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Technical Note

Boiling of methanol and HFE-7100 on heated surface covered with a layer of mesh

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Abstract

This work has experimentally elucidated the effects of boiling saturated methanol or saturated and subcooled HFE-7100 on heated surface covered with a layer of mesh. The whole boiling curves were constructed. The fine mesh layer enhances the heat transfer efficiency of nucleate boiling at low wall superheats. Nevertheless, the presence of mesh would deteriorate the efficiency of film boiling mode and reduce both, the critical heat flux (CHF) and minimum heat flux (MHF). Comparisons between boiling of methanol and that of HFE-7100 were made. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Boiling; Mesh; Enhancement; Burnout

1. Introduction

Investigations analyzing pool boiling heat transfer augmentation are summarized in several books (e.g., see Webb [1]). To change the surface topological structure is commonly adopted for enhancing nucleate boiling heat transfer efficiency. For example, Lu and Chang [2] added a porous layer onto a smooth heating surface, which can markedly enhance the nucleate heat transfer coefficient, raise the critical heat flux (CHF), and broaden the operational region of high heat load. Allingham and Mcentire [3] covered the heating surface by an absorbent wick material. These authors noted that at low heat flux the wick surface exhibits a better heat transfer efficiency than a smooth surface. At high heat flux regime, however, the situation reverses.

To add a layer of mesh to a heating surface, if it could markedly enhance the boiling heat transfer efficiency, deems a promising heat transfer augmentation technology for its simple installation and maintenance. Related studies include Abhat and Seban [4], Hasegawa et al. [5], Asakavicius et al. [6], Shimada et al. [7], and Rao and Balakrishnan [8–10]. Vasil'Yev [11] added a single layer of mesh on the boiling surface. With a coarse mesh, the nucleate boiling heat transfer coefficient could be 30% higher than that of a smooth surface. With a fine mesh, on the other hand, the meshed surface becomes less efficient than the smooth one. Tsay et al. [12] investigated the interactions between coating mesh, water level, and the boiling surface roughness. Rather complicated dependence of heat transfer enhancement on mesh size is noted.

In all the above-mentioned literature works, experiments were conducted focusing mainly on the effi-

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Nomenclature

d	wire diameter (mm)
E	enhancement factor
h	distance between adjacent wires (mm)
q_b	heat flux (W/m^2)
q_C	equilibrium heat flux (W/m^2)
ΔT	superheat (K)
ΔT_{sub}	liquid subcooling (K)

ciency of nucleate boiling mode. In some studies, the heat flux to transit from nucleate boiling to film boiling is noted to largely decrease in the presence of mesh, when compared with a smooth surface. The complete information regarding the whole boiling curves, like the film boiling mode and the minimum heat flux (MHF) points is still largely lacking. This work has experimentally constructed the complete boiling curves for methanol and HFE-7100 (a CFC-substitute from 3 M Corp., which exhibits zero ozone depletion potential) on a meshed surface.

2. Experimental

The experimental setup is modified from that employed in [13,14]. Fig. 1 depicts the experimental setup. The testing section is of dimension ($L \times W \times H$) 24 × 8 × 8 cm^3 with front and rear view glasses (1). The fluid temperature was measured by a thermocouple (2). Under the testing block (3) are two independent heating blocks equipped with cartridge heaters (7), from which the joule heat could be generated separately and transited to the top surface. Temperatures at 24 positions in the testing block (3) were measured by thermocouples (9), whose readings were sent at a rate of 1 Hz to a data acquisition system (10) connected to a personal computer (11).

The upper heating surface is a smooth surface of dimension 80 mm × 15 mm. The covered meshes are made of stainless steel wires (SS304). The mesh dimensions are characterized by the distance between two adjacent wires (h) and the diameters of the wires (d). The meshes of ($h \times d$) = (1.91 mm × 0.63 mm), (1.537 mm × 0.58 mm), (1.288 mm × 0.3 mm), (1.238 mm × 0.35 mm) and (0.17 mm × 0.338 mm) are designated as the meshes 10, 12, 16, 16-1, and 50, respectively.

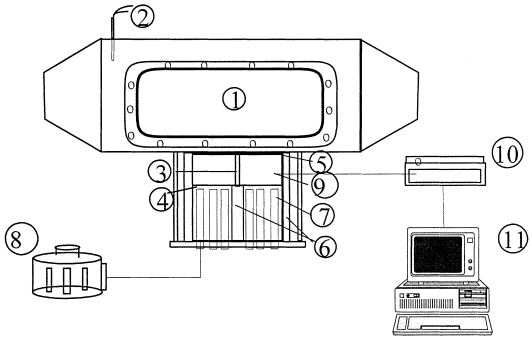

Fig. 1. Experimental setup.

The working liquids were methanol or HFE-7100 (product from 3M Corp., USA: $C_4H_9OCH_3$) at a purity exceeding 99%, which were not degassed prior to use. The testing pressure was atmospheric pressure.

The method of Kline and McClintock [15] was adopted to estimate the uncertainties of heat flux and surface temperature measurements. The uncertainties in the heater surface temperature and the associated heat flux when constructing boiling curves were estimated as ±7 and ±11%, respectively. The so-called "enhancement factor" (E) is herein defined as the ratio of heat flux of a meshed surface to that of the smooth surface at a given superheat (different from that adopted by Rao and Balakrishana [10]. Restated, if $E > 1$, then the heat transfer is enhanced with the presence of a mesh. Otherwise, the heat transfer efficiency is depressed. Since the maximum uncertainty for heat flux measurement is ±11%, the maximum uncertainty for E-factor is ±22%.

3. Results and discussion

3.1. Methanol boiling

Fig. 2 shows the boiling curves for saturated methanol on smooth or meshed surfaces. For the smooth surface, the boiling curve comprises the nucleate boiling curve, the film boiling curve, and two transition boiling curves (temperature-increasing and temperature-decreasing paths). The heat flux at which nucleate boiling mode transits to film boiling mode occurs at 4.92×10^5 W/m^2, which is somewhat less than the value predicted by classical hydrodynamic theory [16] (5.4×10^5 W/m^2). However, the difference is within the experimental uncertainty reported above (±11%). For the sake of further discussions, the heat fluxes of transition from nucleate boiling to film boiling, and vice versa, are denoted as the critical heat flux (CHF) and the minimum heat flux (MHF), respectively.

Although the boiling curves on a meshed surface are similar in shape as those on a smooth surface, however, there are three points worth noting. First, the application of mesh layers does not necessarily assure the enhancement of nucleate-boiling heat transfer. When compared with smooth surface boiling, the presence of a fine mesh layer (mesh-50) enhances heat transfer efficiency in nucleate boiling at the low-superheat ($\Delta T <$ 10 K) regime. Meanwhile, the efficiency becomes worse at high superheats ($\Delta T >$ 10 K). With a coarse mesh (mesh-10), on the other hand, the heat transfer efficiency in nucleate boiling is always less than that on a smooth surface. Such an observation seems contrary to Vasil'Yev [11] and Tsay et al. [12], who noted that the heat transfer enhancement becomes more obvious at a high heat flux. However, the highest heat flux investigated by Tsay et al. [12] is actually only of 3–4 × 10^5 W/m^2, approximately 30–40% of saturated water boiling on a smooth surface (up to 10^6 W/m^2). Restated, their experimental range is not as high as claimed.

Second, the values of both, the CHF and MHF points markedly decrease when mesh is present. Moreover, the decrease in CHF and MHF becomes more apparent when a fine mesh is applied. For example, the CHF for mesh-12 surface is approximately 3.8 × 10^5 W/m^2 (25% reduction). The value becomes less than 2.4 × 10^5 W/m^2 on the mesh-50 surface (53% reduction). The employment of a fine mesh thereby leads to a boiling process that is more ready to burnout. Rao and Balakrishnan [10] also demonstrated the declining trend in CHF for meshed surface boiling.

Third, the presence of mesh reduces the heat transfer efficiency for film boiling. At a superheat of 60 K, for example, the heat flux for smooth surface is 1.2 × 10^5 W/m^2. The corresponding heat fluxes for mesh-12 and mesh-50 surfaces are 0.76 × 10^5 W/m^2 and 0.44 × 10^5 W/m^2, respectively. No direct comparisons with literature are made owing to the lack of availability of literature data. Visual observations reveal that the meshes could retard the removal of vapor bubbles from heating surface, thereby yielding a thick vapor film and a poor film-boiling mode.

Fig. 3 illustrates the enhancement factors for both nucleate boiling and film boiling curves. The E factor depends weakly on the wall superheat except for the high-superheat nucleate boiling regimes. The fine mesh could enhance nucleate boiling at $\Delta T <$ 10 K. A coarse mesh would largely depress the nucleate boiling mode. "Appropriate" meshes thereby exist for enhancing the nucleate boiling heat transfer [3,12]. Furthermore, a fine mesh yields a low E value for film boiling.

3.2. HFE-7100 boiling

Fig. 4(a)–(c) show the boiling curves for saturated and subcooled HFE-7100 on smooth or meshed surfaces. These curves are similar in shape as those depicted for methanol boiling. Liquid subcooling would yield high CHF, MHF, and more efficient film boiling mode. These observations are consistent with the available literature [16]. Nevertheless, the spans of heat flux and wall superheat for HFE-7100 are largely shrunk as compared with these in Fig. 2. For example, the CHFs for saturated and subcooled HFE-7100 (ΔT_{sub} = 10 and 20 K) boiled on smooth surface are approximately 2.2 × 10^5, 2.34 × 10^5, and 2.64 × 10^5 W/

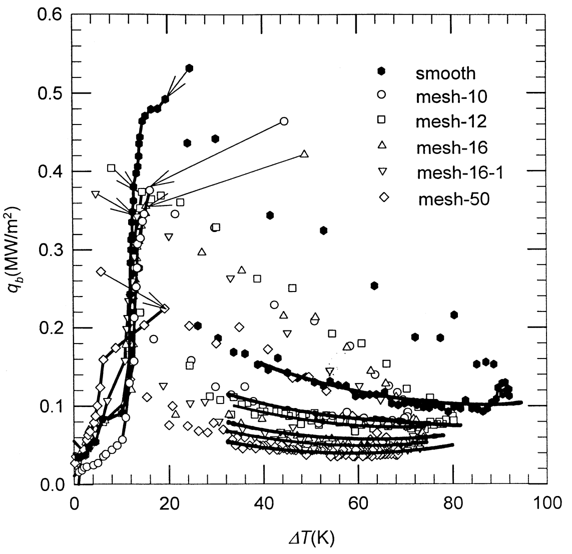

Fig. 2. Boiling curves of saturated methanol.

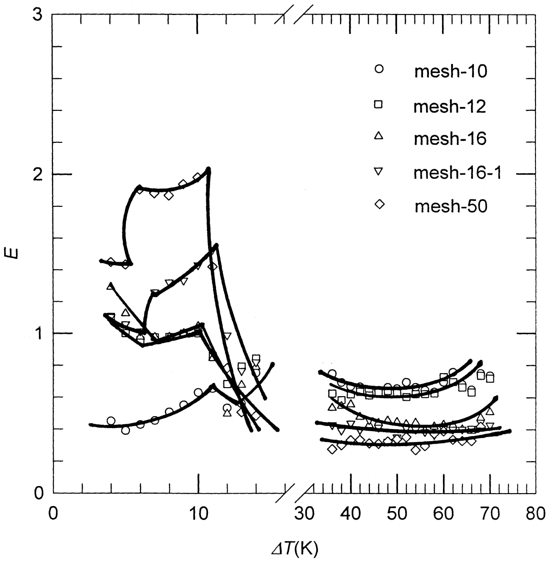

Fig. 3. Enhancement factors of saturated methanol.

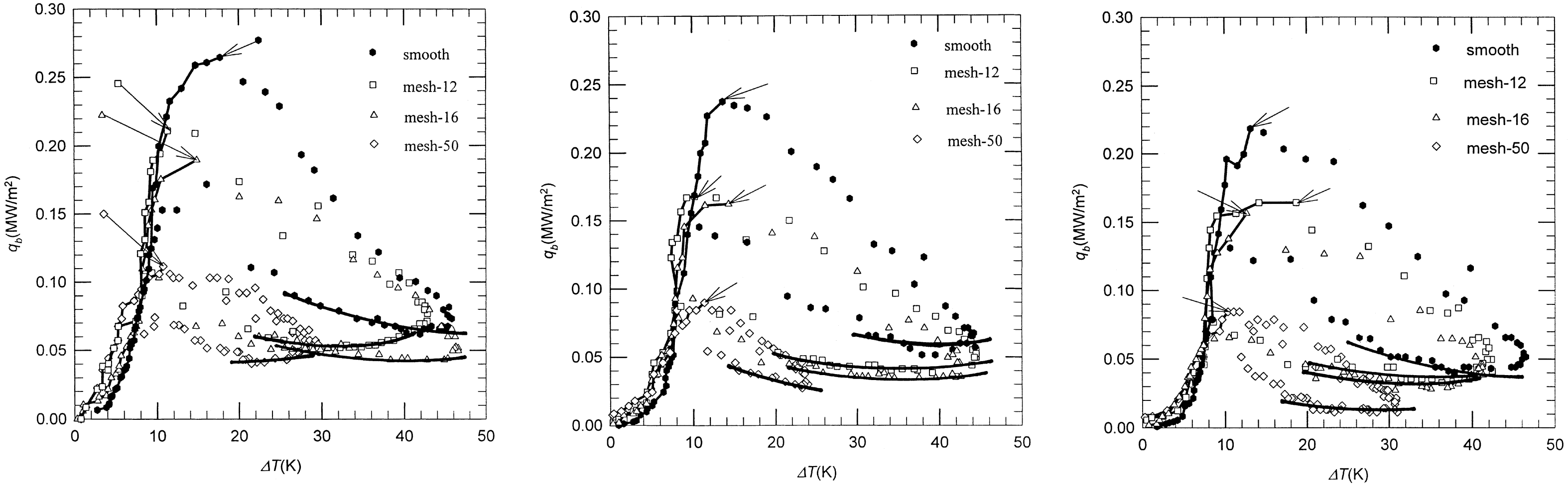

Fig. 4. Boiling curves of (a) saturated HFE-7100; (b) of subcooled HFE-7100, $\Delta T_{\mathrm{sub}} = 10$ K; (c) subcooled HFE-7100, $\Delta T_{\mathrm{sub}} = 20$ K.

m^2, respectively, which are much less than that for saturated methanol. Such an occurrence should be largely attributed to the rather low surface tension (0.0136 N/m at 25°C) and latent heat (132 kJ/kg at 25°C) for the HFE-7100 [17].

Meshed boiling of HFE-7100 has similar effects as those for methanol boiling. These are as follows:

1. The nucleate boiling heat transfer efficiency is enhanced at a low superheat ($\Delta T < 8$–10 K), and is depressed in high-superheat regime ($\Delta T > 8$–10 K);
2. Both the CHF and MHF points are markedly reduced; and
3. The film boiling heat transfer efficiency is deteriorated.

Meanwhile, HFE-7100 boiling has its distinct characteristics from methanol boiling. Fig. 5 illustrates the enhancement factor for $\Delta T_{\mathrm{sub}} = 20$ K. The plots at the other liquid subcoolings are similar to Fig. 5 and are omitted herein for brevity sake.

On comparing with the nearly superheat-independent *E*-factors for methanol boiling, the wall superheat is seen to have a significant effect on the *E*-factors for HFE-7100 boiling: it drops significantly with wall superheat in the nucleate boiling regime, and rises markedly in the film boiling regime. At $\Delta T = 4$–6 K, the enhancement could become 2–4 times when the mesh is presented. The *E*-factor decreases close to unity at $\Delta T = 10$–12 K, indicating no benefits for the application of meshes at a higher wall superheat. For film boiling, on the other hand, the *E*-factor increases with wall superheat. At $\Delta T > 30$–35 K, the meshed surface has a similar heat flux as those for smooth surface.

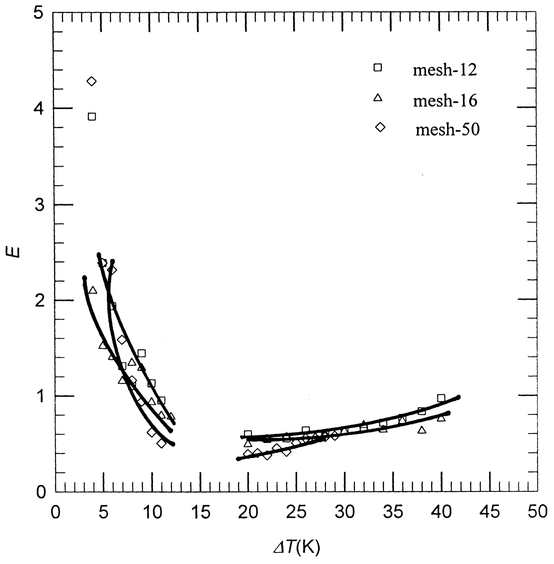

Fig. 5. Enhancement factors of saturated and subcooled HFE-7100.

3.3. Feasibility of mesh boiling

The above-mentioned experimental results clearly reveal the benefit for applying fine meshes on the enhancement of low-superheat nucleate boiling heat transfer. The effects are more apparent for HFE-7100, whose bubble departure diameters are close to the opening size of the mesh-50 screen and are much smaller than those for methanol boiling. However, such an advantage soon deteriorates when wall superheat goes up. These observations together with the lower CHF values for meshed surfaces clearly reveal the possibly dominating roles of thin-layer evaporation at low-superheat regime and the blocking effects at high-superheat regime during nucleate boiling. On the other hand, the mesh tends to trap vapor bubbles from departure in the film boiling mode. Such an action leads to a thicker vapor film at a fixed superheat when mesh is present. The film boiling mode thereby becomes more stable whence a lower MHF point results.

Moreover, recent researches reveal that, despite the critical points such as CHF that characterizes the hydrodynamic burnout, the points separating the metastable and stable boiling regimes are also of essence in boiler design/operations, since they measure the easiness of "non-hydrodynamic burnout" [18]. The so-called "equilibrium heat flux", q_C, characterizes the relative stability between nucleate and film boiling. A higher q_C designates a lesser chance for the occurrence of non-hydrodynamic burnout [19].

q_C is determined by the whole boiling curves. According to the shift in boiling curves for the present meshed system, the corresponding q_C should become much lower than that of a smooth surface. Restated, the application of mesh not only reduces the absolute stability of the system (less CHF), but also lead to a less stable nucleate boiling mode (lower q_C). Restated, for the present system, the mesh should be strictly applied at low-superheat nucleate boiling regime to take the advantage of high enhancement and prevent the occurrence of hydrodynamic or non-hydrodynamic burnout.

4. Conclusions

This work experimentally elucidated the boiling characteristics of saturated methanol and (saturated and subcooled) HFE-7100 on a smooth surface and on those covered with a single layer of mesh. The fine mesh layer enhances heat transfer efficiency of nucleate boiling at low wall superheats ($\Delta T < 10$ K); but depresses at a high superheat ($\Delta T > 10$ K). With a coarse mesh, on the other hand, the heat transfer efficiency in nucleate boiling always becomes worse when compared with that on a smooth surface. Film boiling efficiency is deteriorated when a mesh is presented. In addition, both, the critical heat flux (CHF) and minimum heat flux (MHF) points are markedly decreased for meshed surface boiling. Comparisons between boilings of methanol and HFE-7100 reveal that the former exhibits a nearly superheat-independent enhancement factor while the *E*-factors for the latter change markedly with wall superheat.

Acknowledgements

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