Thermal efficiency of metal foams on pool boiling

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Abstract. This paper presents an experimental work on pool boiling using HFE-7100 at saturated conditions, under atmospheric pressure, and copper and nickel foams as the heating surface with four different thicknesses varying between 0.5 mm and 3 mm, followed by an analysis of the effect of foam fin-efficiency based on Ghosh model. All foams showed a better heat transfer coefficient (HTC) than the plain surface; however, as the heat flux increased, the HTC from the thicker nickel foams decreased due to the bubble vapor flow inside the foam. On the other hand, the thinner nickel foam showed better HTC at high heat fluxes with a maximum enhancement of 120%. The foam efficiency presented a similar tendency with the HTC, i.e., as the thickness decreases the efficiency increases; however, as compared with copper foams with a similar area but different porous diameter, the copper foams are 40% more efficient than the nickel ones due to the foam material, which has a thermal conductivity 4.5 times higher.

1. Introduction
Two-phase cooling systems have been widely studied for thermal management technology. Pool boiling can be used with direct immersion cooling for an increased power density and energy efficiency in cooling high power electronics [1, 2]. Fluorocemical liquids are dielectric and proved to be highly suitable as a liquid medium for electronic immersion cooling [3]. However, these fluids have relatively poor thermophysical properties and extremely small contact angle that causes large superheat to initiate the boiling process - commonly referred to as ‘incipience excursion’ [4]. Therefore, the use of an engineered surface is needed to meet the cooling requirements of modern electronic devices [5]. Strategies to enhance pool boiling heat transfer often rely on changing the surface topography in a trial and error approach, based on measurements of the heat transfer coefficient (HTC) and the critical heat flux (CHF) [6]. According to Doran et al. [7] within the past two decades, a lot of this research has focused on micro- and nanoscale structures intended to enhance the surface area, promote controllable wetting behavior such as greater wickability/rewetting of surfaces, offer an increase in nucleation site density, or a combination of these effects. Porous surface structures have been widely reported to enhance heat transfer performance due to their interconnected
porous, which increases the wetted area and the nucleation site density [8]. The porous thickness and pore size are the two important parameters of a porous surface, and their optimal values mainly depend on the fluid properties [9 - 11].

This paper presents an experimental work on pool boiling using HFE-7100 (at saturated conditions) and copper foam (Cu foam) or nickel foams (Ni foam) at four different thicknesses (δ): 0.5 – 3 mm. The present work aims to compare the results with those reported in Manetti et al. [12] and carry out an analysis of the effect of foam fin-efficiency based on the literature model.

2. Materials and Methods

The results presented in this work were obtained using the same experimental apparatus and the procedure described by Manetti et al. [11, 12]. The experiments were performed under conditions close to the local atmospheric pressure, $p_{ atm } = 98$ kPa. The test section consisted of a copper piece with a square plate on the upper surface ($16 \times 16 \text{ mm}^2$) of the copper cylinder. The copper and nickel foams were soldered on the plain surface to ensure small thermal resistance between the foam and the test section. The nickel foam properties such as porosity ($\varepsilon$), pore diameter ($d_p$), fiber diameter ($d_f$), and area density ($a_{sf}$) are presented in Table 1.

| Material | $\varepsilon$ (\%) | $d_p$ (mm) | $d_f$ (mm) | $a_{sf}$ (m$^2$/m$^3$) | $\delta$ (mm) |
|----------|------------------|------------|------------|-------------------|----------------|
| Cu       | 90               | 0.46       | 0.13       | 2166              | 1-3            |
| Ni       | 98               | 0.25       | 0.07       | 5133              | 0.5 - 3        |

3. Results and Discussion

The boiling curves for copper and nickel foams and plain surface (included for reference) are shown in Figures 1a, and 1b, respectively.

![Figure 1. HFE-7100 pool boiling results from [11, 12] (a) on copper foams and (b) on nickel foams.](image-url)
All nickel foams showed better Heat Transfer Coefficient - HTC than the plain surface, which agrees with the results reported in Manetti et al. [11] for Cu foams. The first two foams, $\delta = 2$ mm and $\delta = 3$ mm, showed no significant difference between them. Moreover, at heat fluxes lower than 100 kW/m$^2$ the ‘Ni foam 0.5 mm’ presented the worst performance due to the lowest wetted area. However, as the heat flux increased the nickel foam results were crossed due to the bubble vapor flow inside the foam. Thicker foams hinder the vapor on the foam structure and vice-versa. In this way, ‘Ni foam 0.5 mm’ showed better HTC at high heat fluxes. The maximum HTC enhancement as compared with that obtained with the plain surface was close to 120%, 72%, 35%, and 24% for thickness from 0.5 mm, 1 mm, 2 mm, and 3 mm, respectively.

Foam thicknesses with similar area enhancement, $r$, were chosen to compare the results obtained with Ni foam with those reported in Manetti et al. [11] for Cu foam. $r$ was calculated as follow:

$$r = \frac{A_{foam}}{A_{plain}} = \frac{a_{sf} \cdot V_{foam}}{A_{plain}} = \frac{a_{sf} \cdot (16 \cdot 16 \cdot \delta)}{16 \cdot 16} = a_{sf} \cdot \delta$$

(1)

In this way, Figure 2a compares the ‘Cu foam 1 mm’ with the ‘Ni foam 0.5 mm’, while Figure 2b compares the results obtained with the ‘Cu foam 2 mm’ with those obtained with the ‘Ni foam 1 mm’. In both cases, the Ni foam even with lower thickness than the Cu foam showed higher $r$ and lower HTC. In general, the Cu foam had an average HTC 17% greater than the Ni foam for the case in Figure 2a and 36% greater for the case depicted in Figure 2b. Mancin et al. [13] reported that HTC cannot be considered proportional to the area added because the structure temperature varies from the heated wall to the top wall. Therefore, an analysis of the foam finned surface efficiency was performed based on the Ghosh model [14] – an analogy with the traditional fin theory, where the foam efficiency is given by,

$$\eta_{foam} = \frac{\tanh (ML)}{ML}$$

(2)

where: $M = m(1 + 4\eta_{1/2})^{1/2}$, $m = \left(\frac{4h}{k_{mat}d_f}\right)^{1/2}$, and

$$\eta_{1/2} = \frac{\tanh m(0.5d_p)}{m(0.5d_p)}$$

(3)

Figure 2. HTC comparison for similar area enhancement: (a) $r$ higher than 2 (b) $r$ higher than 4.
The Ghosh model [14] returns the foam efficiency presented in Figure 3a and Figure 3b for each heat flux. The trend in the results is similar to that observed for the HTC, i.e., the copper foams are more efficient than the nickel ones even with higher thickness. In general, the Cu foam had an average foam efficiency of 30% greater than the Ni foam for Figure 3a and 50% for Figure 3b. So, the Cu foam even with a lower area it has higher foam efficiency, due to the foam material, which has a thermal conductivity ($k_{mat}$) 4.5 times higher.

![Figure 3](image.png)

Figure 3. Foam efficiency from Ghosh [14] model comparison for similar area enhancement: (a) $r$ higher than 2 (b) $r$ higher than 4.

4. Finally remarks

The foams can improve HTC as compared with a plain surface. However, as Ni foam is compared with the Cu foam there is a competition between the area enhancement and foam fin-efficiency. It was found that the metal foams with similar areas have different efficiency, which is related to the HTC enhancement.

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