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Experimental Investigations on Measuring Falling Film Thickness on Vertical Plates with and without Copper Metal Foam

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Abstract **-** The significance of the liquid film thickness is paramount in various engineering applications involving heat and mass transfer. It is imperative to conduct dynamic investigations to comprehensively assess experimental performance and fine-tune operational parameters based on factors like flow rate, longitudinal shifts, temperature, and surface modification. This research focused on dynamically measuring the film thickness on a vertically positioned plate, both with and without surface modifications. Employing a Plate heater ensured consistent maintenance of the plate's centre temperature at a specific range. For the surface modification, a copper metal v foam with a pore count of 50 pores per inch (PPI) and a thickness measuring 0.1 cm was layered onto the vertical plate. Through dynamic analysis over a span of time, the evolution of film thickness characteristics across the vertical plate was scrutinized. Notably, it was observed that instances of higher flow rates correlated with more pronounced fluctuations in film thickness. The study delved into the impact of flow rates ranging from 0.9 lpm to 2.1 lpm on film thickness, revealing a direct relationship – an increase in flow rate resulted in increased film thickness. The inclusion of the metal foam in this investigation gave rise to intricate flow patterns characterized by tortuosity, boundary layer detachment, and reattachment. These outcomes facilitated enhanced intermixing. Plotting the variation in film thickness along the plate's length, spanning distances from 0 to 20 cm, disclosed insightful trends. The film thickness steadily increases to 5 cm along the plain plate and Copper metal foam plate length. The copper metal foam structure creates uniform dispersion across the surface, permitting effective operation at lower flow rates than a plain surface.

Keywords**:** Film Thickness, Copper Metal Foam, Air-coupled Ultrasonic sensor, measurement study.

1. Introduction

The film thickness has played a vital interest in various engineering applications. Particularly vertical falling film, chemical industry, electronic cooling, refrigeration application, and thermal energy sectors. The liquid film thickness directly influences the heat and mass transfer from the surface. Also, the behavior of the film will affect the heat transfer characteristics. So, understanding the nature of the film with respect to different operating conditions will give critical insight into its application. Nusselt [1] proposed a theoretical equation for film thickness as a function of the Reynolds number on vertical flat surfaces, assuming a shear-free gas-liquid interface. Equation 1 shows the film thickness derived by Nusselt. Takahama et al. [2] gave a correlation in 1980 for the turbulent flow regime in vertical falling liquid film thickness as a function of Reynolds number, represented in equation 2. The technique employed for the wavy liquid film was needle contact and electric capacity type, one of the earliest non-contact type measuring techniques. Brauer et al. [3] gave an expression of average film thickness as a function of Reynolds number and fluid property in 1956 as given in equation 3 below , Aragaki et al. [4] conducted experimental studies on falling liquid film and gave the correlation as shown in equation 4 below.

Many measurement studies were carried out to accurately calculate the falling liquid film thickness; Takamasa et al. [5] used a non-contact type measurement technique on a vertical flat plate using two laser focus displacement meters. Studied the waves produced in the falling film surface, evaluating film thickness and wave velocity. The results were in good agreement with the theoretical and experimental results. Ambrosini et al. [6] investigated the effect of plate inclination like 45° and 90° on falling film thickness, and some interesting observations were noted. The plate inclination has less influence on the wave velocity of the falling liquid film. However, the inclined plate's film thickness was slightly higher than the vertical flat plate. Also, as the plate's temperature increases, the mean film thickness decreases relatively in both the incline and vertical plate. It was observed that the fluctuations in film thickness for the vertical plate were comparatively higher than for the inclined plate. All the measurements were recorded with the help of the non-contact type Capacitance probe method.

The non-contact type air-coupled ultrasonic sensor were developed to measure falling film thickness on horizontal circular tubes by Jayakumar et. al.[7] . Akhil et. al.[8] developed a non-contact type novel interferometric method to simultaneously measure the falling film thickness and film interface temperature on a horizontal circular tube. Zhou et. al. [9] conducted an experimental investigation of flat plate using the confocal chromatic sensor technique to measure falling film thickness on flat plate. It was observed that the liquid feed mode plays a vital role in film thickness characteristics. The film thickness increases with an increase in Reynolds number; as the plate inclination decreases, the film thickness increases.

Yan lu et. al.[10] studied the wetting behavior on a vertical flat surface due to two different liquid feed distributions using the fluorescence technique. At a lower flow rate, the distributor with a higher number of holes shows better wettability coverage of the surface than the distributor with fewer holes. The minimum wetting threshold required for achieving full surface coverage was consistent for both distributor types. Beyond this point, once the plate was entirely wetted, there was no discernible impact from the distributors. Different surface modifications were used to increase the heat transfer characteristics on the horizontal circular tube. Raju et. al [11] carried thermal spray coating on the outer surface of the tube, Arjun et al.[12] used metal foam-wrapped Cooper tube to increase the heat transfer coefficient of the film.

As the literature shows, film thickness is critical in improving thermal performance. Many measurement techniques were developed to measure the falling film accurately. The liquid feed distributor was used to increase the wettability of the surface. However, it was observed that the surface modification techniques still have not been explored much on vertical flat plates. As can be seen, liquid distributor affects only till the entire surface is wet, so to improve the heat transfer characteristics surface modification is suggested. The copper metal foam seems to be a better option as it increases the intermixing of the fluid due to the tortuous flow path, leading to better thermal performance. However, the film thickness information on the modified surface on a vertical flat plate is still scarce. So, a detailed comparative study was conducted to understand the falling film behavior under different operating conditions like varying flow rate, location, and surface temperature.

$$\bar{\delta} = \left(\frac{3\vartheta\dot{m}}{b\mu}\right)^{1/3} \tag{1}$$

$$\bar{\delta} = 0.473\left(\frac{\vartheta_l^2}{g}\right)^{1/3} Re^{0.526} \tag{2}$$

$$\bar{\delta} = 0.302\left(\frac{3\vartheta^2}{g}\right)^{1/3} Re^{0.526} \tag{3}$$

2. Experimental Setup and Procedure

The experimental setup consists of a water tank with an even distribution of water, a vertical plate, an ultrasonic transducer, an ultrasonic flow meter, a constant temperature water bath, a recirculation pump, and a supporting platform. An ultrasonic flow meter and an ultrasonic transducer provide real-time liquid flow rate and film thickness measurements. The water tank is 10×10×10 cm in size and has two baffles that separate it into three compartments to stabilize the flow and make it uniform before it passes over the vertical plate (length 30 cm, width 10 cm). As pressure increases, the compartments fill one at a time. For the experiment, drinking water was used as the working fluid.

Fig. 1 shows that the water from the constant temperature water bath is pumped through the pipe into the water distribution tank. The water will flow in the tank through compartments so that any bubble formation, if any will be suppressed, and the flow will be uniform. The slot at the tank outlet will allow the flow to flow on the vertical surface. The flow rate was controlled with the help of a flow control valve and bypass valve. The flow measurement was done with a non-contact ultrasonic flow meter to avoid disturbance. The Plate heater heats the film flow on a vertical surface. The Plate heater of the same size is fixed at the backside by applying the thermal paste between the plate and the heater to avoid any air gap. The heater is then covered with the plate. The thermocouple is attached at the center of the plate to maintain the center temperature at a constant value. The constant temperature water bath controlled the inlet temperature of the film. The air-coupled ultrasonic sensor was used to measure the film thickness. The water at the exit of the plate gets collected at the water-containing tank. Then, it is transferred back to a constant temperature water bath.

The air-coupled ultrasonic sensor is kept perpendicular to the plate. It is connected to the JSR control panel and through JSR to NI DAQ into the system. The signal was first taken without flow and then with flow. Due to flow, the time travel by the signal will be low. Due to this, there will be a shift in the signal. This shift in signal is captured, and the time delay is found by post-processing using cross-correlation. It is then used in equation 1 to find the film thickness.

Table 1: Specification of experimental setup and instruments.

Vertical plate material	SS316
Operating Flow rate	0.6 lpm – 2.1 lpm
Ambient operating condition	27°C
Fluid Temperature	30°C
Heater Temperature range	50°C - 70°C
Flow meter	Ultrasonic flow meter with an accuracy of ±0.03 m/s
Constant temperature water bath	Sub-zero make with an accuracy of ± 0.1°C
T-type Thermocouple	Accuracy ±0.1°C

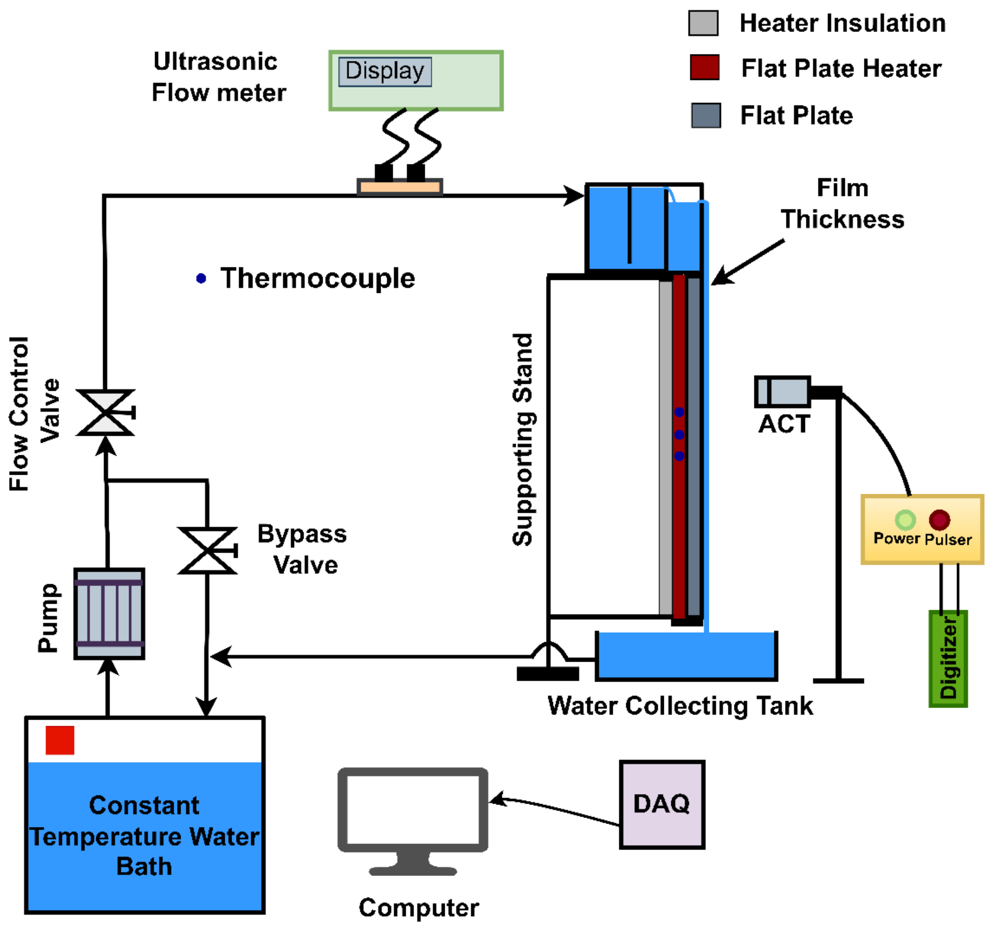

Fig. 1: Schematic diagram for film flow on vertical surface.

3. RESULTS AND DISCUSSION

The Air-Coupled Ultrasonic sensor was used to measure the time shift in signal represented in Fig.2. Initially, without flow the signal is adjusted to the region of maxima by processing in NI LabView and giving the input energy pulse from JSR Control panel. The reference signal considered without flow is taken. Later, once the flow gets stabilized, the signal is recorded. The processing of the signal by Matlab Code was carried out to find the shift in the signal by using cross-correlation. Using equation 1, the δ_i value can be evaluated by knowing the time delay(t_d).

$$\delta_i = \frac{t_d * V_{air}}{2} \tag{5}$$

$$\bar{\delta} = \frac{1}{n}\sum_{i=1}^{n}\delta_i \tag{6}$$

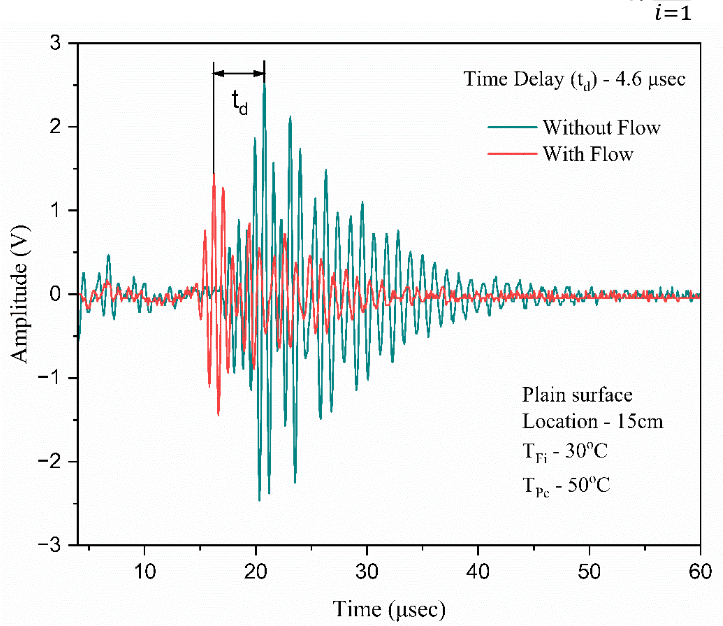

Fig. 2: Shift in signal with and without flow

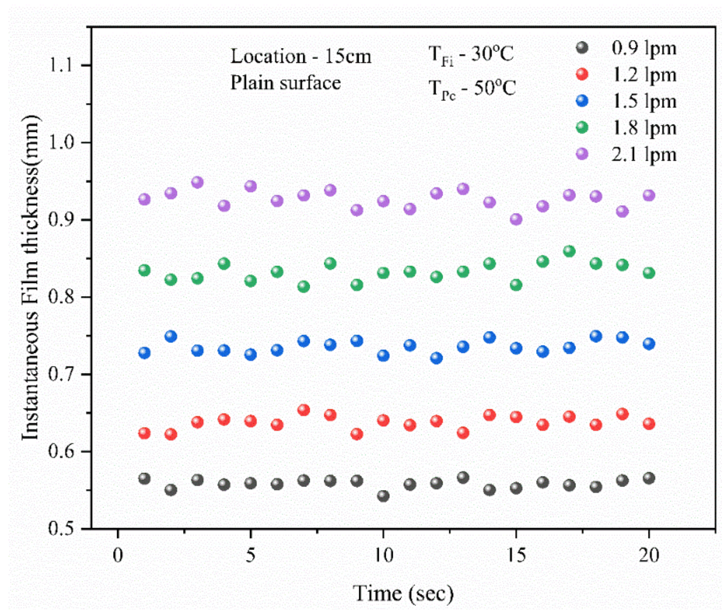

Fig. 3: Variation of Instantaneous Film thickness with time

The variation of film thickness dynamically is represented in Fig 3. It can be seen that the film thickness fluctuation increases at a higher flow rate. Also, the variation in film thickness was observed to be high at higher operating conditions compared to a lower flow rate. The measurements was taken at the inlet water temperature of 30°C supplied from a constant temperature water bath. The plate center temperature was maintained at 50°C during the entire operating range by the Temperature controller.

3.1. Film thickness variation with location

Fig. 4 shows the film thickness change along the plate's length. It is observed that the film thickness increases initially up to approximately 5 cm along the plate's length in the plate's centreline. A similar trend was observed on inclined plates by Bing Tan et al.[13] , however, it was observed for inclined plates of different inclinations. But, the trend follows the same, and the sharp change decreases after 5 cm. After 5 cm, the film thickness still changed a bit, possibly due to fluctuation in film flow. Also, the flow rate influences the film thickness and increases with the flow rate increase. However, the trend remains the same; the fluctuation may increase since the flow becomes more turbulent at a higher Reynolds number.

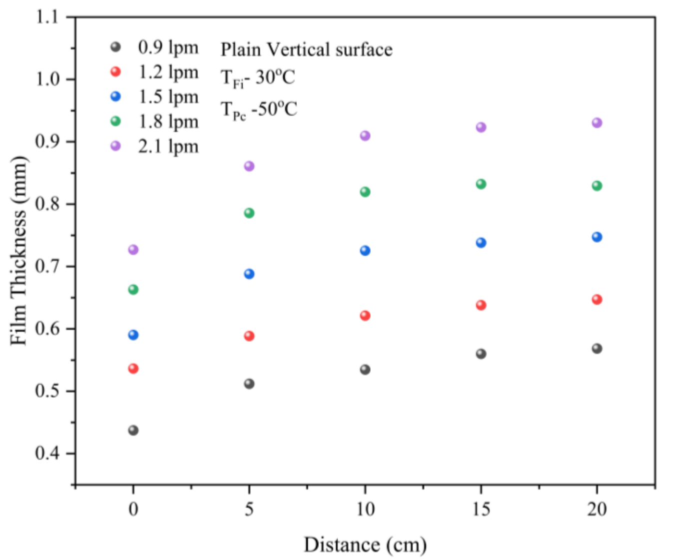

Fig. 4: Film thickness variation along the length of the Plain plate

The metal foam layered surface has a similar trend in film behaviour, as represented in Fig. 5. The film thickness increases sharply until 5 cm from the entrance. After approximately 5 cm, the film thickness does not vary much with distance. The film thickness for the plain surface was 0.5 to 0.9 mm for the Reynolds number range of 800 to 1800. But, in a metal foam layered surface, the film thickness was 0.8 to 1.3 mm for the same range. This comparison was made at a distance of 15cm for both surfaces.

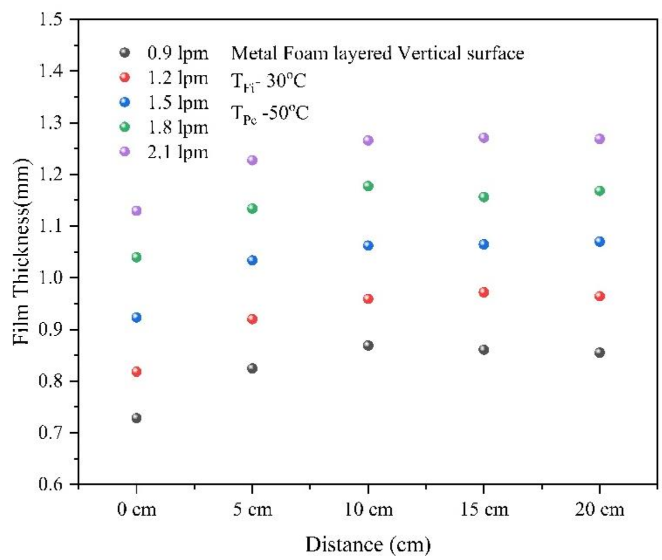

Fig. 5: Film thickness variation along the length of the Metal Foam layered plate

3.2. Validation with Literature

Fig. 6 illustrates the validation process wherein the measured values obtained from the air-coupled ultrasonic sensor are compared against established correlations in existing literature. As the Reynolds number rises, the average film thickness demonstrates a corresponding increase. It is worth noting that the deviations in the average film thickness, as reported by

Brauer et al. [3], Aragaki et al. [4], and Takahama et al. [2], amount to 3.6%, 4.2%, and 9.6%, respectively. This collective analysis underscores that the deviation in the average film thickness remains consistently within the range of ±10%. The experiment value shows a lower value when compared to literature in the range of Reynolds number. However, Takahama [2] over-predicts the value of film thickness compared to other correlations.

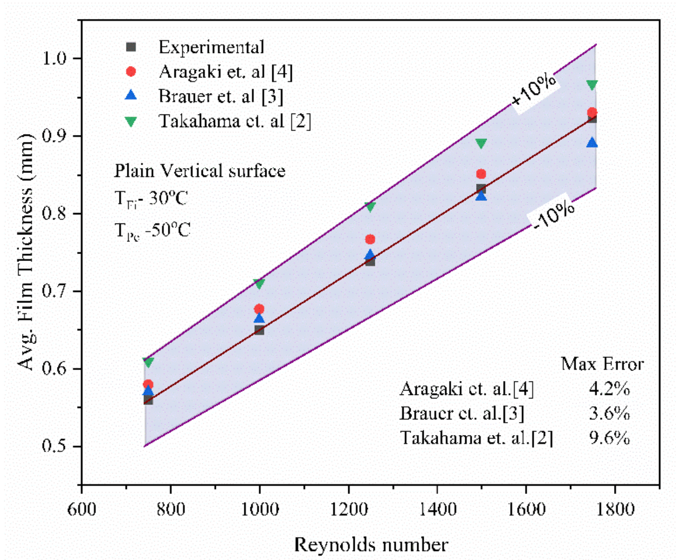

Fig. 6: Validation of Experimental data with correlation

The relative increase in film thickness with respect to the modified plate is represented in Fig. 7. It is observed that film thickness will increase on both the plain and modified surface, with an increase in film thickness. However, it was also observed that metal foam, due to its tortuous flow, will increase the disturbance in the flow and make it more turbulent even at a lower flow rate. Due to this, the film thickness variation is high, and the film thickness increases from 1.3 to 1.6 times higher than the plain vertical surface. The increase in film thickness in tubes was 2.1 times higher than in plain tubes, whereas in vertical plate, the maximum increase in film thickness was 1.6 times. However, it was observed that the heat transfer coefficient was still 2.7 times higher than the plain tube by Jayakumar et al. [12]. This shows that the vertical surface has the potential to transfer more heat, as the film thickness will be comparatively lower, so the thermal resistance will be relatively lower. Leading to an increase in heat transfer coefficient even though the film thickness is relatively high.

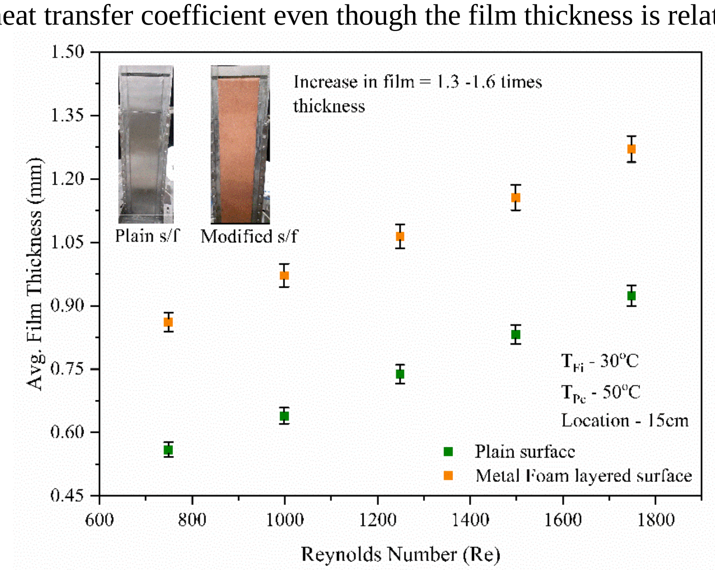

Fig. 7: Film thickness variation for plain and modified surface with Reynolds number

3.3. Film thickness variation with plate surface temperature

The film thickness will decrease due to increased plate surface temperature, depicted in Fig. 8 for the plain surface. Film thickness will increase with an increase in Reynolds number irrespective of temperature. However, at 70°C, the film thickness is relatively lower compared to temperatures at 50°C and 60°C. At lower Reynolds numbers, the film thickness decreases more than at higher Reynolds numbers. This may be because as the flow rate increases, the time available for the film to increase its temperature gets reduced. Hence, there is less difference between film thickness irrespective of temperature at a higher Reynolds number.

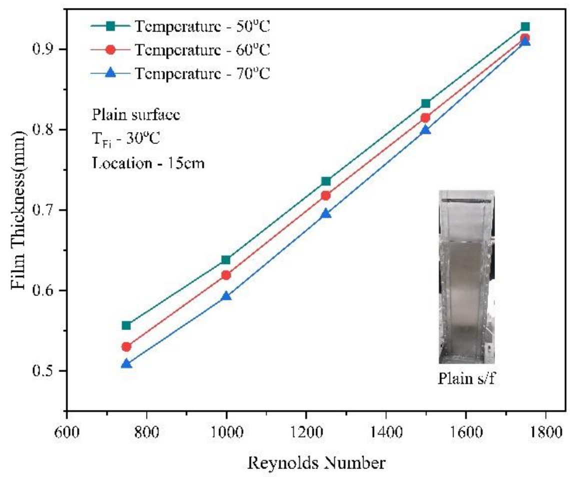

Fig. 8: Film thickness variation due to different plate surface temperature

The variation in film thickness on the modified surface is depicted in Fig. 9. A similar pattern to that seen on the plain surface is seen. At lower Reynolds numbers, the variation in film thickness between temperatures of 50°C, 60°C, and 70°C is significant. The gap between the film thicknesses narrows as the Reynolds number grows, regardless of the increase in film thickness. However, the film wettability of the surface was better in the case of a Copper metal foam layered surface than a plain surface. Because the metal foam makes the surface more turbulent, it diminishes the water's cohesive effect. At lower flow rates, the dominant cohesive force of the water causes the film flow to exhibit non-uniform surface wetting and concentration in the centre region of the plate. In a Copper metal foam layered surface, we may decrease the flow rate up to 0.6lpm (while still completely wetting the entire surface), which was not achievable on a plain surface. A low Reynolds number will also result in a further reduction in film thickness.

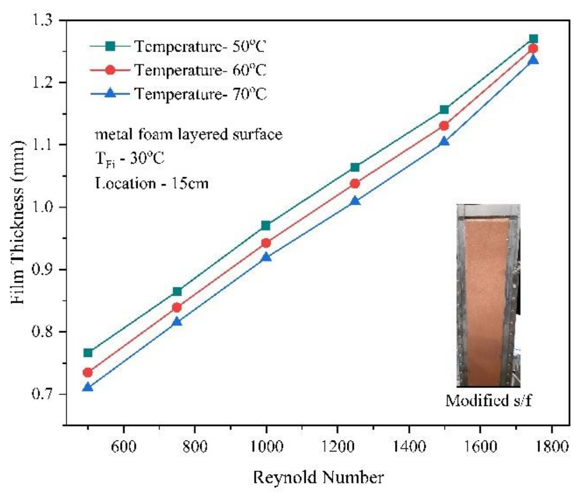

Fig. 9: Film thickness variation due to different plate surface temperatures with Copper foam

4. Conclusion

The air-coupled ultrasonic sensor is employed to gauge film thickness on unaltered and modified surfaces. When comparing the results obtained from our experimental measurements to various existing correlations in the literature, the film thickness falls within a range of ±10%. On the plain surface, the average film thickness is smaller than the copper metal foam-coated plate. Specifically, the average film thickness on copper metal foam layered plate ranges from 1.3 to 1.6 times greater than the plain vertical flat plate. The dynamic fluctuations in film thickness increase with higher Reynolds numbers. The inclusion of copper metal foam introduces a tortuous flow path, which enhances the mixing of the flow and promotes uniform distribution.

Consequently, the minimum flow rate achievable on the plain surface is restricted to 0.9 litres per minute (lpm), whereas on the modified plate, it can be further reduced to 0.6 lpm. This reduced flow rate also ensures uniform flow across the surface due to the foam structure's ability to mitigate water's cohesive effects. The film thickness increases approximately to 5 centimeters on plain and modified surfaces. Later, a minor change in film thickness is observed, likely attributable to film fluctuations. As the surface temperature of the plate rises, the average film thickness decreases on both surfaces. Notably, the decrease in film thickness is less pronounced at high flow rates but becomes more substantial at lower flow rates.

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