in comparison with increasing water Re number to 350, we can see that the density of peaks of PDFs is increasing for

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different frequency values in sequence. We can interpret that the comprising passing wave at high water Re number is causing higher density of PDFs.

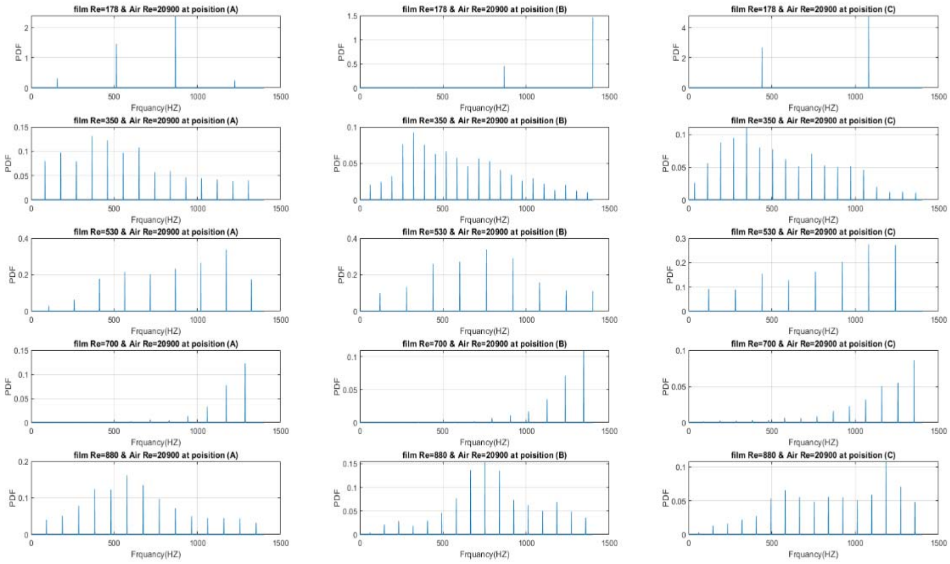

Figure 9 PDF with respect to frequency

4.5 The behavior of the wave with PSD examination

As shown in Figure 10, the power spectral density profile of the film, for different water Re numbers is approximately similar. The wave distribution all over the frequency set shows the huge-frequency features of film thickness variation. For each graph, between 0 kHz and 0.25 kHz, the curve falls rapidly and after the fall is more gradual. Moreover, in that range the height of the PSD stays considerably within a line of change. This Figure reveals that this signal has multi-frequency with energy variation.

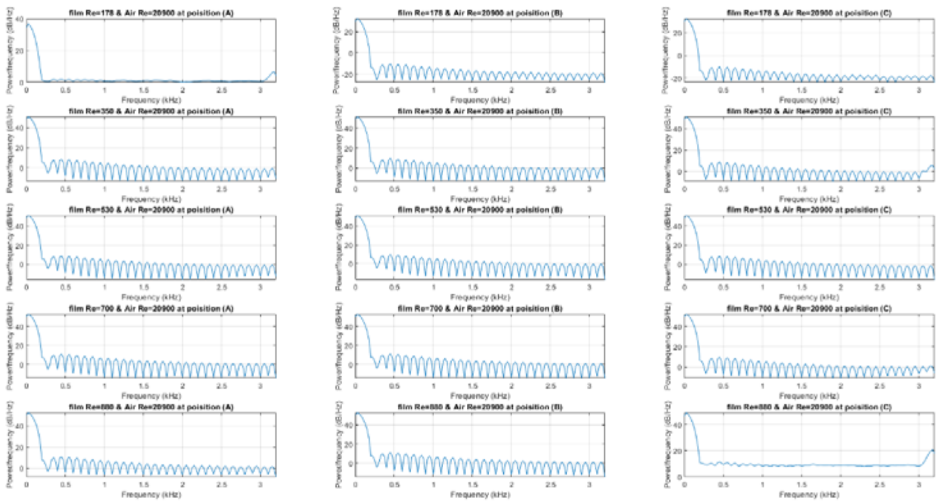

Figure 10 Power spectral analysis

4.6 The behavior of the wave with spectral analysis

Film frequency is spread all over the frequency set as shown in Figure 11, considering the multi-frequency film features variation, although frequency set is not clear. With increasing the water Re number the multi-frequency scattering is more evident in the spectral diagram. Continuous spreading happens through all diagram area and it is regular spreading. The specific frequency spreading of the film thickness at all Reynolds numbers, that is, the characteristic frequency has a particular time periodicity.

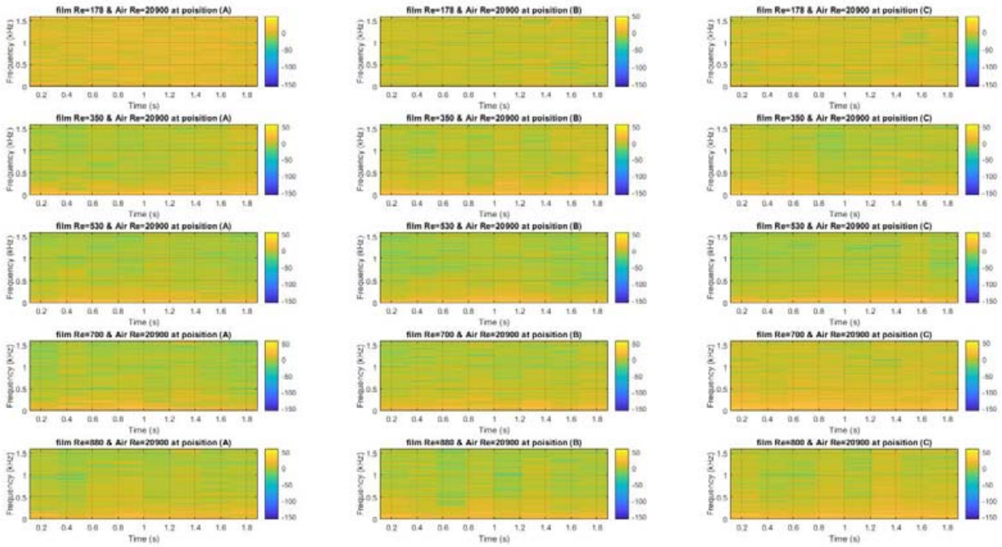

Figure 11 Spectrogram

5. Conclusion and summary

Research on water film features over the horizontal plate is investigated in this paper using (PLIF) method. The film thickness is estimated by the application of time domain, FFT analysis, probability density function, and spectrogram and power spectral density. Water film fluctuation characteristics are investigated and a brief illustration of the conclusion is pointed as:

1. The wave has changed in the x-direction and depending on the combination of air and water Re number, the different types of waves have been detected.
2. The wave of the film changed with time at three-point of study and the behavior of the wave at each point is the same for each case, but the waves that occur are not simple harmonic motion.
3. There is no clear periodical time for the studied wave. Some waves like solitary, capillary, and airily wave are caught on film of wave behavior.
4. With PDF analysis we can notice the compressing wave and PSD analysis reveals that the water film surface has multi-frequencies.

Reasons for different wave occurrences at different air and water Re numbers have not been part of this research and we propose that the next research on thin liquid film should be to investigate the roughness of the plate and relation between air shear stress and free water surface.

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