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EFFECT OF POROUS MICROSTRUCTURED ON POOL BOILING OF DI-WATER

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Abstract. *The technology industry's growth has motivated the development of optimized thermal control techniques, such as pool boiling. Different microstructure surface designs have been developed to enhance the two main parameters of pool boiling: heat transfer coefficient and critical heat flux. Micro-pin fins and microchannels are commonly used to enhance heat transfer in various applications; however, the capillary effect can be inhibited as heat flux increases due to the large vapor amount on the heating surface. Alternatively, metal foams provide a large surface area and can promote liquid replacement on the surface, enhancing the capillary action and improving heat transfer performance. The current work aims to analyze the influence of different porous microstructured surfaces, based on microchannels and micro pin fins, on pool boiling heat transfer of DI water. Porous microstructures with a thickness of 1 mm, 1.5 mm width, and 0.5 or 1 mm inter-fin space were used. The copper metal foams with a thickness of 1 mm were welded on the copper block, and the different structures (microchannels and micro pin fins) were fabricated using the electric discharge machining process. The results indicate that porous copper microchannels are the best alternative as intensification techniques for pool boiling heat transfer. They can reduce the resistance to bubble departure for high heat flux values by combining the effect of a continuous supply of liquid to the boiling interface without compromising the effect of the surface area-to-volume ratio.*

Keywords: *Pool boiling. Metal foam. Micro pin fins. Enhancement techniques.*

1. INTRODUCTION

Technological advancements have demanded thermal management devices capable of dissipating high heat fluxes with increasing dimensional restrictions. Thus, the cooling systems have used phase-change heat transfer (boiling) because they are thermally more efficient than those operating on single-phase heat transfer. The main parameters of nucleate boiling are heat transfer coefficient (HTC) and critical heat flux (CHF), the maximum heat flux that can be applied. Some applications that rely on boiling for thermal management include nuclear power plants, cryogenic applications, hybrid vehicle power electronics, commercial and military avionics systems, spacecraft thermal control, and high-performance processors.

Nukiyama (1934) was the first to introduce the boiling curve that relates heat flux and the gradient temperature (Figure 1). For practical applications, it is convenient to anticipate the activation of the nucleation sites (leading to HTC intensification) and postpone the CHF (point D, Figure 1) because, when reaching it, the heat transfer is degraded.

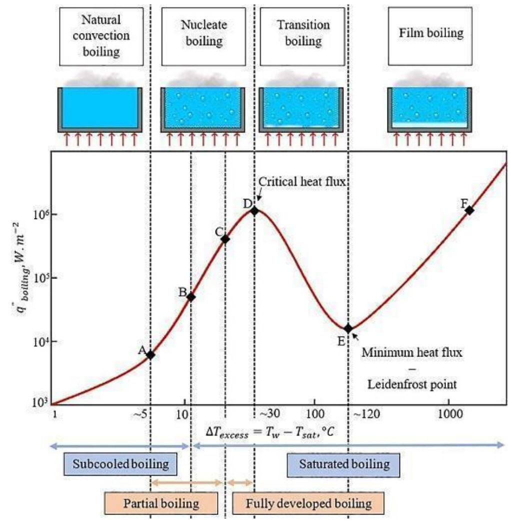


Figure 1. Pool boiling curve (Guichet et al., 2019).

Liang and Mudawar (2021) estimate that an increase of 2 ºC in processors represents a decrease of 10% in their performance. In order to intensify the HTC and CHF using passive techniques, there are two possible ways: modify the working fluid and/or modify the heating surface. Regarding the working fluid, the most used technique is the dispersion of metallic nanoparticles in the base fluid, producing the so-called nanofluids. However, this technique is difficult to repeat because the HTC behavior varies with time and heat flux, so the technique behaves randomly (MANETTI et al., 2017). Thus, heating surface modifications are presented as more viable solutions. Surface modifications can occur at different scales, with the nano and micro scales being the most used since they cause small disturbances in the fluid, favoring the micro convection.

Surfaces with microfins have great potential for heat dissipation due to increased surface area in contact with the working fluid. In addition, they increase the density of nucleation sites and the disturbance of the fluid, which increases the heat transfer coefficient. For this reason, some authors sought to identify the influence of the geometric parameters of these surfaces on pool boiling.

According to Chen et al. (2022), when a nucleation site is activated, the gap between the fins promotes a limitation in the vapor bubble radius, reducing its departure diameter. Then, there is an increase in the vapor bubble frequency, promoting the HTC intensification. This gap also increases the heat transfer area since the smaller the inter-fin space, the higher the number of fins on the heating surface.

Moreover, the inter-fin space is also responsible for increasing CHF since by reducing the gap size between micro pin-fins, the capillary wicking increases, promoting the rewetting effect on the surface and preventing hotspot formation. However, as identified by Zhang et al. (2018), the porosity of microstructures and the relation between hydraulic diameter and capillary length have a threshold value, where from this, CHF degradation occurs. Therefore, the increase in CHF is given by the balance between the capillary wicking effect and the increase in effective heat transfer area.

Another factor is wettability, which also influences the pool boiling behavior. Li et al. (2022) developed microstructures with hydrophobic and hydrophilic characteristics. By conducting water pool boiling tests, the authors realized that surfaces with mixed wettability characteristics presented better results than those with uniform wettability. At high heat fluxes, channels with hydrophobic characteristics had a higher resistance to liquid replenishment, increasing dry zones; moreover, non-wetting channels anticipate the nucleation of the vapor bubbles compared to wetting ones. Thus, according to the authors, an effective modification technique must combine the hydrophilic behavior, which reduces the flow resistance of the liquid replenishment at high heat fluxes, and the hydrophobic behavior, which can promote bubble nucleation at low heat fluxes.

Ma et al. (2021) reported that most microscale techniques use microchannels, but those are limited in reducing the capillary effect for high heat fluxes. Despite this, Kaniowski and Pastuszko (2018) noticed that due to the low Bond numbers of the microchannels and the higher contact area ratio, water pool boiling presented higher HTC and CHF than micropillars with similar geometric characteristics. Thus, improving the wickability of microchannels by modifying their geometric parameters is a promising solution to intensify the pool boiling heat transfer.

Alternatively, metal foams, Figure 2, have also been used as an alternative to modified surfaces because they have an increased surface area compared to other modification techniques. They are ideal in applications requiring high heat dissipation rates and/or limited space for the cooling system. On porous surfaces, the improvement in heat transfer is mainly due to a combination of four factors: (i) increased surface area; (ii) increased nucleation site density; (iii) increased capillary effect, which facilitates the liquid replenishment; (iv) increased wettability (THIAGARAJAN et al., 2015).

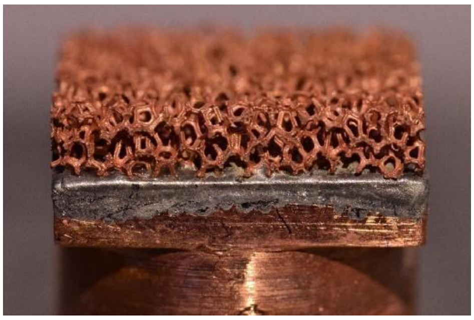


Figure 2. Heating surface with copper metal foam (Manetti et al., 2020).

Porous structures, under the action of surface tension force, suck the working liquid and the smaller the pore diameter, the more significant such effect. However, the smallest pore diameter not only increases wickability but also has the greatest resistance to vapor bubble departure at high fluxes due to the increased vapor bubble diameter.

The most significant foam parameters influencing pool boiling heat transfer are pores per inch (PPI), porosity (ε), and foam thickness. Jin et al. (2011) investigated the boiling process of FC-72 and HFE-7000 using graphite foam and evaluated the effects of porous size on heat transfer; the larger porous favored the departure of vapor bubbles compared to smaller pores, leading to a higher heat transfer performance than that for a plain surface.

Manetti et al. (2020) observed that as the foam thickness increases, the vapor bubble's departure resistance also increases since the vapor accumulates in the foam structure, inhibiting the cooling effect and degrading heat transfer. Therefore, the thinnest foam presented the highest HTC at high heat fluxes, even with a smaller contact area with the fluid. According to the authors, the growth and detachment of the vapor bubble and the ability to 'pump' the liquid to the hotspot regions are the main reasons for this HTC improvement. Thus, creating alternative ways to reduce the vapor bubble's departure resistance can promote better results in pool boiling.

According to Zhou et al. (2019), extended surfaces increase the nucleation site's density and promote better liquid replacement through improvements in surface capillarity. Xu et al. (2022) tested a surface coated with V-shaped porous channels, and the results indicated higher superheating for the uniform foam than for surfaces with V-shaped porous channels. In the uniform foam, the resistance to the vapor bubble's departure is higher due to the accumulation of vapor in the region adjacent to the heated surface, degrading the heat transfer performance; in the case of V-shaped porous channels, the inter-fin space promotes the micro convection and the liquid replacement. This effect was intensified with an increase in the number of pore channels due to increased liquid recirculation within the metallic foam.

When departing through alternative paths, the vapor bubbles coalesce with those from adjacent channels but do not experience departure resistance as in a uniform foam. Furthermore, by reducing the inter-fin space, the vaporization rate can be improved due to the contact of the vapor bubble with the foam structure, which leads to a heat transfer enhancement.

As the main techniques involve surfaces with porous coating and structures with different geometric configurations, the current work evaluates the influence of porous micro pin fins and microchannels on the pool boiling heat transfer performance, using deionized water as the working fluid at saturated conditions.

2. METHODOLOGY

2.1 Experimental setup

Figure 3 shows the schematic drawing of the experimental setup, which consists of a boiling chamber with an auxiliary electrical heater to control the temperature of the working fluid; (1) a data acquisition system; (2) a power source; (3) a power source for the pressure transducer (4); (5) a thermal bath and (6) a computer. The DAQ AGILENT 394970A system captures all signals from thermocouples, pressure transducer and electrical heater.

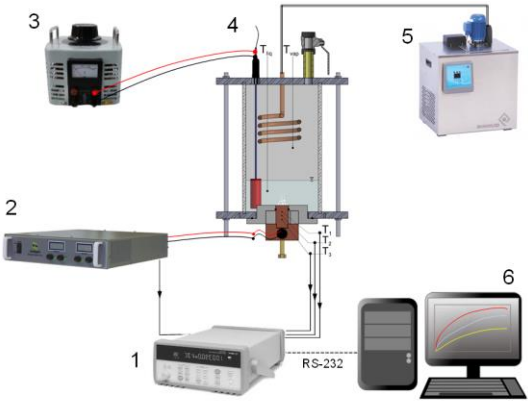


Figure 3. Pool boiling experimental setup (Manetti et al., 2021).

The boiling chamber consists of a rectangular glass (120 × 100 mm), 5 mm thickness and 200 mm height, between two stainless steel plates whose tightness was guaranteed with nitrile rubber and silicone. A thermal bath, QUIMIS® Q241M, is used to control the temperature of the condenser located at the top of the boiling chamber. An absolute pressure transducer, Omega PXM309-2A (uncertainty of ±0.05 kPa), measures the pressure inside the boiling chamber, which is maintained close to the local atmospheric pressure. The top of the boiling chamber has a valve for vacuum, which is necessary to remove the air and to feed the working fluid. An auxiliary heater, cartridge type (350 W/220 V) controlled by VARIAC, is located inside the boiling chamber to maintain the fluid temperature at saturated conditions. Two K-type thermocouples with 0.5 mm diameter are located on liquid and vapor regions with different heights and are opposed to the auxiliary heater for monitoring the liquid and vapor temperature.

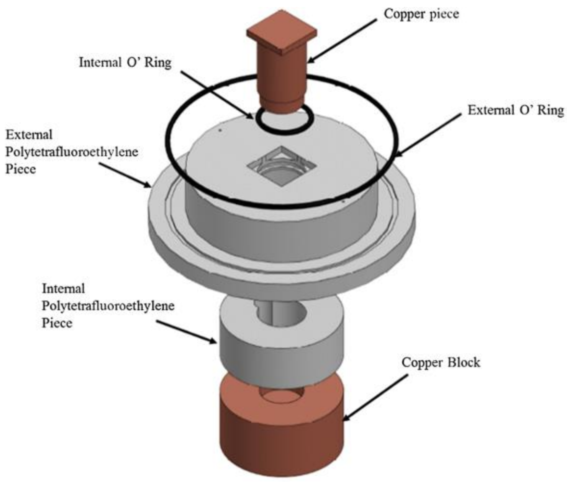


Figure 4. Exploded view of the test section (Kiyomura et al., 2020).

The test section, Figure 4, consists of a circular piece of copper with a square top surface (16 × 16 × 3 mm) made from a 60 mm high copper block (the test section was manufactured from a single piece of copper in order to avoid thermal contact resistance). Three K-type thermocouples (T_1, T_2 and T_3) are embedded in the cylindrical part of the test section, and this, in turn, is fixed to the copper block containing the electrical heater responsible for heating the test section. The FCC 75-30i power source of up to 750 W, with voltage ranging from 0 to 300 VDC, is connected to the electrical heater. In order to ensure the thermal insulation of the test section, a piece of polytetrafluoroethylene (PTFE) and ceramic fiber tape are used.

2.2 **Surface preparation and data reduction**

Initially, all square top surfaces of the samples were polished using an abrasive alumina paste (average particle diameter of 0.3 μm), cleaned with acetone, and dried using compressed air. After that, one sample was set aside to be tested as a reference surface (Plain surface, R_a = 0.67 ± 0.08 μm); the remaining surfaces were used with the metallic foam welded on them.

The copper (Cu) foam was obtained from Nanoshel® in 500 × 500 mm sheets with a thickness (δ) of 3 mm, and the foam characterization was made by Manetti et al. (2020). The porosity (ε) is 90%; the average PPI value is 31.75, with a standard deviation of 6.2; the foam porous and fiber diameters are 0.52 and 0.1 mm, respectively; and the specific area (α_{sf}) is 2166 m^2/m^3.

The foam was cut into 16 × 16 mm squares using electrical discharge wire cutting. The copper foams of 3 mm in thickness were welded on the polished surface of the samples. A thin tin layer of 0.1 mm thickness was applied to avoid thermal resistance; after that, the copper block was heated up to the tin alloy melting point (≈ 200 °C), and weight was put on the foam to pressure it against the surface. The assembly was cooled and cleaned with alcohol and acetone.

Manetti et al. (2020) reported that thinner thicknesses are better for high heat fluxes. Therefore, metal foams with 1 mm thickness were chosen to verify such influence on heat transfer behavior. The electric discharge machining process was used for the thickness level variation, where a square flat copper block (20 × 20 mm) was used as an electrode tool.

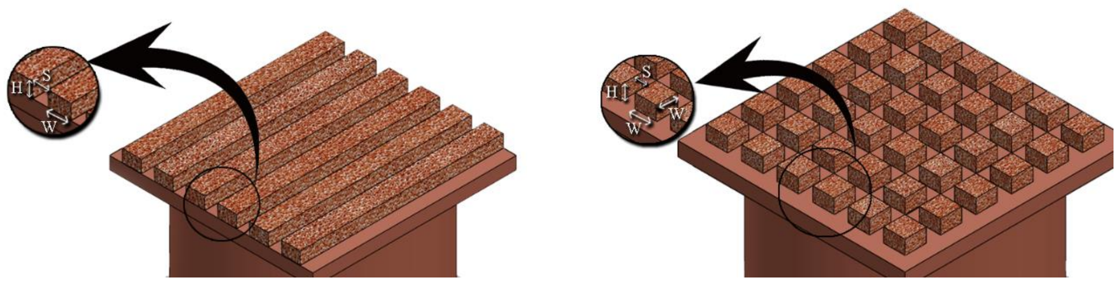
Porous micro-pin fins and microchannels were also tested; the electric discharge machining process was used, and a copper plate with the desired inter-fin space was used as the electrode tool. The geometric parameters for all samples are presented in Table 1 and illustrated in Figure 5.

Table 1. Geometric parameters of the different test sections analyzed in the current work.

Surface	**Width (W)**	**Height (H)**	**Inter-fin space (s)**	**Effective Area***
Plain (Reference)	–	–	–	–
Uniform Foam (UF)	–	1 mm	–	555 mm²
MP1_0.5	1.5 mm	1 mm	0.5 mm	312 mm²
MP1_1	1.5 mm	1 mm	1 mm	175 mm²
MC1_0.5	1.5 mm	1 mm	0.5 mm	416 mm²
MC1_1	1.5 mm	1 mm	1 mm	312 mm²

*$A_{foam} = \alpha_{sf} \forall . N$

This study analyzes six samples: a plain surface (reference surface), a uniform foam, two micro-pin fins (Figure 6a) and two with microchannels (Figure 6b). Based on the foam volume (∀) and amount of porous structures (N), it was possible to determine the effective area (A_{foam}) of each porous surface.



(a) (b)

Figure 5. Schematic representation of test section with porous (a) microchannels and (b) micro-pin fins.

(a) (b)

Figure 6. SEM porous surface view: (a) micro-pin fins (MP1_1); (b) microchannels (MC1_1).

In order to remove non-condensable gases, the working fluid was preheated using an auxiliary heater. The K-type thermocouples, embedded in the cylindrical part of the test section, were used to estimate the heat flux and the surface temperature.

The heating effect was imposed by increasing the electrical power according to heat flux steps of 50 kW/m^2 until a condition close to the dryout heat flux corresponding to a maximum footprint heat flux of 850 kW/m^2. Data were recorded for each heat flux after establishing steady-state conditions, characterized by variations in the measured temperatures within their uncertainty (±0.3 °C). At least 100 data points were recorded, corresponding to 500 s steady-state.

The heat flux was determined using Fourier's Law, Eq. (1), assuming one-dimensional heat conduction along the copper block (Figure 7):

$$q''_{measured} = \frac{\pi}{4} \cdot \left(k_{Cu} \frac{T_3 - T_1}{L_{13}} \right) \quad (1)$$

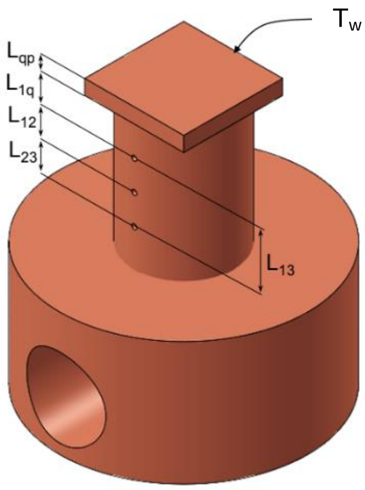


Figure 7. Thermocouple locations on copper block.

where k_{Cu} is the thermal conductivity of copper, L_{13} and ΔT_{13} are the distance from the thermocouples 1 to 3 and the temperature difference between them, and the factor $\pi/4$ is used to correct the circular area to the square area. Then, $q''_{measured}$ was used to determine the wall temperature (T_w):

$$T_w = T_1 - \frac{q''_{measured}}{k_{Cu}} \left(\frac{4}{\pi} L_{1q} + L_{qp} \right) \quad (2)$$

where L_{1q} is the distance from thermocouple T_1 to the beginning of the square cross-section, and L_{qp} is the thickness of the square surface. Finally, using Newton's cooling law, the heat transfer coefficient (*h*, HTC) could be determined as:

$$h = \frac{q''_{measured}}{T_w - T_{sat}(p_{atm})} = \frac{q''_{measured}}{\Delta T_{sat}} \tag{3}$$

The uncertainty in the K-type thermocouples was ± 0.3 °C (obtained through the calibration process). The experimental uncertainty of the heat transfer coefficient is higher for low heat fluxes and decreases as the heat flux increases. Considering all tested surfaces, the average experimental uncertainty for the heat flux and heat transfer coefficient was 5.8% and 6.9%, respectively.

3. EXPERIMENTAL RESULTS AND DISCUSSION

From Figure 8, one may observe that all the modified surfaces were able to minimize surface superheating compared to the reference surface (plain surface) regardless of the heat flux values. On the modified surfaces, there are two governing and competing effects of intensification: the increase in the contact area and the liquid and vapor flow paths. The increase in the contact area provides greater heat flux dissipation due to increased nucleation site density; the metal foam fibers promote the effects of transient conduction and micro-convection throughout their structure. Moreover, the micro-pin fins and microchannels provide additional pathways for vapor escape and liquid replenishment, which delays the dryout phenomenon.

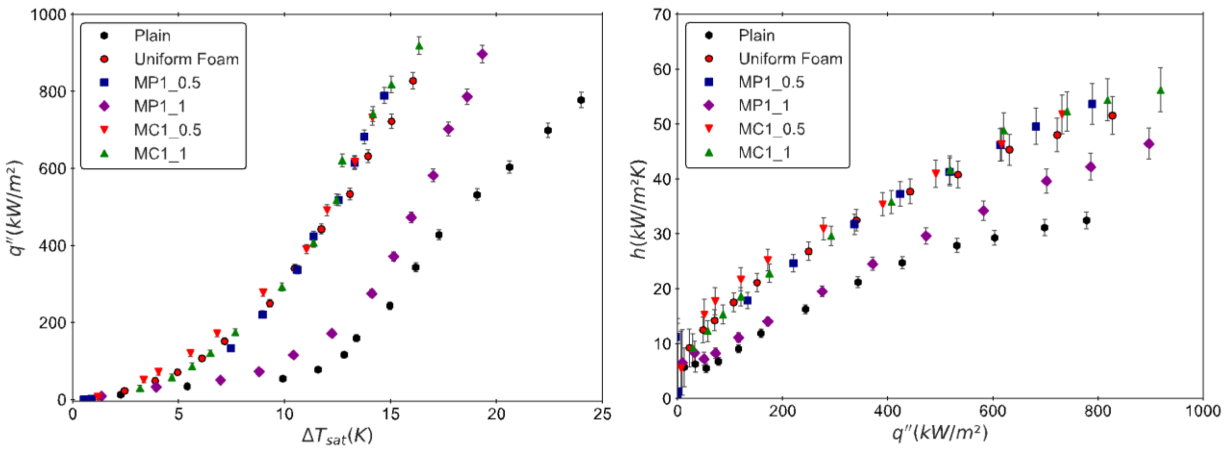


Figure 8. Influence of the modified porous surfaces on (a) boiling curve and (b) HTC.

In order to better observe the effect of porous surfaces on the enhancement/deterioration of HTC, the experimental results were evaluated using the heat transfer intensification factor **η** (Figure 9). This factor is defined as the heat transfer coefficient ratio for micro-pin fins and microchannels surface to the heat transfer coefficient for uniform foam surface.

$$\eta = \frac{h_{MP/MC}}{h_{Cu\ Foam}} \tag{4}$$

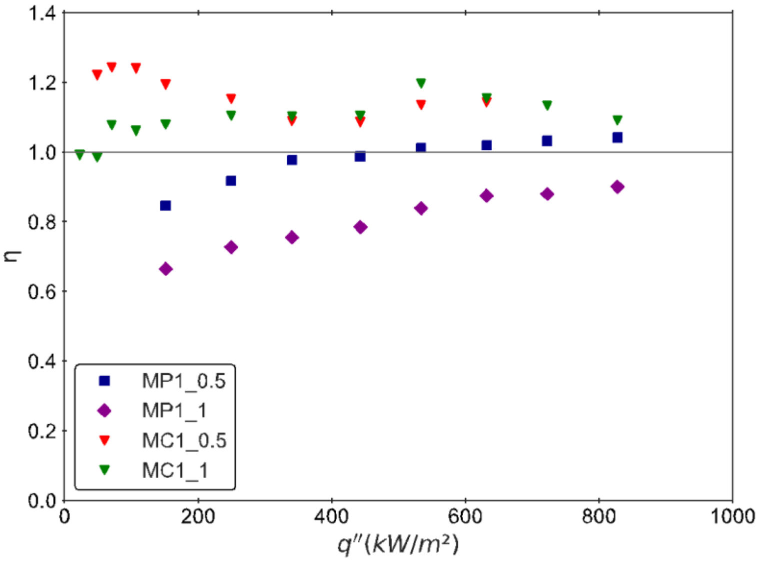


Figure 9. Intensification factor as a function of heat flux.

The porous micro-pin fins present worse results than uniform metal foam, which can be due to the reduced area in contact with the working fluid overlapping the positive effect of the additional vapor flow paths. Despite this, the micro-pin fins with the smallest inter-fin spacing showed slightly favorable results (compared to the uniform foam surface) at high heat flux values due to the separate liquid and vapor pathways facilitating vapor removal.

Although the MP1.5_0.5 has a similar contact area with the working fluid as MC1_1, the latest presents higher heat transfer performance since microchannels with larger inter-fin spacing yields a lower flow resistance for the bubble/vapor lift-off mainly at high heat fluxes.

The porous microchannels showed an HTC enhancement regardless of the heat flux applied; there was a preference for vapor bubbles to flow through the additional paths, while the porous fins promoted liquid replacement. Microchannels with the smallest inter-fin spacing showed better results at low heat flux since the diameter of the vapor bubbles is reduced, and the capillary effect (due to the additional pathways) is more pronounced (Figures 10 and 11).

Using a capillary tube and the same method as Manetti et al. (2020) and Kiyomura et al. (2020), Figure 10 indicates that the porous microchannel surfaces have better wickability than the uniform foam surface.

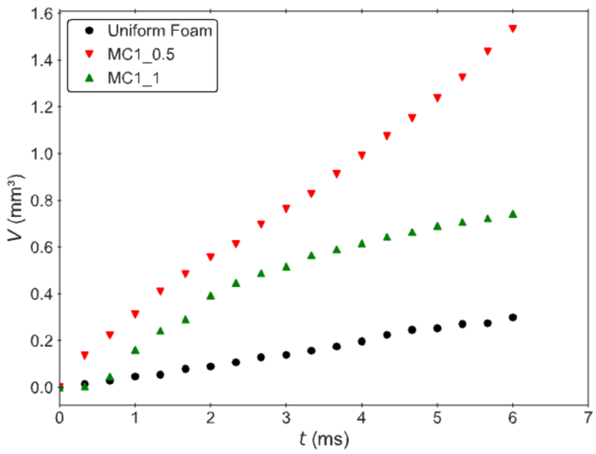
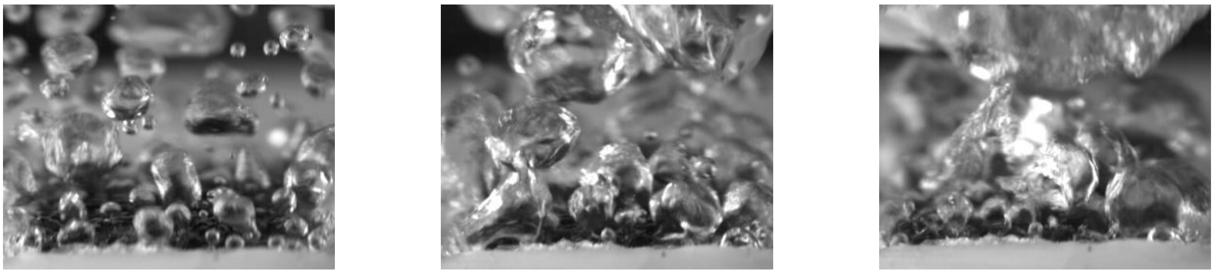


Figure 9. Volume wicked behavior for uniform and microchannel porous surfaces.

As the heat flux increased, it is observed a reduction in this effect due to vapor bubble coalescence, which hindered the liquid replenishment, as illustrated in Figure 10 and in the Supplementary Material (available online).



(a) (b) (c)

Figure 10. Vapor bubble dynamic for MC1_0.5 surface for heat fluxes of (a) 150 kW/m², (b) 300 kW/m², and (c) 600 kW/m².

Based on the authors′ results and literature review, a summary can be drawn (Figure 11). Larger inter-fin spacing presents better results for high heat fluxes due to promoting less bubble departure resistance, while smaller inter-fin spaces present an HTC enhancement for low heat fluxes due to the greatest contact area and the capillary-wicking ability increase.

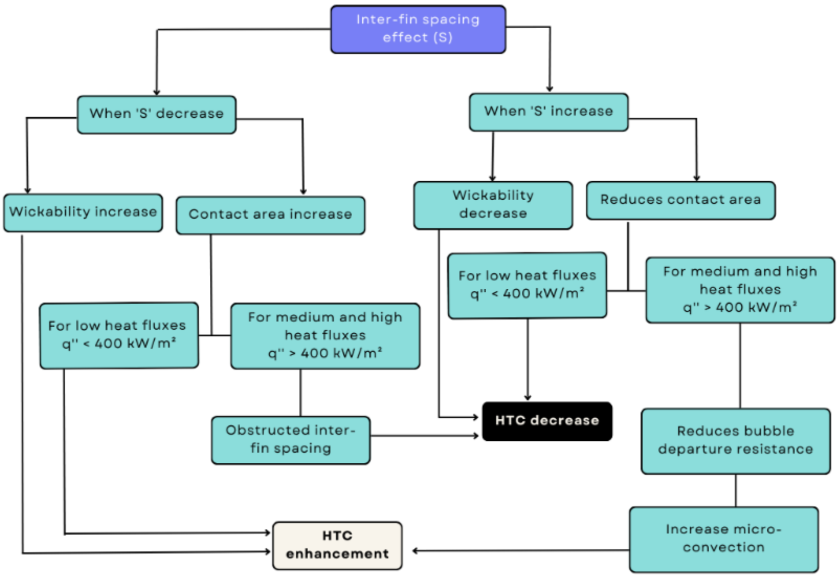


Figure 11. Effect of inter-fin spacing on pool boiling of water.

The use of microchannels is justified by the improvement of local micro-convection promoted by the drag effect caused by the vapor bubble's departure, thus intensifying the heat transfer; additionally, the 'pump' effect promoted by the geometric characteristics of the foam delay the occurrence of hot spots.

4. CONCLUSIONS

Based on the analysis, using metal foam significantly increases the boiling heat transfer coefficient compared to a plain surface due to the increased effective heat transfer area, higher density of nucleation sites, and improved liquid replenishment to the heated surface (capillary wicking effect).

For porous micro-pin fins and microchannel surfaces, even though the inter-fin spacing is smaller than the capillary length (related to a Bond number lower than 1), which would suggest a reduction in the heat transfer intensification effect, the HTC is enhanced due to the additional pathways for vapor bubble departure without compromising the liquid replenishment to the hotspot regions on the surface.

The porous microchannel surfaces can reduce the flow resistance, suppress the larger bubbles, and provide sustainable liquid replenishment by enhanced wicking. At low heat fluxes, the smaller the inter-fin spacing, the higher the heat transfer performance due to the greatest contact area and the capillary-wicking ability increase. At high heat fluxes, larger inter-fin spacing is better for pool boiling heat transfer due to promoting less bubble departure resistance.

5. ACKNOWLEDGMENTS

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