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Study of orientation effects to pool boiling heat transfer performance from the circular pin fins structure

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ABSTRACT

Increasingly sophisticated technological advances generate heat that needs to be managed properly to ensure the optimality of the operation of these components. One solution offered is the pool boiling cooling method, which has a high heat transfer coefficient. This research aims to study how the orientation angle of the boiling pool affects the heat transfer coefficient. This approach aims to improve cooling effectiveness, especially in the context of moving systems, where the influence of orientation angle is an important factor. In the research related to pool boiling, various orientation angles from 0° to 20° were used on aluminum-based fins in the form of inline pin fins. These fins have a circular shape with a size of 30 mm × 30 mm. The working fluid used in this study is HFE-7100, which has dielectric properties. This study was conducted with heat levels ranging from 10 to 50 W before reaching the Critical Heat Flux (CHF) value. The results show that the orientation angle has a significant impact on the heat transfer coefficient as well as the dynamics of bubble formation. The results also indicate that the greater the orientation angle, the smaller the area of spread and bubble growth that occurs. This decrease in bubble growth area results in an increase in surface temperature. With the circular pin fins test specimen, an increase in surface temperature was found in this study, when the angle $\theta = 10°$ amounted to 1.08℃, for the angle $\theta = 20°$ amounted to 2.37℃ under the condition of $q'' = 55.56$ kW/m^2. While the highest average value of heat transfer coefficient $(\bar{h})$ occurs at angle $\theta = 0°$, the value $(\bar{h})$ reaches 3.91 kW/m^2·K and decreases at angle $\theta = 10°$ by 3.79%, for angle $\theta = 20°$ by 6.56%

Keyword: Angle orientation; circular pin fins; heat transfer coefficient; pool boiling; boiling phenomena

1. INTRODUCTION

Advanced cooling systems are now more commonly applied to electronic devices. In this system, the increasing value of heat to be reduced is due to the increasing number of chips in electronic devices to increase their speed. Among other things, electronic products are currently made with increasingly smaller sizes. Along with the development of this technology led researchers to find out the latest ways to keep electronic temperatures at reasonable limits [1]. An effective cooling system must be able to remove high heat flux and keep the device temperature at 85℃ [2].

Conducted research by utilizing a two-phase cooling system which also uses sensible alone [3]. While the use of fan-cooled heatsinks and single-phase liquid cooling is still not optimal for keeping electronic temperatures at reasonable limits [4].

The research of phase change heat transfer and its enhancement methods is one of the most frequently used fields in the entire field of thermal engineering studies. One of them is pool boiling, which is a system with a high heat transfer rate and is exploited in many engineering fields including electronic cooling, process engineering (evaporation and separation of various media) and refrigeration. Many new surface treatments or working fluid variations are also angle oriented in order to enhance this phase change phenomenon [5].

Describe that the pool boiling heat transfer system can also be applied to battery thermal management systems. It is also important to pay attention to the orientation of the battery when the car is moving, especially when going uphill because the orientation affects the heat transfer efficiency. Therefore, determining the optimal orientation is very important to support maximum heat transfer [6]. The ideal temperature of lithium-ion batteries is between 25–40 °C and the temperature difference between batteries should be less than 5 °C [7]. Examined the effect of orientation on pool boiling where the measured boiling curve results showed that the boiling heat flux was insensitive to orientation in the lower heat flux region and increased with decreasing orientation in the higher heat flux region [8].

Described the effect of surface orientation on the boiling point heat transfer of saturated pools and CHF. Heat transfer improved at heat transfer between 0° and 90° and deteriorated between 90° and 180° for bare surfaces [9]. Jung, et al. examined the effect of surface orientation on wall boiling heat flux and bubble parameters in a nucleate boiling pool. They reported that the heat flux and nucleation site density increased as the orientation of the heating surface increased [10]. Conducted pool boiling experiments at different heating angles and different roughness values. The results obtained increased bubble size and decreased bubble departure frequency as the tilt angle increased. The boiling point heat transfer capability also decreases as the angle of the heater increases [11]. State that vapor bubbles are a significant cause of heat dissipation from the heating surface. Bubble diameter and frequency affect the heat transfer from the surface to the surrounding liquid [12]. In the analysis of bubble dynamics, it is suggested that the attachment of bubbles to the heating surface is caused by surface tension forces while their detachment is caused by buoyancy forces [13].

The orientation angle is a major part of this case because it affects the ability of the cooling fluid to form vapor bubbles on the heating surface and flow through the vapor bubbles. If the orientation angle is not correct, it is possible for vapor bubbles to not form properly, or it can even increase the overheat of the system. Studied the nucleate boiling of FC-72 and HFE-7100 on porous graphite at different orientations and subcooling conditions of both working fluids on the surface of porous graphite with a size of 10 mm × 10 mm. The study varied the surface orientation from θ = 0 to 180° in 30° increments with subcooling conditions up to 30 K as shown in *Figure 1*.

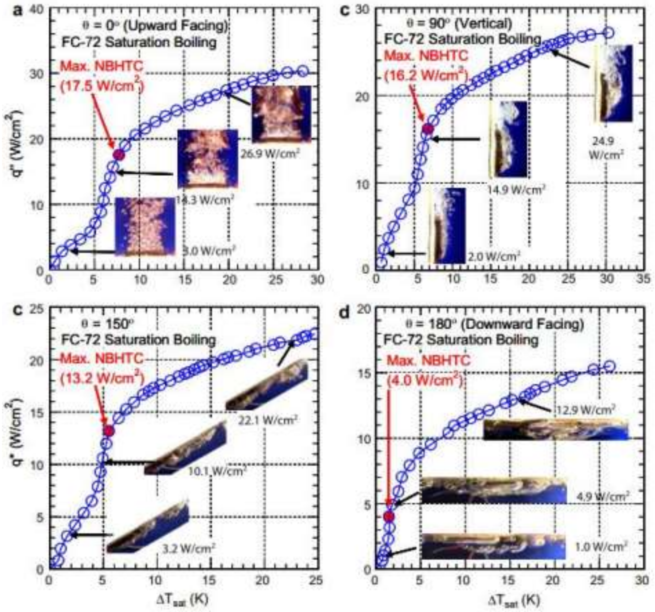


Figure 1. FC-72 boiling curves at four surface orientations.

The value obtained from the critical heat flux (CHF), shows that the heat transfer coefficient (HTC) using FC-72 working fluid on the surface of porous graphite results obtained increased up to

52% higher than the working fluid HFE-7100. This increase in heat transfer coefficient can be influenced by the increase in temperature during the subcooling state [14].

Conducted research to determine the effects of orientation in pool boiling systems and bubble movement. In this study, the working fluid used was water. The results of this experiment can be seen that the coupled bubble diameter and departure frequency increase with increasing heater orientation. However, the density of active nucleate sites was measured to be independent of the tilt angle. The relationship of bubble dynamics with wall superheat and heater orientation can be obtained by means of least-square-error regression. With the input of this regression correlation, the wall heat flux partition model can be assessed by the boiling curve of the structure when under various heater orientations [15]. It can be seen from the visualization results in Figure 2.

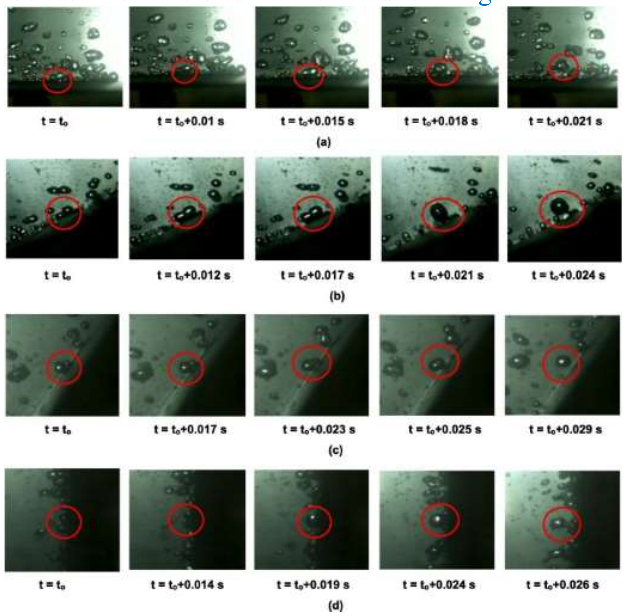


Figure 2. Bubble coalescence process and bubble detachment characteristics from the hot surface for (a) θ = 0°; (b) θ = 30°; (c) θ = 60°; (d) θ = 90°

A boiling process is characterized by the formation of vapor bubbles that develop and detach from the heating surface. In the context of bubble formation, various factors such as excessive temperature difference, heating surface characteristics, as well as thermophysical properties of the working fluid such as surface tension play an important role [16]. On the other hand, the formation of dynamically moving vapor bubbles is affected by the movement of the liquid around the surface, which is measured by the convection heat transfer coefficient. The rate of heat transfer in the boiling process is often described using Newton's cooling law, which can be expressed in the form of Eq.

$$q''_{boiling} = h\,(T_s - T_{sat}) = h\,\Delta T_{excess} \tag{1}$$

The actual wall surface temperature (T_s) is the temperature used in the generation of the boiling curve. (T_s) is obtained through calculation by considering the temperature read on the wall surface (T_w). The equation for calculating the actual temperature on the wall surface (T_s) can be formulated as follows:

$$T_s = T_w - q\left(\frac{L}{k\,A_s}\right) \tag{2}$$

In conduction heat transfer, a material has thermal resistance on the wall surface. Thermal resistance is the calculation of the heat conductive capacity of a material per unit of a material. Calculation of conduction thermal resistance contained in a flat plane is seen in Eq.

$$R_w = \frac{L}{k\,A} \tag{3}$$

Conducted experiments where the results showed that the heat transfer coefficient (HTC) will decrease when the surface orientation angle increases [17]. On the contrary, the HTC value increases when the temperature difference at the wall surface (ΔT) decreases or when the heat flux q'' increases.

The decrease in HTC caused by an increase in surface orientation angle has a significant impact on the boiling performance in liquid-filled containers. The equation to calculate the heat transfer coefficient can be found in Eq.

$$h = {q''}/{(T_s - T_w)} \tag{4}$$

2. METHODS

2.1 Schematic of pool boiling test apparatus

This pool boiling system research is to examine the effect of orientation angle variation on the geometry of circular pin fins as well as on the characteristics of the bubble phenomenon. Some of the important components used in this research are boiling chamber, condenser, heater block, sensor, data acquisition system (DAQ), and macro camera. We can see the schematic of the orientation boiling pool test facility in Figure 3 and Figure 4. It is shown that the boiling chamber functions as a reservoir of working fluid made of aluminium base material with two windows made of acrylic. Heater block in this study uses a cartridge heater mounted into copper. Heat will enter through the input and change the phase from liquid fluid to vapor phase. The condenser used is coil-shaped which is safe in that it will be watered by the coolant driven by the pump. The photograph of the experimental facility is presented in Figure 5.

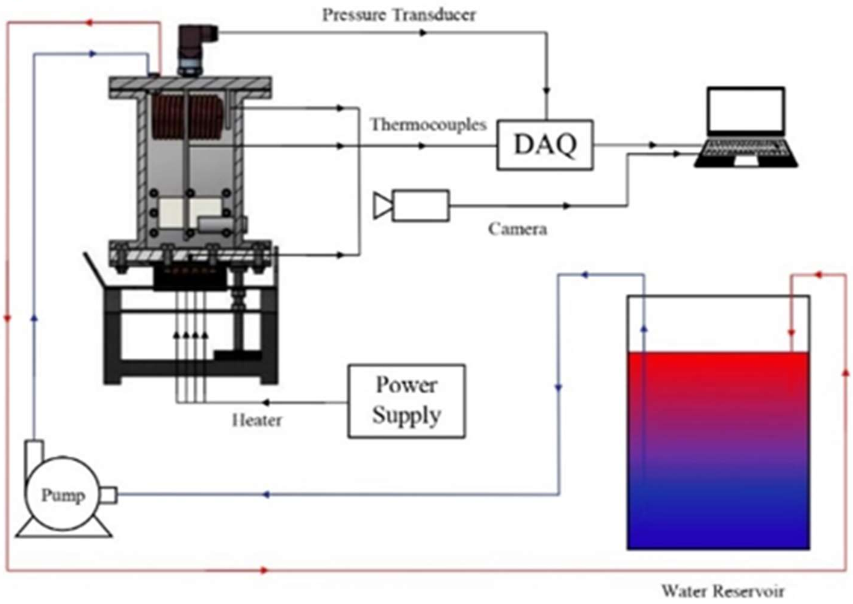
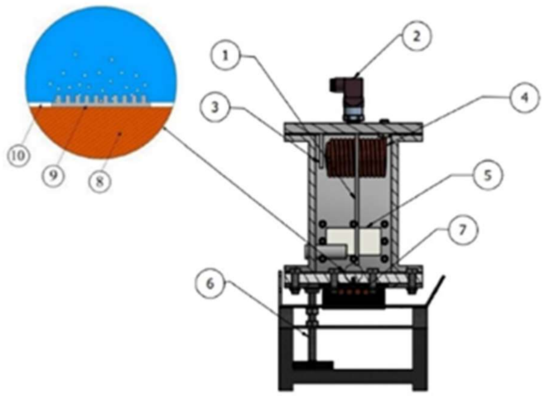


Figure 3. Schematic diagram of the orientation boiling pool test facility



1. Thermocouple
2. Pressure transducer
3. Thermocouple
4. Cooling Pipe
5. Viewing Window Wall
6. Orientation Lever
7. Heaters
8. Copper Block
9. Fins
10. Teflon Insulator

Figure 4. Schematic of pool boiling test material placement and orientation angle

Figure 5**.** Photograph of pool boiling test facility

2.2 Working fluids

In this study, the working fluid used is HFE-7100 dielectric fluid due to its low boiling point and excellent thermal and chemical stability, which allows nucleate boiling to occur at low surface temperatures. Such a low boiling point can keep the components of the experimental test facility working in good condition. Table 1 like other phase change liquids, HFE-7100 is chlorine-free which minimizes the potential for ozone depletion.

Table 1**.** Properties of HFE-7100 at 25°C, 1 atm pressure

Properties	Value
Boiling point at 1 atm (°C)	61
Vapor pressure (kPa)	28
Density of liquid (kg/m^3)	1418
Density of vapor (kg/m^3)	9,7
Specific heat (J/kg·°C)	1170
Enthalpy of vaporization (kJ/kg)	112
Thermal conductivity (W/m·K)	0,068
Surface tension (mN/m)	13,6
Dielectric strength 0.1" gap, E_{max} (kV)	40

2.3 Circular pin fins

In this study, circular pin fins were used as workpieces. Circular pin fins serve to increase the surface area of the test sample in the boiling pool. This is so that more heat can be absorbed and result in better cooling efficiency or reduce excess heat buildup. Aluminum was chosen as the base material for circular pin fins in this pool boiling research because it has high thermal conductivity. The pin fins design can be seen in Figure 6.

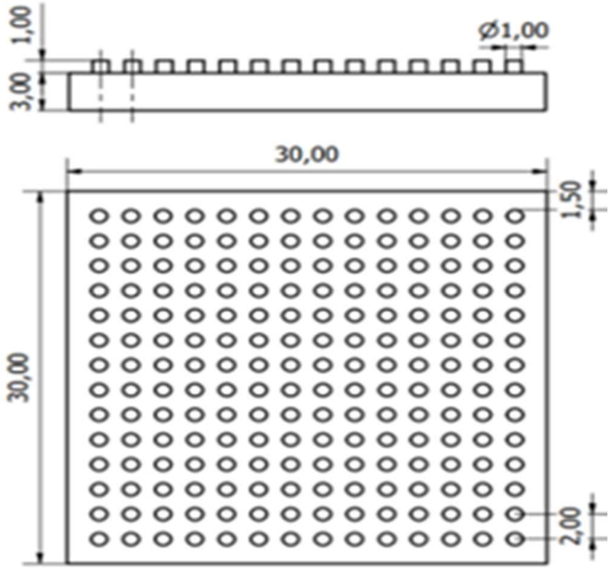


Figure 6**.** Circular pin fins test specimen

3. RESULTS AND DISCUSSION

3.1 Calculation of heat transfer coefficient

The calculation results of circular pin fins with orientation angles of 0°, 10°, and 20° obtained heat transfer coefficient values as Table 2, Table 3, and Table 4.

Table 2. Heat transfer coefficient of circular pin fins at $\theta = 0°$

q (W)	**T_W (°C)**	**T_S (°C)**
10	38.36	37.44
15	44.69	43.30
20	49.17	47.31
25	57.41	55.10
30	64.99	62.21
35	70.80	67.56
40	76.07	72.36
45	81.34	77.17
50	86.27	81.63

q (W)	**q'' (kW/m^2)**	**$T_S - T_{sat}$ (K)**	**h (kW/m^2·K)**	**h_{avg} (kW/m^2·K)**
35	38.89	6.56	5.93	3.91
40	44.44	11.36	3.91	
45	50.00	16.17	3.09	
50	55.56	20.63	2.69	

Table 3. Heat transfer coefficient of circular pin fins at $\theta = 10°$

q (W)	**T_W (°C)**	**T_S (°C)**
10	39.01	38.08
15	43.03	41.64
20	47.63	45.78
25	56.26	53.94
30	63.32	60.54
35	71.08	67.83
40	76.34	72.63
45	82.07	77.90
50	87.34	82.71

q (W)	**q'' (kW/m^2)**	**$T_S - T_{sat}$ (K)**	**h (kW/m^2·K)**	**h_{avg} (kW/m^2·K)**
35	38.89	6.83	5.69	3.76
40	44.44	11.63	3.82	
45	50.00	16.90	2.96	
50	55.56	21.71	2.56	

Table 4. Heat transfer coefficient of circular pin fins at $\theta = 20°$

q (W)	**T_W (°C)**	**T_S (°C)**
10	40.14	39.22
15	46.91	45.52
20	54.38	52.53
25	62.93	60.61
30	68.19	65.41
35	75.72	72.47
40	81.70	78.00
45	86.89	82.72

q (W)	T_W (°C)	T_S (°C)
50	90.64	86.00

q (W)	q'' (kW/m^2)	$T_S - T_{sat}$ (K)	h (kW/m^2·K)	h_{avg} (kW/m^2·K)
35	38.89	7.15	5.44	3.65
40	44.44	12.23	3.63	
45	50.00	17.35	2.88	
50	55.56	21.01	2.64	

As the level of heat flux increases, the frequency of formation of growing bubbles also increases. This bubble motion transports heat from the heated surface and moves the heat away from the heat source surface to the free surface. This bubble formation occurs due to the phase change from liquid to gas. The cooler liquid around the bubble will fill the space left by the bubble and a new bubble will form again. As the bubble growth area increases, the faster the frequency of bubble growth, the faster the heat transfer process that occurs.

In the observations made, the effect of increasing the orientation angle given by the bubble growth area decreases. The difference in bubble growth is due to the flow resistance that affects bubble growth, which also affects the speed of heat transfer in the pool boiling system. To find out more about the effect of the orientation angle on the heat transfer of the boiling pool, it is necessary to compare the HTC value with the increase in orientation angle. The results of the research obtained the relationship between heat flux q'' and $T_s - T_{sat}$. In this study, the difference in the results obtained at each variation of orientation angle is due to the influence of the difference in the area of bubble growth that has a significant impact on the results obtained at various orientation angles. At an angle of $\theta = 0°$, the bubble growth area is the largest compared to other angles. Any increase in the angle value results in a decrease in the bubble growth area. This difference in bubble growth is due to the fluid flow resistance that affects the bubble growth process. The bubble growth area affects the heat transfer rate in the pool boiling system. Bubbles carry heat from the surface of the fins to the free surface. The surrounding cooler fluid then fills the space left by the bubbles (rewet) and forms new bubbles. The larger the bubble growth area and the faster the frequency of bubble emergence and release, the faster the heat transfer process takes place. Figure 7 shows the boiling curve of circular pin fins.

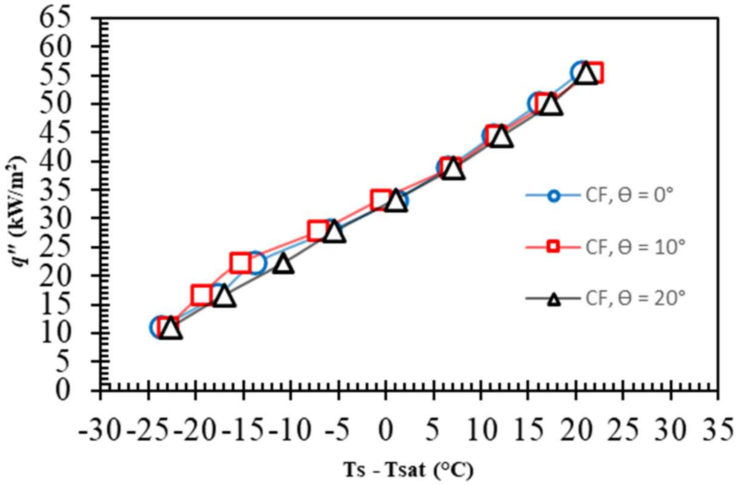
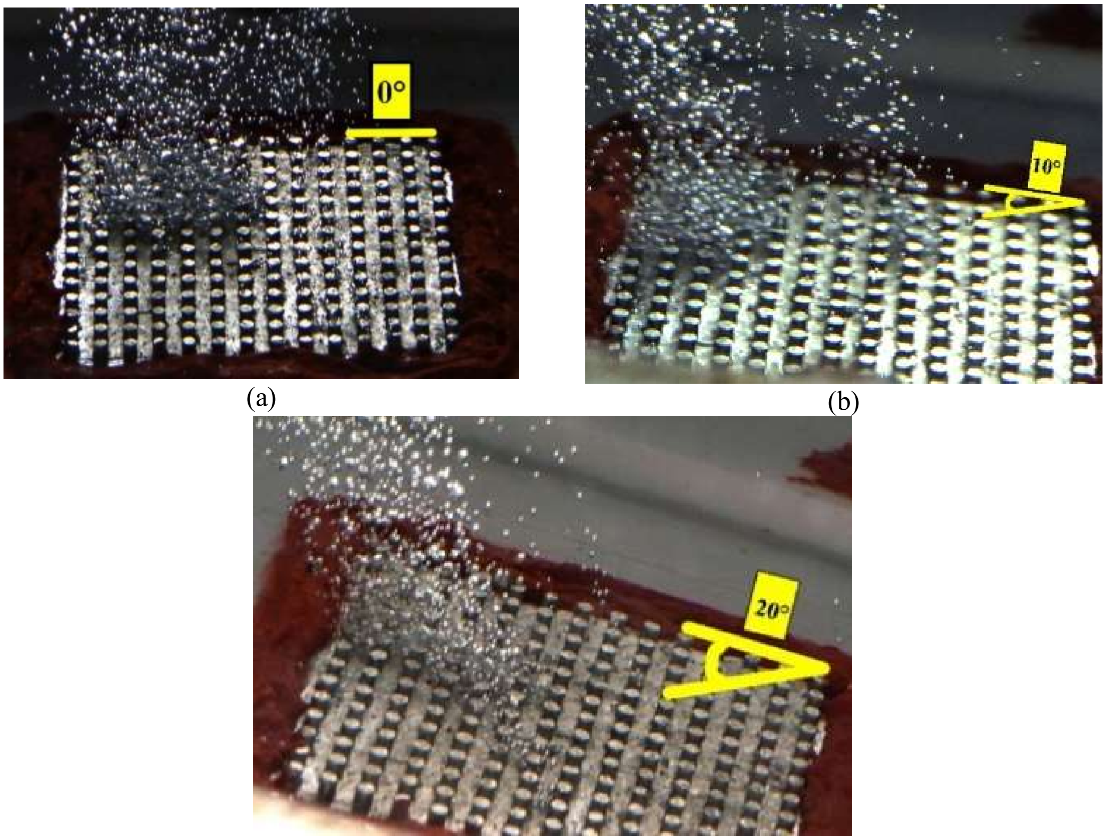


Figure 7. Boiling curve for circular pin fins

3.2 Visualization

In the results of this study under the condition of $q'' = 55.56$ kW/m^2 from the three orientation angles of $\theta = 0°$, $\theta = 10°$ and $\theta = 20°$, but the orientation angle of $\theta = 0°$, the bubble growth area has the largest area compared to other orientation angles. While with increasing orientation angle, the bubble growth tends to decrease. Thus in this study, the orientation angle $\theta = 20°$, produces the most minimal bubble growth. It can be seen in Figure 8 the visualization results of pool boiling experiments with orientation angles of 0°, 10°, and 20°.



(a) (b)

(c)

Figure 8. Visualization of pool boiling at orientation angles of (a) 0°; (b) 10°; and (c) 20°

3.3 Heat transfer coefficient analysis

The main objective of the analysis is to understand how the heat transfer coefficient changes with the variation of heat flux and orientation angle, so as to find the best performance in heat transfer under the given experimental conditions. From the experimental results of the pool boiling test equipment, the relationship between HTC and heat flux can be seen, where HTC can change smaller with high heat flux changes. Where the average value of heat transfer coefficient for various orientation angles as follows: for θ = 0° of 3.91 kW/m^2·K, for θ = 10° of 3.76 kW/m^2·K and for θ = 20° of 3.65 kW/m^2·K. shown in Figure 9 below.

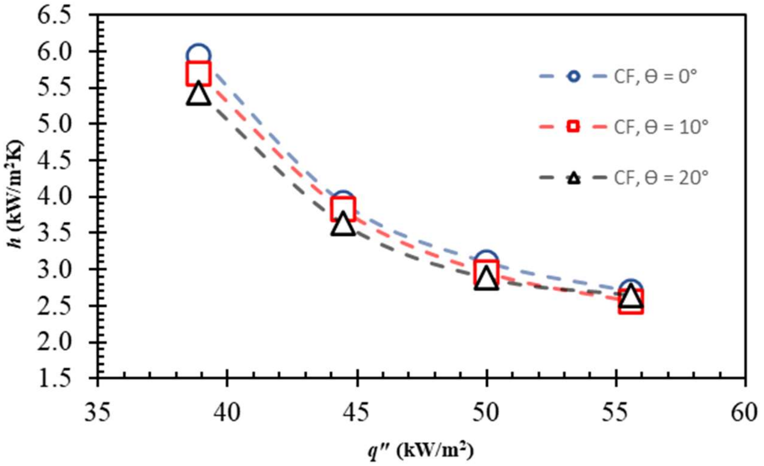


Figure 9. Heat transfer coefficient value of circular pin fins

4. CONCLUSIONS

From the results of the calculation and analysis of the effect of orientation angle and geometry on the fins that have been carried out, it can be concluded that the results of the pool boiling experiment visualization show that when the orientation angle value is greater, there is a reduction in the distribution area and bubble growth on the circular pin fins. This results in an increase in surface temperature and heat flux, but a decrease in heat transfer performance. The orientation angle has a significant impact on the heat transfer coefficient in the pool boiling process. For all types of fins tested, the orientation angle $\theta = 0°$ resulted in a high average value of heat transfer coefficient, while $\theta = 20°$ resulted in a low average value $(\bar{h})$. When the surface temperature rises after reaching the saturation temperature, it results in a significant increase in heat flux, but at the same time, the resulting heat transfer coefficient value decreases.

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