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Boiling of HFE-7100 on straight pin fin

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Abstract

This paper, for the first time, experimentally elucidated pin fin boiling characteristics of saturated and subcooled HFE-7100, a CFC-substitute, under atmospheric pressure. Fin base temperature and heat flux data are, for the first time, measured along with the fin tip temperature. For a given liquid/fin combination there exist upper steady-state (USS) branch, lower steady-state (LSS) branch, and a large, unstable regime located in between the two branches. Zones with different stability characteristics are mapped according to boiling on fins with different aspect ratios. Liquid subcooling enhances heat transfer performance and boiling stability. Calculation of boiling curve qualitatively describes the experimental results.

Keywords: Fin; Boiling; HFE-7100; Stability; Experiments; Calculation

1. Introduction

When boiling occurs on a fin, the heat transfer coefficient along the fin is not a constant. Fin boiling process has received extensive attention. Kraus and Yeh [2,3] reviewed related literature. Both the heat transfer rate from the fin base and the burnout base temperature increase markedly compared with the case without a fin. Fin boiling is thereby potentially useful in compact heat exchanger design.

Multi-mode boiling of liquid may occur on a fin. By assuming simple power-law type temperature dependence of the heat transfer coefficient for each mode, the steady-state temperature distribution along the fin and the base heat flow for various configurations can be found [14,15]. The fin effectiveness and the fin efficiency evaluated from these data are valuable to fin design. A prerequisite for using these steady-state solutions in practice is that they are stable to external perturbations.

Liaw and Yeh [4] analyzed the stability characteristics for only one boiling mode on the fin. Lin and Lee [7] provided the first comprehensive stability analysis on the steady-state solution for multi-mode boiling on a straight pin fin. When transition and nucleate boiling coexist on a fin, or in the three-mode boiling (film + transition + nucleate boiling), the existence of nucleate boiling mode at the fin tip will stabilize the boiling process. Lin and Lee [8] later experimentally verified the theoretical findings reported in [7]. Effects of tip insulation were discussed in [11]. Lin and Lee [9] theoretically investigated stability characteristics of boiling on annular fin and plate fin. Lin and Lee [10] discussed the effects of temperature-dependent thermal conductivity on boiling stability. Lin et al. [12] investigated the boiling process on a conical spine.

Chlorofluorocarbon (CFC) substitutes have a great potential in electronic cooling applications [1,17]. Information regarding fluorocarbon boiling on pin fin is still largely lacking in available literature. Liu et al. [13] recently conducted experiment on the FC-72 boiling on an fin. HFE-7100, methoxy-nonafluorobutane ($C_4F_9OCH_3$), is a new product from 3M company, USA, whose ozone-depleting potential (ODP) is essentially zero. As a result, it is superior to most CFCs and hydrochlorofluorocarbons (HCFCs) for the observed depletion of stratospheric ozone. As a result, it is of practical interest for understanding the boiling characteristics of HFE-7100 on a straight pin fin, which is the main theme of this work.

2. Experimental

Fig. 1 depicts the experimental setup. The testing chamber is 300 (L) × 300 (W) × 300 (H) mm^3 in dimension and has front and back view glasses. A copper

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Nomenclature

D fin diameter, m
L fin length, m
q_b base heat flux, W/m^2
ΔT_b base superheat temperature, K
ΔT_{sub} degree of liquid subcooling, K

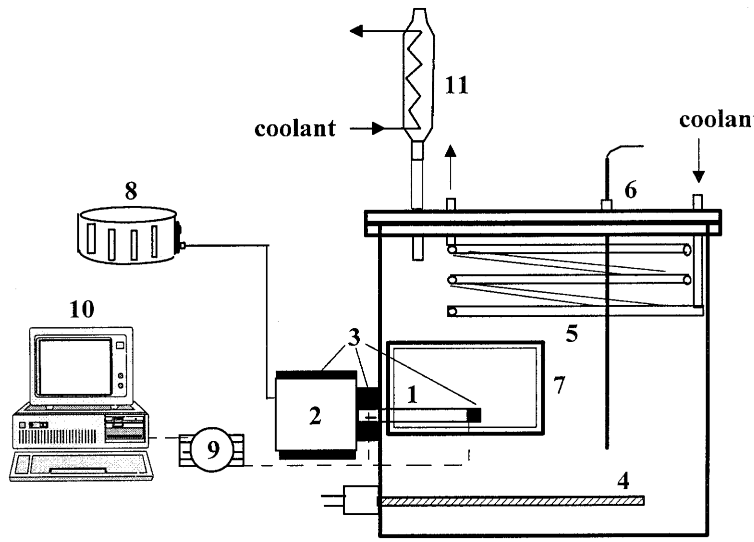

Fig. 1. Experimental setup: (1) fin; (2) bottom heating block; (3) insulation; (4) preheater; (5) cooling coil; (6) thermocouple; (7) view glasses; (8) transformer; (9) data acquisition; (10) personal computer; (11) condenser.

fin is attached to the bottom-heating block, from which the joule heat is supplied to the fin base. The liquid temperature is adjusted by the preheater and the cooling coil, and is measured by a thermocouple. Temperatures at four axial positions in the heating block and at the fin tip were measured by thermocouples at a rate of 1 Hz. The operation pressure is atmospheric and the working liquid is HFE-7100 (of purity exceeding 99%) from 3M (USA).

The fin diameter is 5 mm; as a result, the fin Biot number is well below unity. The fin length under investigation is from 1.2 to 2.2 cm, giving an aspect ratio (L/D) ranging from 2.4 to 4.4.

Experimental procedures were stated as follows. First the liquid temperature was adjusted to a prescribed value. After achieving the steady-state condition, turn on the transformer to heat up the bottom-heating block. The fin then transfers heat to the surrounding liquid via convection and/or boiling. The voltage of transformer is adjusted once the fin has reached a steady-state. The fin base heat flux and superheat can be estimated by extrapolating the temperature readings from the four thermocouples within the heating block, which resembles a 'boiling curve' based on the fin base area. Since the thermal response of the heating fin is found to be slow-varying, the process can thereby assume pseudo steady-state except at the transition between steady-state branches (discussed later). Repeated experiments show statisfactory reproducibility. The errors in fin base heat flux and superheat estimation are within 6% and 4%, respectively.

3. Results and discussion

3.1. Fin boiling curves: saturated liquid

Fig. 2 depicts the fin base heat flux vs base superheat temperature data for saturated HFE-7100 boiled on a fin of aspect ratio 2.4–4.4. For comparison's sake, the boiling curve obtained from a flat plate heater is also depicted in the same figure. For flat plate heater, the critical heat flux (CHF) and its corresponding wall superheat are 1.5×10^5 W/m^2 and 14 K, respectively. For MHF, on the other hand, the values are 5.8×10^4 W/m^2 and 23 K. Notably, according to these data, the multimode boiling on a fin can be easily identified from the fin base and the fin tip superheat temperatures. For example, when the fin base and the fin tip are at a superheat of 80 and 20 K, respectively, the fin is under FT mode (CHF $<$ 23 K $<$ MHF $<$ 80 K). Other situations can be similarly identified.

Hysteresis appears in Fig. 2, which is also reported in [3]. Consider the case of aspect ratio of 4.4. In the fin base temperature increasing phase, along curve OA, the fin heat transfer mode is nucleate boiling, denoted as regime N. Along curve AB, the fin heat transfer mode is transition + nucleate boiling, denoted as regime TN. At

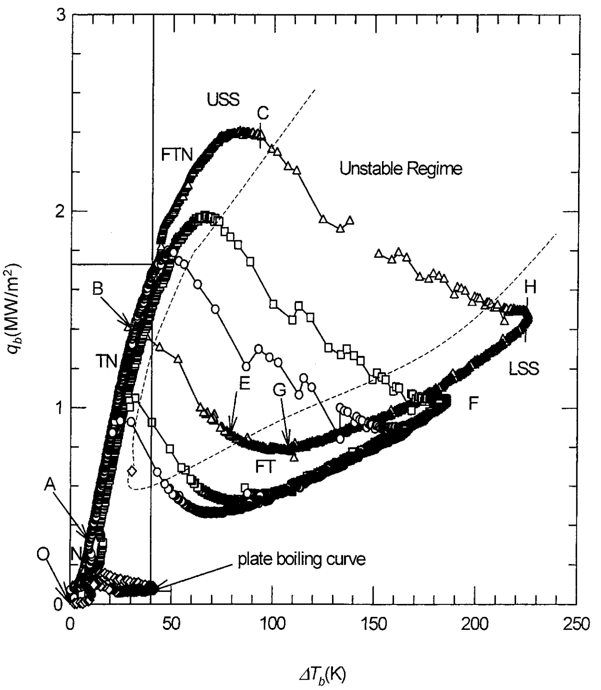

Fig. 2. Fin base heat flux vs base superheat plot. $D = 5$ mm. Saturated HFE-7100. N: nucleate boiling mode; T: transition boiling mode; F: film boiling mode. Dashed envelope: inaccessible regime. Plate pool boiling: boiling curve obtained from a plate pool boiling apparatus. △: $L = 2.2$ cm; □: $L = 1.7$ cm; ○: $L = 1.2$ cm. Boiling curve obtained from a plate pool boiling apparatus. Straight lines are for fin design example.

point B the fin base reached MHF. Along curve BC, the fin heat transfer mode is film + transition + nucleate boiling, denoted as regime FTN. At point C, both visual observation and the fin tip temperature reading suggest that nucleate boiling has been pushed away from the fin tip, or the fin has just entered FT mode. The corresponding base heat flux has raised to approximately 2.4×10^6 W/m^2, which is 16 times of the CHF (approximately 0.15 Mw/m^2). Such a high heat flux reflects the main superiority in employing fin boiling: to further promote the original highly efficient boiling heat transfer, rather than to enhance the heat transfer from an environment with poor heat transfer characteristics (which is the purpose of conventional fin). The base superheat accessible range shifts from 16 K for CHF on a flat plate heater to more than 90 K when a fin is present. The data on curve OC constitute the upper steady-state (USS) branch.

After passing point C, transition occurs suddenly. Evidently, when the fin is under FT mode, the operation becomes unstable. The base heat flux drops markedly, owing to the incorporation of less efficient film boiling mode. Increase or decrease in base superheat would then bring the fin to move along the lower steady-state (LSS) branch, as denoted by the curve EH in Fig. 2. On curve HG one can find only the film boiling mode on the fin surface, while on the curve EG, a short portion of transition boiling mode enters at fin tip. When the base temperature further goes down nucleate boiling mode will suddenly appear at fin tip, thereby enhancing the heat flux markedly and bringing the operation point back to the USS, curve OC, The FT mode with a short portion of transition boiling can stably sustain along the LSS branch (curve EG). However, along the USS branch, the tolerance for the FT mode is much weaker just a very small FT region close to point C is stable). The push-away action of nucleate boiling mode from fin tip would introduce instability and cause transition.

Similar boiling processes are noted for shorter fins. Fig. 2 also depicts the saturated boiling data on the fin of $L = 1.7$ and 1.2 cm. However, the maximum heat flux becomes slightly less: 2.0×10^6 and 1.8×10^6 W/m^2, respectively. The corresponding superheat for transition to the LSS branch also reduces: 70 and 50 K. As a result, in as much as a longer fin has more space to allow the nucleate boiling mode to sustain, it can operate at higher heat flux as well as at wall superheat to prevent burnout. On the other hand, along the LSS branch the base heat flux is greater for a longer fin. The superheat of transitional point back to the USS branch also increases with fin length. Restated, a longer fin also becomes easier to transit back to USS once it had burntout.

The experimentally stable and unstable fin boiling curves with different fin aspect ratios resemble the zones of stable and unstable fin boiling. Fig. 2 shows such a 'map' by dashed-curve enveloped zone, which opens in the direction of higher base heat flux and base superheat. The upper steady-state (USS) branch, the USS regime, is little influenced by the fin aspect ratio; however, the lower branch (LSS regime) shifts markedly with the fin aspect ratio. A larger aspect ratio can prevent the fin to transit easily to the LSS regime, which is hence recommended for safety consideration. However, the fin effectiveness would quickly level off as fin length becomes long.

3.2. Theoretical fin boiling curves

Lin [6] proposed the calculation procedures for fin boiling heat transfer characteristics on the basis of boiling curve on plate heater. Fig. 3 depicts the calculation results for HFE-7100 on the copper fin. The qualitative agreement between Figs. 2 and 3 is obvious, including the trends in change of heat transfer performance, the fin efficiency, and the associated stability characteristics. However, certain deviations exist between theoretical results and experiments. For example, the calculation results seriously underestimate the maximum heat flux as well as the accessible fin base range. Experimental film boiling curves change mildly with fin's aspect ratio, which contradict the theoretically predicted trend. Significant deviations were also reported in [4,16]. This might be due to the inadequateness of employing a power-law type correlation to describe the complicated boiling process. Use of one-dimensional heat conduction equation, together with plate boiling curve, for modeling fin boiling process, although qualitatively feasible, still faces difficulties in fin design practice.

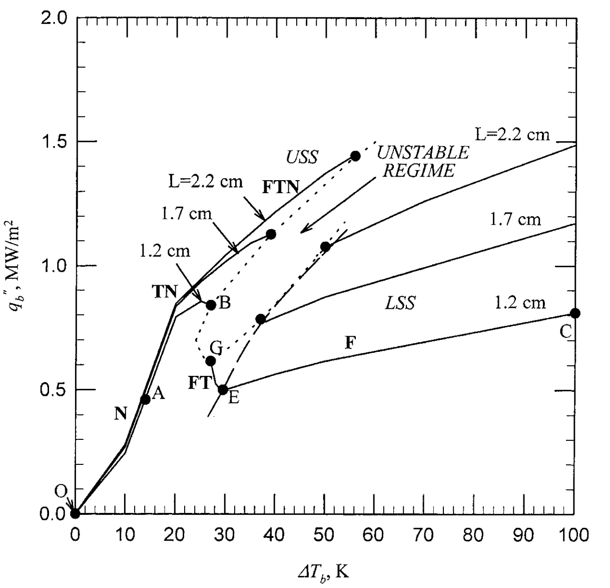

Fig. 3. Theoretical results for fin base heat flux vs base superheat plot. $D = 5$ mm. Saturated HFE-7100. N: nucleate boiling mode; T: transition boiling mode; F: film boiling mode; USS: upper steady-state; LSS: lower steady-state. Dashed envelope: unstable regime.

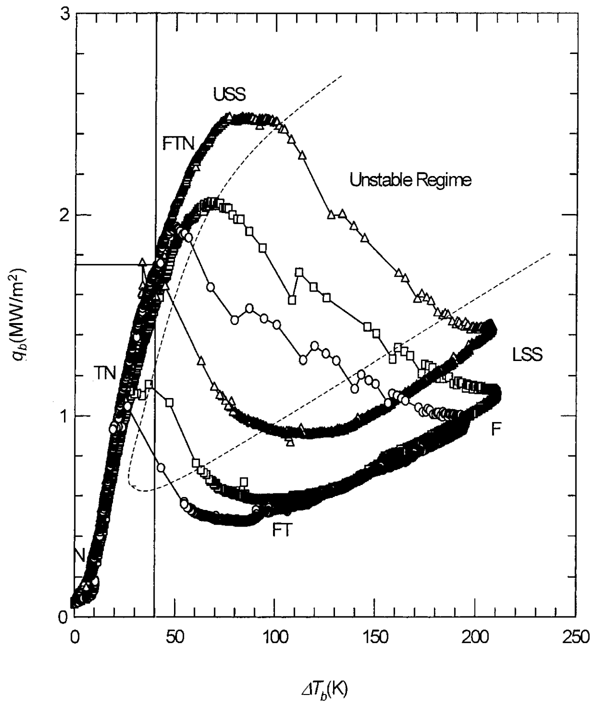

Fig. 4. Fin base heat flux vs base superheat plot. $D = 5$ mm. Subcooled HFE-7100. $\Delta T_{sub} = 10$ K. Dashed envelope: inaccessible regime. △: $L = 2.2$ cm; □: $L = 1.7$ cm; ○: $L = 1.2$ cm. Straight lines are for fin design example.

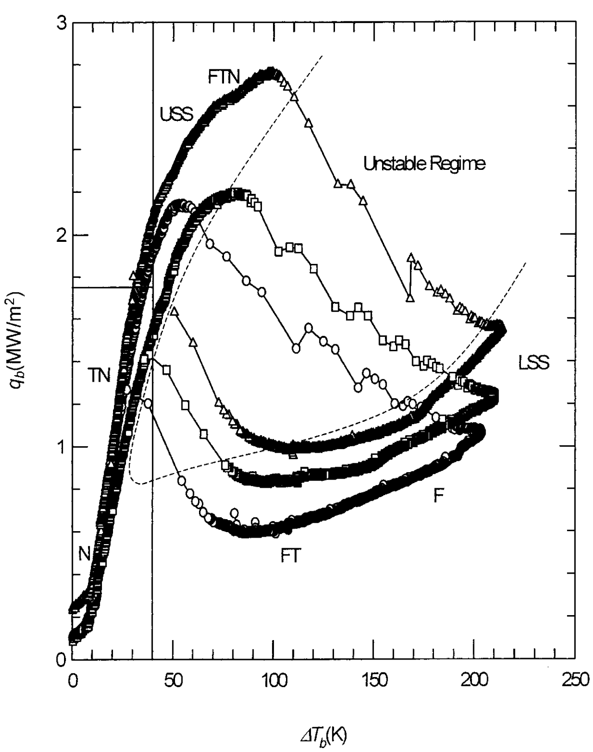

Fig. 5. Fin base heat flux vs base superheat plot. $D = 5$ mm. Subcooled HFE-7100. $\Delta T_{sub} = 20$ K. Dashed envelope: inaccessible regime. △: $L = 2.2$ cm; □: $L = 1.7$ cm; ○: $L = 1.2$ cm. Straight lines are for fin design example.

3.3. Fin boiling curves: effects of subcooling

Figs. 4 and 5 depict the subcooled boiling data of HFE-7100. Similar characteristics noted in saturated boiling tests persist in subcooled tests except that a higher liquid subcooling leads to a slight shift in the stable N and TN modes; and the maximum heat flux attainable has enchanced by 15–20% for liquid subcooling increases by 20 K. The F mode with a lower base temperature and the FT mode on the LSS branch shift upward with liquid subcooling. These observations correlate with the plate boiling test [5].

3.4. Accessible regimes

In accordance with the above-mentioned experimental observations, the boiling characteristics of HFE-7100 are qualitatively similar to those of methanol and of FC-72, which had been empolyed as testing liquid in available literature [8,13]. Restated, the boiling curves for fin boiling constitute the USS, LSS, and an unstable regime located in between. Only the USS and LSS are accessible in practice. The dashed-curve enveloped regimes in Figs. 2, 4 and 5 represent the unstable regimes, which are inaccessible in practice. Notably, the USS regime shifts upwards and leftwards as liquid subcooling increases, reflecting a more efficient boiling transfer. The unstable regime shifts along with the USS regime as well. As a result, on the basis of the heat transfer performance and the associated stability charactersitic consideration, a higher liquid subcooling is recommended for fin operation.

Design information regarding the single pin fin boiling of HFE-7100 could be extracted from Figs. 2, 4 and 5. For example, consider a heat load of 40 W from a device, which has to be dissipated at a wall temperature less than 100°C (base superheat less than 40 K on the basis of saturation temperature of HFE-7100). The available heat transfer surface is equivalent to a circle of diameter of 5 mm. In as much as the heat flux is approximately 2.0 MW/m^2, in accordance with the data depicted in Figs. 2, 4 and 5, to employ fin boiling is a feasible option. Part of the USS and unstable regime can satisfy the design duty. However, to achieve a stable operation, the unstable regimes should be avoided.

4. Conclusions

This work reports, for the first time, an experimental work for saturated and subcooled HFE-7100, a CFC-substitute, boiling on a straight pin fin. The maximum heat flux can be reached is 16 times of CHF of a flat plate heater if a fin of diamter 5 mm were employed. The operational base temperature range has been markedly broadened. For a given liquid/fin combination there exist USS branch and LSS branch. In between large regime including most of film + transition (FT) and transition (T) boiling mode exists, which is unstable and should be avoided in fin design. Maps of accessible regimes are built up according to the experimental data. Longer fin provides a safer boiling process, while liquid subcooling markedly enchances heat transfer efficiency along the USS branch.

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