International Seminar on Student Research in Education, Science, and Technology
ISSN 3047-1532 | Volume 2 April 2025, pp. 382-390
https://www.issrestec.id/
http://journal.ummat.ac.id/index.php/issrestec
Universitas Muhammadiyah Mataram, Indonesia

Study of Heat Transfer and Bubble Dynamics in Pool Boiling with Orientation Angle Variations Using Dielectric Fluids on Porous Metal Foams

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Abstract: The advancement of technology in various fields has increased the demand for efficient thermal management systems, one of which is two-phase cooling through pool boiling. This study investigates the effect of heater orientation angle variation on the heat transfer coefficient (HTC) and bubble dynamics using the dielectric working fluid HFE-7100 and metal foam as the test material. Experiments were conducted at orientation angles of 0°, 15°, and 30° using image processing techniques and measurement instruments such as thermocouples, pressure transducers, and a data acquisition system. The measurement data results show that as the orientation angle (θ) of the heater and test material increases, the HTC value decreases. The orientation angle (θ) = 0° has the highest h value of 4.019 kW/m²K, while the orientation angle (θ) = 30° has the lowest $\bar{h}$ value of 1.042 kW/m²K. Image processing data show that as the orientation angle (θ) increases, the bubble distribution and growth area on the metal foam decrease. This reduction in bubble distribution and growth affects surface temperature and heat flux, which increase, but the overall heat transfer performance declines.

Keywords: Bubble Dynamics, Heat Transfer Coefficient, Metal Foams, Orientation Angle, Pool Boiling.

Article History:
Received: 23-04-2025
Online : 26-04-2025

A. INTRODUCTION

The development of technology in the electronics, healthcare, electric transportation, avionics, and manufacturing sectors has contributed to the increase in heat generated from these processes (Mudawar, 2013). This high heat increase leads to a decline in performance and reduces the lifespan of electronic devices. An effective cooling system must be capable of dissipating heat and maintaining the device temperature at a desired level, typically below 85°C. Consequently, conventional single-phase cooling approaches fail to meet the current heat dissipation demands. The pool boiling system offers a novel solution by utilizing cooling fluids effectively for thermal management applications. This system is beneficial for keeping electronic components within the normal operating temperature range (Wang et al., 2024). The data in Figure 1 illustrate the heat transfer capability comparison between two-phase cooling (pool boiling) and conventional single-phase cooling. Based on the data, it can be concluded that the two-phase cooling method is a more effective solution for addressing excessive heat and has become a primary focus in the development of future cooling methods (Liang & Mudawar, 2018b).

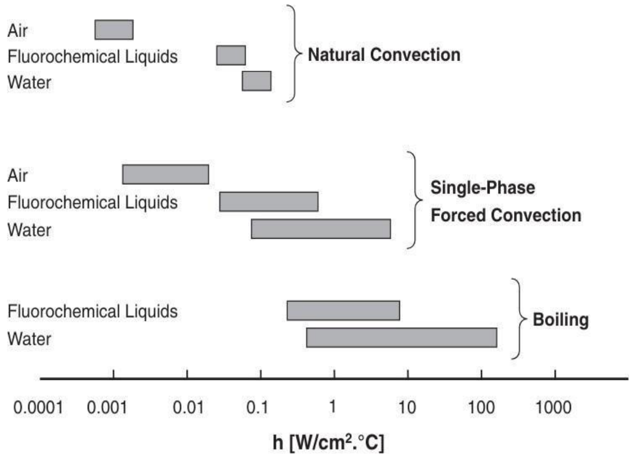


Figure 1. Comparison of HTC values for natural convection, single-phase forced convection, and boiling (Source: Liang & Mudawar, 2019).

Previous researchers have made numerous efforts to enhance pool boiling performance. These include modifications to the heating surface and adjustments to the position or orientation angle of the heating surface, all aimed at improving the heat transfer coefficient (HTC) of the cooling system (Sajjad et al., 2021). The orientation angle plays a significant role in the cooling system as it can affect overall performance. Pool boiling is a process in which the cooling fluid moves across a heated surface until it reaches its boiling point. In this context, the orientation angle becomes a key factor as it influences the ability of the cooling fluid to form and release vapor bubbles from the heating surface. An improper orientation angle can hinder bubble formation or even cause bubbles to become trapped on the surface, ultimately reducing cooling efficiency and increasing the risk of overheating. (UL Standard, 2019). With the rapid advancement of electronic technology, research on effective cooling systems has become essential. Advanced cooling system studies focusing on variations in orientation angles are crucial, as they can impact the optimal performance, lifespan, and application of electronic devices.

Previous studies have examined orientation angle variations ranging from $\theta = 0°$ to 20° in 5° increments on aluminum fins with different geometries, namely circular and square, each measuring 30 mm × 30 mm. The working fluid used was dielectric HFE-7100. The experiments were conducted at heat levels ranging from 10 W to 50 W, with observations made before reaching the critical heat flux (CHF). The results indicated that the orientation angle significantly affects the heat transfer coefficient and bubble dynamics. This study found that as the orientation angle (θ) increases, the bubble growth and distribution area tend to decrease. The highest average heat transfer coefficient ($\bar{h}$) was achieved at $\theta = 0°$, with a value of 5.18 $kW/m^2{\cdot}K$ for Circular Pin Fins (CPF). However, $\bar{h}$ decreased as θ increased. Meanwhile, Square Pin Fins (SPF) exhibited the best performance at $\theta = 0°$, with an $\bar{h}$ value of 3.97 $kW/m^2{\cdot}K$, as shown in Figure 2. A comparison between the two pin fin variations, CPF and SPF, demonstrated that CPF performed better than SPF. (Perbawa & Pranoto, 2023).

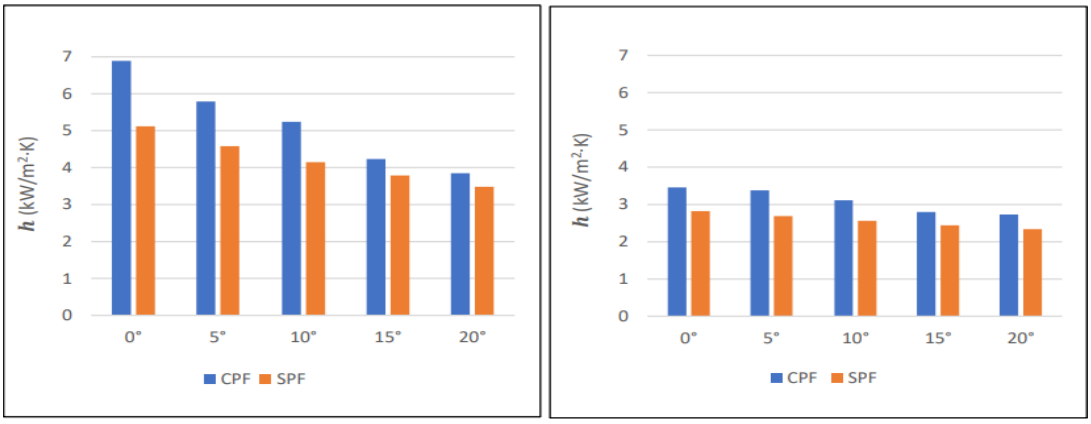


Figure 2. Comparison of Heat Transfer Coefficient (HTC) values for Circular Pin Fins (CPF) and Square Pin Fins (SPF) at heat flux values of (a) q" = 44.44 kW/m² and (b) q" = 55.56 kW/m². (Source: Prabawa & Pranoto, 2023).

Based on the research conducted by Khoiri (2024) on the effect of fin orientation angles ranging from 0° to 30° with experimental data collected at 10° intervals, the study results indicate that orientation angle has a significant impact on the heat transf er coefficient and bubble formation dynamics. As the orientation angle increases, there is a reduction in bubble growth and distribution area, which in turn affects heat transfer and increases surface temperature. When comparing the two fin variations, circular pin fins (CPF) and square pin fins (SPF), CPF demonstrated superior performance. Overall, the highest average heat transfer coefficient ($\bar{h}$) was observed at θ = 0°, reaching 3.91 kW/m²·K for CPF. However, $\bar{h}$ decreased with increasing orientation angles. For CPF, the reduction in $\bar{h}$ at θ = 10° was 3.79%, at θ = 20° it was 6.56%, and at θ = 30° it declined by 11.63%. Meanwhile, for square pin fins (SPF), the best performance was also at θ = 0°, with an $\bar{h}$ value of 3.32 kW/m²·K. The reduction in $\bar{h}$ for SPF at θ = 10° was 5.03%, at θ = 20° it dropped by 20.84%, and at θ = 30° it decreased by 22.46%, as shown in Figure 3 (Khoiri et al., 2024).

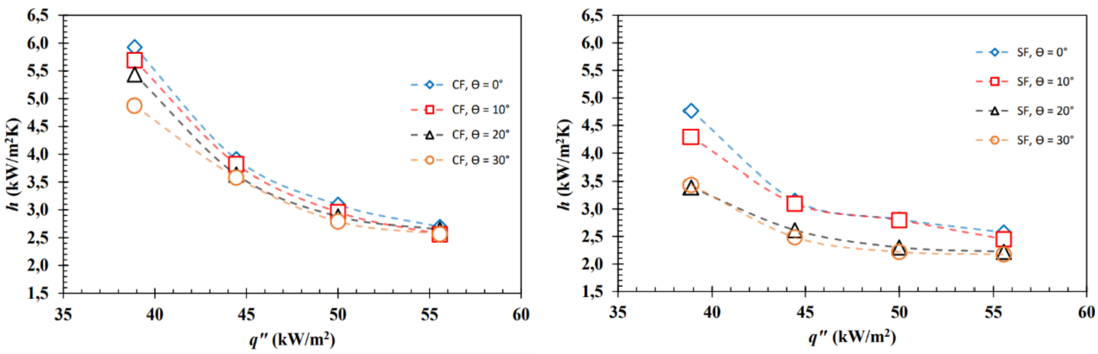


Figure 3. Comparison of Heat Transfer Coefficient (HTC) values for (a) Circular Pin Fins and (b) Square Pin Fins. (Source: Khoiri et al., 2024)

Boiling heat transfer has been demonstrated to be an effective cooling mechanism, offering a high heat transfer coefficient due to the chaotic movement of bubbles. In addition to natural convection in single-phase liquids, the cooling process is further enhanced by bubble evaporation and surface rewetting, leading to improved thermal performance. The nucleation, growth, and departure of bubbles from the heated surface contribute to efficient heat dissipation, as the bubbles carry away thermal energy and promote continuous liquid replenishment. This process ensures that the surface remains effectively cooled, preventing excessive temperature buildup. The combination of bubble dynamics and liquid rewetting makes boiling heat transfer a highly efficient mechanism, especially in applications requiring rapid and effective cooling (Pranoto et al., 2022).

One promising approach to optimizing boiling heat transfer is the use of structured porous evaporators, which have been identified as effective in enhancing thermal performance in electronic cooling applications. These porous evaporators facilitate improved bubble nucleation and liquid distribution, allowing for more uniform and efficient heat transfer. Among the various materials investigated for this purpose, porous graphite foam has shown significant potential due to its high surface area-to-volume ratio, low density, and superior thermal conductivity. These properties enable it to support high heat flux applications by enhancing boiling efficiency and maintaining stable cooling performance. The ability of porous graphite foam to sustain efficient phase-change heat transfer makes it a valuable material for advanced thermal management systems in high-power electronic devices (Pranoto et al., 2012). A study on pool boiling with an emphasis on orientation angles still requires further research as a foundation for future studies and industrial developments. The investigation of orientation angles is crucial since devices are not always positioned at a horizontal 0° but may have inclinations based on practical field requirements, affecting the heat transfer coefficient (HTC). Limitations in previous designs restricted the test materials that could be installed in the research apparatus to only fin materials. Given this background, this study aims to experimentally analyze the effect of orientation angles on the he at transfer coefficient (HTC) using a new design capable of testing foam materials.

Building upon these findings, this study investigates the effect of heater orientation angle variation on the heat transfer coefficient (HTC) and bubble dynamics using the dielectric working fluid HFE-7100 and metal foam as the test material. Experiments were conducted at orientation angles of 0°, 15°, and 30° utilizing image processing techniques and measurement instruments such as thermocouples, pressure transducers, and a data acquisition system. Understanding the influence of heater orientation on boiling characteristics will provide valuable insights for optimizing thermal management systems in high-performance applications.

B. METHOD

1. Research Flowchart

This study was conducted experimentally to investigate the effect of orientation angle variations on heat transfer in the pool boiling process using HFE-7100 as the working fluid and metal foam as the material. The applied orientation angle variations included 0°, 15°, and 30° aiming to evaluate bubble distribution and growth as well as changes in the heat transfer coefficient (HTC). The following flowchart illustrates the research or experimental stages of two-phase cooling in pool boiling.

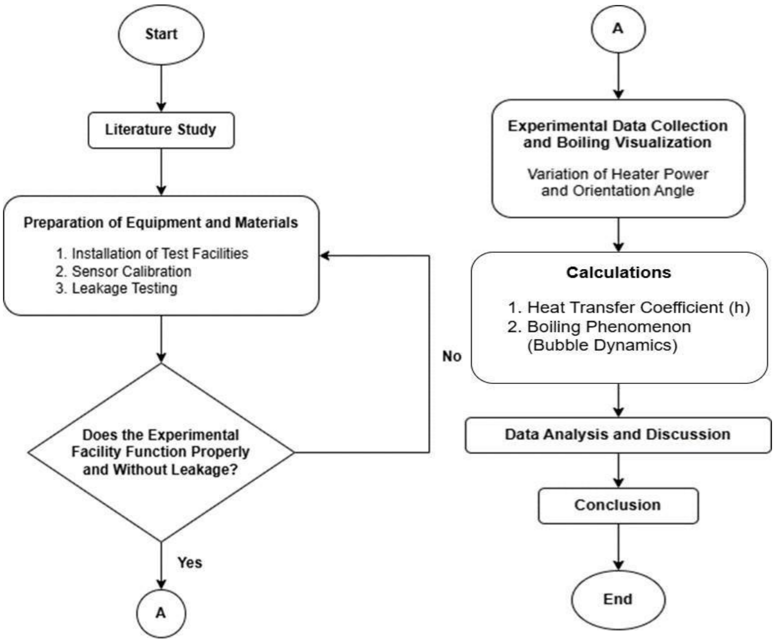


Figure 4. Research Flowchat

2. Schematic of Experimental Facility

The pool boiling experimental facility developed in this study is a device that enables testing of various types of materials, orientation angles on the heating surface, and different working fluids using the pool boiling cooling method. The components of experimental facility include a boiling chamber, condenser, heater block, sensors, data acquisition system (DAQ), and a camera. The heater block, consisting of a cartridge heater, serves as the heating element for the copper block. The heat generated by the heater is transferred to the test material, which then boils the working fluid inside the boiling chamber. The vapor formed is cooled by a coil-shaped condenser located at the top of the boiling chamber. The cooling liquid flows through the coil with the help of a pump to ensure smooth circulation.

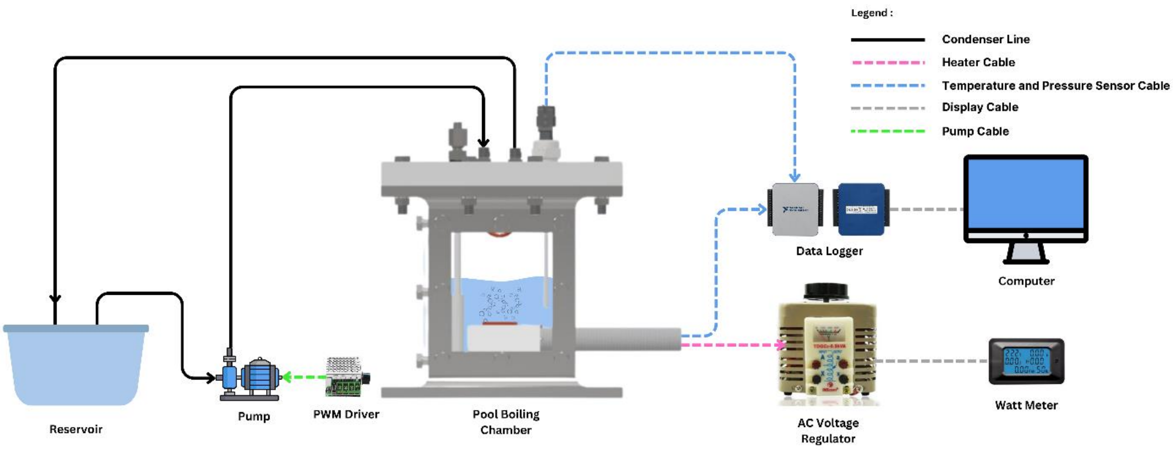


Figure 5. Schematic Diagram of the Pool Boiling Experimental Facility

3. Materials

The selection of the working fluid in this study is based on several factors, including boiling point, density, viscosity, thermal conductivity, and latent heat. HFE-7100 was chosen as the working fluid due to its low boiling point and excellent thermal and chemical stability, allowing boiling to occur at lower surface temperatures. This low boiling point also helps maintain the integrity of the test apparatus components during experiments. As a dielectric fluid, HFE-7100 has high inertness and significantly lower surface tension compared to water. Additionally, HFE-7100 is environmentally friendly with a zero-ozone depletion potential (ODP) as it does not contain chlorine.

Table 1. Properties of the test fluid at 1 atm pressure (Source: 3M, 2014).

Thermophysical Properties	HFE-7100
Boiling Point (°C)	61
Saturation Pressure (kPa)	28
Liquid Density (kg/m3)	1620
Specific Heat (J/kgK)	1170
Enthalpy of Vaporization (kJ/kg)	112
Thermal Conductivity (W/mK)	0.068
Surface Tension (mN/m)	13.6
Dielectric Strength (kV)	28

4. Experimental Data Calculation Parameters

Experimental data is collected through temperature measurements, fluid pressure monitoring, and high-speed imaging of bubble dynamics Data analysis is conducted by calculating the two-phase cooling HTC and analyzing the distribution and detachment of bubbles on the heater surface or test material, with the corresponding equations provided below. (Cengel & Ghajar, 2015).

$$T_s = T_w - q\,\Sigma\left(\frac{L}{k\,A_s}\right) \tag{1}$$

$$q" = \frac{q}{A_s} \tag{2}$$

$$h = \frac{q"}{(T_s - T_{sat})} \tag{3}$$

Descriptions:

Ts : Actual wall surface temperature (°C)
Tw : Thermocouple reading temperature (°C)
$Tsat$: Saturation temperature of the testing fluid (°C)
As : Heat exchange surface area (m^2)
q : Heater power (W)
q'' : Heat flux nucleate boiling (W/m^2)
k : Thermal conductivity of copper (W/m·K)
h : Convective heat transfer coefficient ($W/m^2 \cdot K$)

C. RESULTS AND DISCUSSION

The calculation of the heat transfer coefficient (HTC) is performed for metal foam material and the working fluid HFE-7100. After obtaining the values of q″ and $Ts - Tsat$ from the metal foam material, we can proceed to determine the heat transfer coefficient using Equations (1)-(3).

1. Calculation of Heat Transfer Coefficient in Pool Boiling with Variations in θ and q".

In the pool boiling experiment using variations in orientation angles on metal foam material, it was found that a higher heat flux (q") is inversely proportional to the heat transfer coefficient (h), as shown in Figure 6.

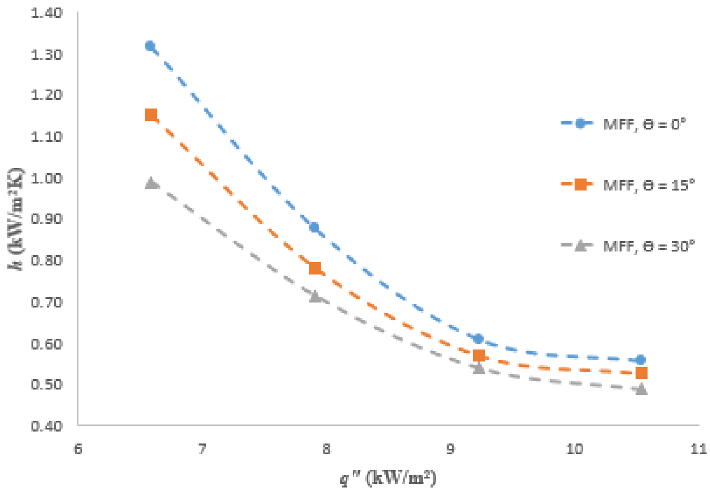


Figure 6. Comparison of heat flux and HTC values for metal foam at orientation angles (0°, 15°, and 60°).

From the experimental tests, the heat transfer coefficient values for the metal foam material were obtained with variations in orientation angles. Initially, it was found that the orientation angle and bubble growth distribution area also influence the h value. The heat transfer coefficient values for the metal foam material with different orientation angles can determine whether the heat transfer process is more efficient or less efficient. As shown in Figure 6, the greater the orientation angle of the metal foam test material, the lower the average heat transfer coefficient ($\bar{h}$) in the two-phase cooling system.

In the experimental test with a metal foam material at an orientation angle of θ = 0° the average $\bar{h}$ value was obtained. For the metal foam test material, the average $\bar{h}$ was found to be 4.019 kW/m^2.K. When q" = 9.22 kW/m^2 and q" = 10.54 kW/m^2, the heat transfer coefficient values for the metal foam were h = 0.61 kW/m^2.K and h = 0.56 kW/m^2.K, respectively. At an orientation angle of θ = 0°, the h value for the metal foam was the highest, resulting in the most extensive bubble growth distribution. Conversely, in the experimental test with the metal foam material at an orientation angle of θ = 30°, the $\bar{h}$ value was also obtained. For the metal foam test material, the $\bar{h}$ was found to be 1.042 kW/m^2.K. When q" = 9.22 kW/m^2 and q" = 10.54 kW/m^2, the heat transfer coefficient values for the metal foam were h = 0.54 kW/m^2.K and h = 0.49 kW/m^2.K.

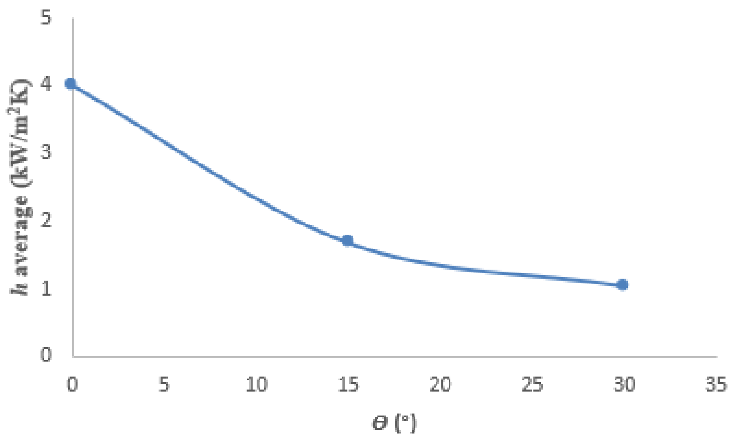
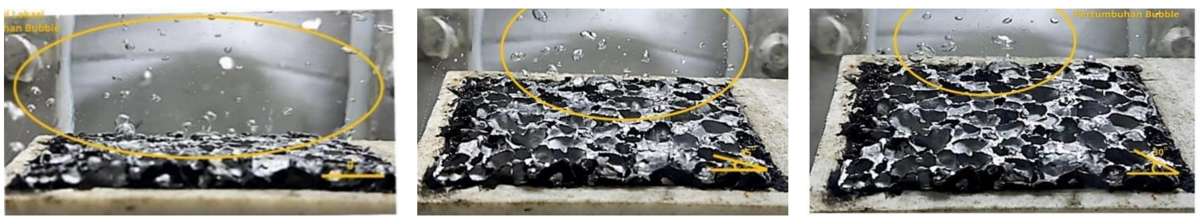


Figure 7. Comparison of θ and $\bar{h}$ with q" from 5.27 kW/m² to 10.54 kW/m².

As seen in Figure 7, as the inclination angle (θ) of the metal foam test material increases, the heat transfer coefficient in the two-phase cooling system decreases. This is due to the reduced bubble growth distribution on the heater surface with a steeper orientation, which lowers the heat transfer efficiency through the pool boiling mechanism.

2. Analysis of Boiling Phenomena

In the conducted experiment, the phenomenon of bubble merger occurs due to the increasing frequency of bubble formation as temperature and heat flux rise. This process takes place at q"= 10.54 kW/m² on the metal foam test material across all orientation angle variations. The higher the frequency of bubble growth and the greater the number of nucleation sites, the faster the heat transfer process.



(a) Distribution of Bubble Growth (b) Distribution of Bubble Growth (c) Distribution of Bubble Growth

Figure 8. Visualization of Bubble Merger at q" = 10.54 kW/m² for orientation angles (a) θ=0°, (b) θ=15° and (c) θ=30° on the metal foam test material

The increase in orientation angle affects the distribution area and growth of bubbles. As shown in Figure 8, the distribution and growth of bubbles at θ=0° have a higher and more uniform frequency, whereas at θ=60°, the frequency of bubble distribution and growth is the lowest and less uniform. This is due to the greater inclination angle causing higher bubble release resistance, resulting in poorer heat transfer performance.

D. CONCLUSIONS AND SUGGESTIONS

From the study conducted, it can be concluded that for the metal foam test material and the working fluid HFE-7100, with variations in heat flux (q") and orientation angle (θ), the following aspects are affected:

1. For the metal foam test material at the same orientation angle of 30° with q" = 5.27 kW/m², a decrease in the average heat transfer coefficient ($\bar{h}$) of 80.37% was observed compared to q" = 10.54 kW/m². For orientation angles of 15° and 0°, the decrease in $\bar{h}$ was 90.23% and 96.66%, respectively.
2. The orientation angle (θ) affects the heat transfer coefficient in pool boiling for metal foam material. The θ = 0° angle demonstrated the highest performance with $\bar{h}$ = 4.019 kW/m²K, whereas the θ = 30° angle had the highest performance at $\bar{h}$ = 1.042 kW/m²K. The decrease in $\bar{h}$ from an orientation angle of 30° to 15° was 61.52%, while the decrease from 15° to 0° was 138.6%.
3. The orientation angle (θ) reduces the bubble distribution area and growth occurring in metal foam. This reduction in bubble distribution and growth affects the surface temperature and heat flux, which increase, while the heat transfer performance declines. Therefore, it can be concluded that as q" and θ increase, the heat transfer coefficient in pool boiling decreases.

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