Methanol Boiling on a Straight Pin Fin

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Several textbooks have surveyed investigations analyzing fins with a constant heat-transfer coefficient [such as Kern and Kraus (1972)]. When boiling occurs on a fin, the heat-transfer coefficient along the fin is definitely not a constant. Motivated by the pioneering works of Haley and Westwater (1965), as well as Lai and Hsu (1967), the fin boiling process has received extensive attention. Kraus (1988) and Liaw and Yeh (1994a) reviewed related literature. The heat-transfer rate from the fin base might significantly increase more than with the case without a fin. The burnout-wall superheat temperature for saturated isopropanol boiled on a copper cylinder shifts from 18.5 to 280 K, thereby broadening the operational temperature range (Liaw and Yeh, 1994b). Consequently, applying boiling on a fin does not serve the conventional purpose of enhancing heat transfer from a fluid with poor heat-transfer characteristics. In contrast, it further enhances the high heat-transfer rate that could be achieved by boiling and is highly promising for compact heat-exchanger design (Liaw and Yeh, 1994a).

When liquid boils on a fin, complicated heat-transfer configurations might appear. For instance, when the fin base temperature is located in the film boiling region, at least three situations might occur on the fin surface: film boiling alone, film followed by transition boiling, and film + transition + nucleate boiling. Obviously, the material's melting point must be higher than the maximum temperature considered herein to allow for the possibility of boiling. By assuming a simple power-law-type temperature dependence of the heat-transfer coefficient for each boiling mode, the steady-state temperature distribution along the fin and the base heat flow for various boiling configurations can be observed (Unal, 1985; Yeh and Liaw, 1990a; Sen and Trinh, 1986). From these data, fin effectiveness and fin efficiency can be evaluated, subsequently allowing one to obtain the fin design information (Liaw and Yeh, 1990; Yeh and Liaw, 1990b). Using these steady-state solutions in practice supposes that they are stable to external perturbations.

Liaw and Yeh (1994b) analyzed the stability characteristics for only one boiling mode on the fin. According to their results, a fin with only transition boiling on it cannot function properly except with a small fin aspect ratio and/or a quite low thermal conductivity; both conditions are unfavorable to heat-transfer augmentation. Therefore, the steady-state solutions with only transition boiling on the fin are largely *unstable* in nature and are of little practical interest. On the other hand, relatively little information regarding the stability characteristics for multimode fin boiling is available.

Lin and Lee (1996) provided the first detailed stability analysis on the steady-state solution for multimode boiling on a straight pin fin. Their results demonstrated that when film and transition boiling coexist on the fin surface, or only the transition boiling has covered the entire fin, the operation is stable only if the fin length is less than some critical value. When transition and nucleate boiling coexist on a fin, or in the three-mode boiling (film + transition + nucleate boiling), the entry of nucleate boiling at the fin tip stabilizes the boiling process. Moreover, those investigators strongly contended that a fin designed in the stable regime can function well and transport more than ten times the amount of heat flux than that from a wall without a fin. However, if a fin is designed under an unstable regime, although the corresponding analytical steady-state solutions are available in the literature, the fin cannot function properly and may cause subsequent device burnout. Related theoretical works discussing some essential factors included Lin and Lee (1998a,b).

In light of these discussions, this study experimentally verifies the theoretical findings of our earlier work. Fin base temperature and heat flux data are measured, along with the tip temperature, as saturated or subcooled methanol boiled on a straight pin fin. Also demonstrated herein are the complete heat performance ''map'' associated with the stability characteristics of fin boiling and the effects of liquid subcooling.

Experimental Studies

Figure 1a depicts the experimental setup. The operational pressure is atmospheric, and the working liquid is methanol (purity 99%). The testing chamber is $300(L)\times 300(W)\times 300(H)$ mm in dimension and has front and back view glasses (7) for observation. A pure copper fin (1), heated by the bottom-cartridge heating block (2) whose energy is supplied by a transformer (8), served as the boiling surface. In the lower section of the testing chamber, a preheater (4), 1.2 kW in capacity, was installed. This chamber was vented to the atmospheric pressure through a condenser (11). The liquid tem-

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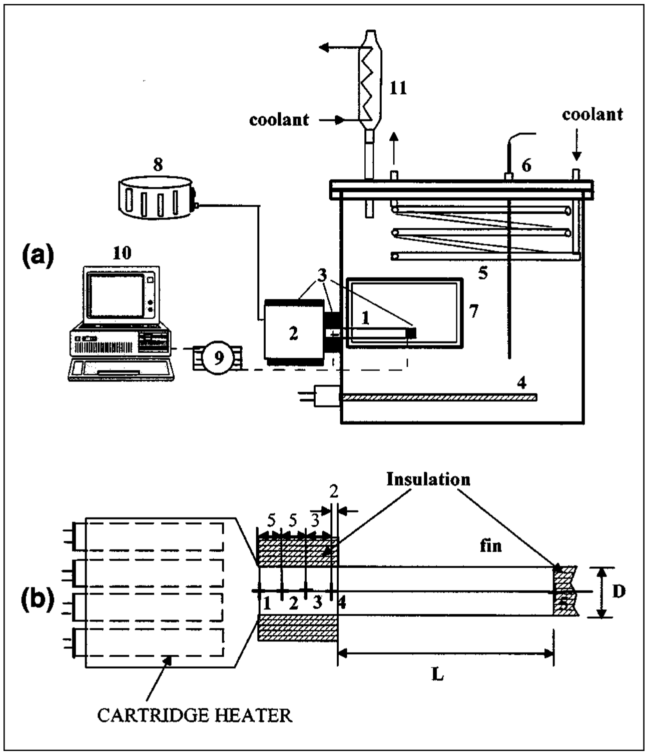

Figure 1. (a) Experimental setup; (b) details of the copper fin and the bottom heating block.

(a) (1) Fin; (2) bottom heating block; (3) insulation; (4) preheater; (5) cooling coil; (6) thermocouple; (7) view glasses; (8) transformer; (9) data-acquisition system; (10) personal computer; (11) condenser. (b) The cross symbols denote the locations of thermocouples. Other numerical values are in mm.

perature was adjusted by the preheater and the cooling coil (5), and then measured by a thermocouple (6). A CCD camera recorded the boiling dynamics.

Figure 1b displays the details of the boiling section. The bottom-heating block contained four cartridge heaters, each of 500-W capacity, producing a maximum of 2-kW capacity. As illustrated in Figure 1b, temperatures at four axial positions in the heating block (1–4) and at the fin tip (5) were measured by thermocouples at a rate of 1 Hz, sending automatically to the data-acquisition system (9) connected to a personal computer (10).

The fin, made of pure copper, is attached to the bottom-heating block. The bottom-heating block is well insulated, with most of the joule heat from the bottom cartridge heaters transiting into the fin base. Because the fin diameter is 5 mm, the fin Biot number is well below unity. The fin length under investigation is from 1.0 to 4.0 cm, and has an aspect ratio (L/D) ranging from 2 to 8. The fin tip was insulated to simulate the theoretical prediction made in Lin and Lee (1996).

Experimental procedures were as follows. The liquid temperature was initially adjusted to the desired value. After achieving the steady-state condition, the prescribed voltage was set so the transformer heated the bottom-heating block. The fin then transferred heat to the surrounding liquid via convection and/or boiling. Next, the transformer voltage was adjusted once steady-state of fin boiling has been reached. The fin base heat flux and superheat temperature can be estimated by extrapolating the temperature readings from the four thermocouples shown in Figure 1b, which resembles a "boiling curve" based on the fin bottom area (Liaw and Yeh, 1994a,b). A pseudo-steady-state approximation can be adopted, since the thermal response of the heating fin is a slow-varying process, except during the transition between the upper and the lower steady-state branches (discussed later). Repeated experiments indicate that the reproducibility is satisfactory. The errors in fin base heat flux and superheat estimation are within 6% and 4%, respectively.

Results and Discussion

Fin boiling curves: $L/D = 6.0$

Figure 2 shows the time evolution of extrapolated fin base heat flux vs. base superheat temperature data for saturated methanol boiled on a fin of aspect ratio 6.0. For comparison, this figure also contains the corresponding methanol boiling curve on a flat copper plate (without a fin). The critical heat flux (CHF) temperature and the minimum heat flux (MHF) temperature are 14 and 90 K, respectively. Notably, multimode boiling 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 300 and 60 K, respectively, the fin is under FT mode. Other situations can be similarly identified.

Hysteresis appears in Figure 2, as Liaw and Yeh (1994a) also observed. (*Note:* For convenience, the natural convection contribution is hereinafter lumped into the nucleate boiling mode.) In increasing phase of the fin base temperature, the base operation point moves first from point O to A. Along curve OA, the fin heat-transfer mode is nucleate + convection, denoted as regime N. At point A, the base temperature has reached the CHF condition. The operation point then moves from point A to point B. Along curve AB, the fin heat-transfer mode is transition + nucleate + convection, denoted as regime TN. At point B the fin base reaches MHF. Along curve BC, the fin heat-transfer mode is film + transition + nucleate + convection, denoted as regime FTN. Figure 3a illustrates an FTN boiling situation. The corresponding slope of the boiling curve becomes less when film boiling is incorporated. 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 is raised to approximately 6.5 MW/m^2, that is, ten times higher than the CHF (approx. 0.6 MW/m^2). Such a high heat flux reflects the main advantage of employing fin boiling: to further promote the originally highly efficient boiling heat transfer rather than enhancing the heat transfer from an environment with poor heat-transfer characteristics. The accessible range for the base superheat shifts from 14 K, for CHF on a flat plate without a fin, to more than 260 K, when a fin is present. The data on curve OC resemble the upper steady-state branch.

After passing point C, transition to a lower branch suddenly occurs. Obviously, the operation becomes unstable when the fin is in FT mode. The base heat flux markedly drops owing to the incorporation of a less efficient film boiling mode. Increasing or decreasing base superheat would then

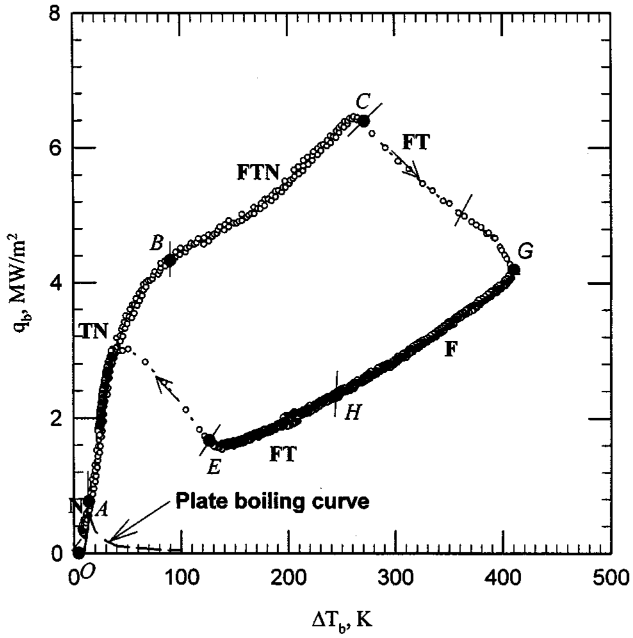

Figure 2. Fin base heat flux vs. base superheat plot.
$D = 5$ mm, $L = 30$ mm. Saturated methanol. N = nucleate boiling mode; T = transition boiling mode; F = film boiling mode.

cause the fin to move along the lower branch, as denoted by curve EH in Figure 2. Curve HG contains only the film boiling mode on the fin surface. Figure 3b provides an illustrative example. On curve EG, a short portion of the transition boiling mode enters at fin tip. Notably, the tip superheat temperature corresponding to point E is approximately 40 K, which is between CHF and MHF, and the tip should be located in the transition boiling region. With a further decrease in the base temperature, the nucleate boiling (and the convection) suddenly appears at fin tip, thereby enhancing the heat flux markedly and bringing the operation point back to the upper branch, curve OC. The FT mode with a short portion of transition boiling can be stably sustained along the lower branch (curve EG). Along the upper branch, however, 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 the nucleate boiling mode from the fin tip would introduce instability and cause transition.

Fin boiling curves: L/D = 2.0

Figure 4 summarizes the saturated methanol boiling data on a fin with $L = 1$ cm (an aspect ratio of 2.0). As the base superheat gradually increases, the base operation point initially moves from point O to A (nucleate + convection, regime N); in doing so, the base temperature reaches the CHF condition. The operation point then moves from point A to point B′. Along curve AB′, the heat-transfer mode is transition + nucleate + convection, denoted as regime TN. At point B′, the fin tip reaches CHF and the nucleate boiling is entirely pushed away from the fin tip. However, since the fin length is too short to allow for film boiling at the fin base, the entire fin surface is under transition boiling along or in the T mode. A shift slightly upwards from point B′ results in a sudden

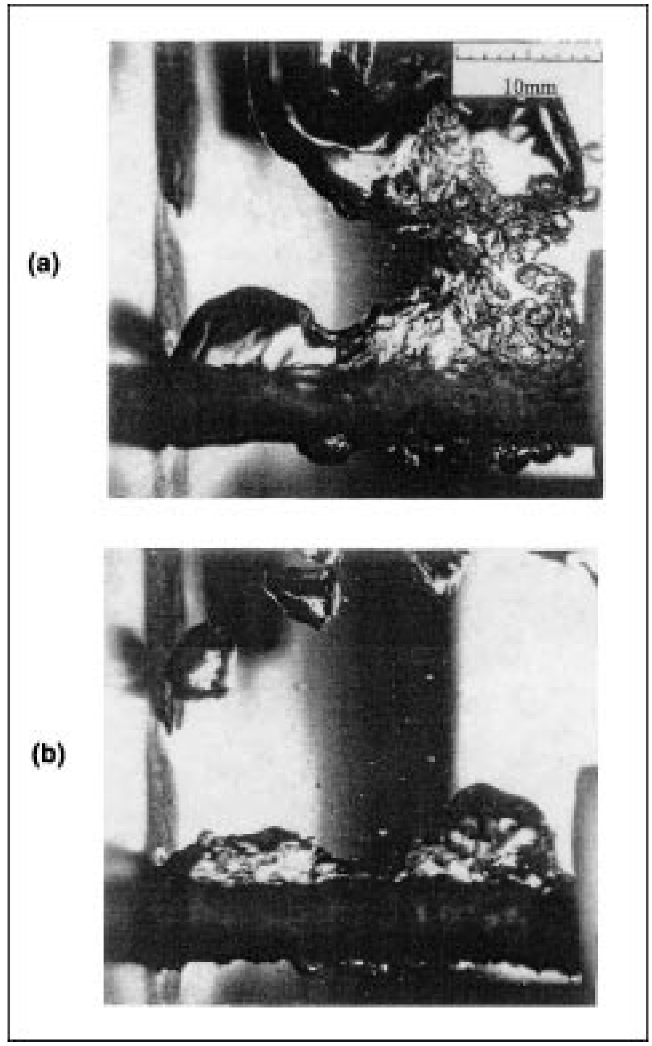

Figure 3. (a) Photographs for FTN boiling; (b) photographs for F boiling.

jump to the lower steady-state branch. Restated, the boiling mode T existing on the fin surface alone is essentially unstable. This means that the corresponding maximum heat flux is 4.0 MW/m^2, while the base temperature is 61 K; both are less than those for the $L/D = 6.0$ case.

Along the lower steady-state branch, the base heat flux is much lower than that on the upper steady-state branch, due to the lower boiling heat-transfer coefficient of the film. Increasing or decreasing the base superheat would cause the fin to move along the lower branch, as denoted by curve E′H′ in Figure 4. On curve H′G′, only the film boiling mode can be found on the fin surface; meanwhile, on curve E′G′, a short period of transition boiling begins at the fin tip. Beneath point E′, nucleate boiling reappears at the fin tip, thereby enhancing the heat flux markedly and bringing the operation point back to the upper branch, curve OB′.

Fin efficiency

Figure 5 demonstrates that the fin efficiency corresponds to Figure 2, as calculated by dividing the base heat flow rate

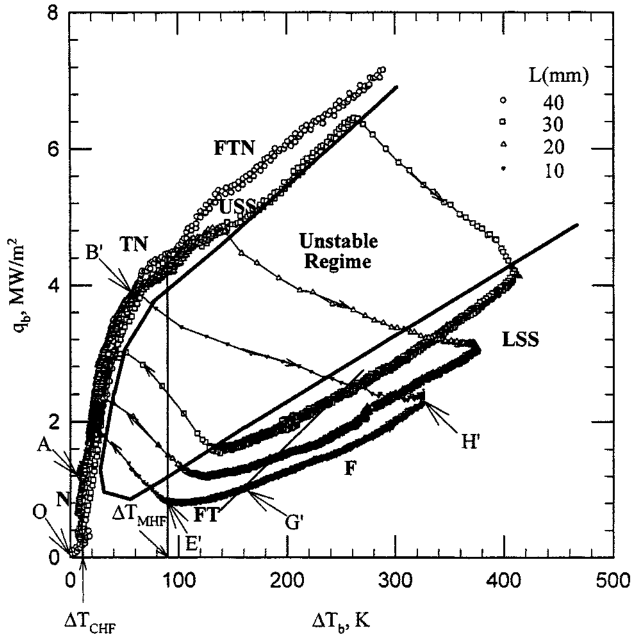

Figure 4. Experimental fin boiling plot with associated stability characteristics.

Saturated methanol. LSS: lower steady-state regime; USS: upper steady-state regime. N = nucleate boiling mode; T = transition boiling mode; F = film boiling mode.

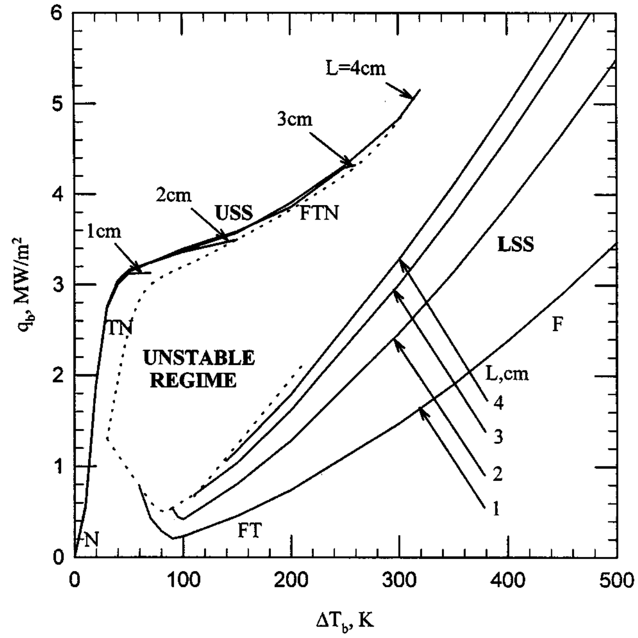

Figure 6. Calculated base heat flux vs. base superheat plot.

D = 5 mm; L = 1−4 cm. Saturated methanol boiled on copper fin, with parameters for boiling modes listed in Lin (1998).

(heat flux times cross section) by the hypothetical heat flow rate from the whole fin surface if it is located at the base condition. Lin and Lee (1996) suggested that the fin efficiency can be well above unity when transition boiling is incorporated. According to Figure 5, the efficiency decreases in N mode (curve OA), then increases quickly when transition boiling occurs at the fin bottom (curve AB). Fin efficiency reaches a maximum when fin base is at point MHF, then decreases in the following FTN, FT, and the final F boiling mode.

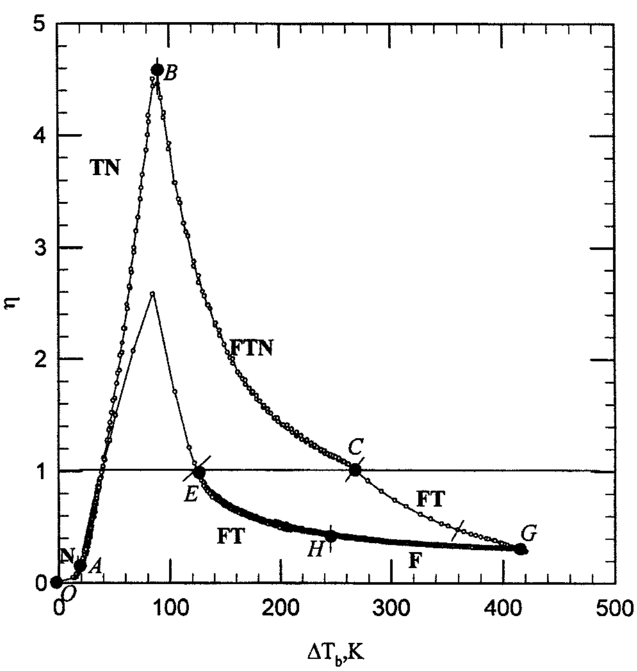

Figure 5. Fin efficiency vs. fin bottom superheat temperature; L/D = 6.0.

In the decreasing base temperature phase (the lower HA curve in Figure 5), fin efficiency increases in the F and FT modes, reaches a maximum (less than that for the increasing base superheat phase) when the fin base is at MHF, then decreases again in the subsequent TN and N boiling mode.

The fin efficiency for $L/D = 2.0$ reveals a similar trend to that for $L/D = 6.0$, except that the corresponding maximum fin efficiencies for the upper and the lower branches decrease. Notably, the maximum fin efficiency is found at $\Delta T_b = \Delta T_{\mathrm{MHF}}$, or when the fin base is at the MHF point.

Comparison with theoretical predictions

For the sake of comparison, Figure 6 depicts the calculated (stable) base heat flux vs. superheat plot, with the boiling mode parameters listed in Lin (1998). The qualitative agreement between Figures 2, 4, 5, and those predicted in Lin and Lee (1996) is obvious, including the trends in change of heat-transfer performance, the fin efficiency, and the associated stability characteristics. These results thus confirm the theoretical findings in Lin and Lee (1996). [*Note:* Although the trend is qualitatively similar, certain deviations exist in between. Marked deviations were also reported in Unal (1987) and Liaw and Yeh (1994b). This might be because a power-law-type correlation was used to describe the complicated boiling process. However, the qualitative features are the same for both theory and experiments.] Experimental obser-

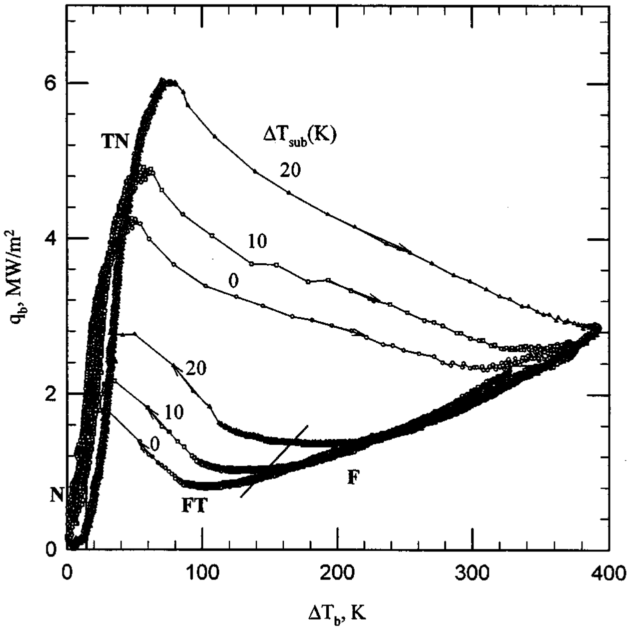

Figure 7. Fin base heat flux vs. base superheat plot.

$D = 5$ mm; $L = 10$ mm. Saturated and subcooled methanol. N = nucleate boiling mode; T = transition boiling mode; F = film boiling mode.

vation shows that stable steady-state boiling can occur for the following boiling modes: N, TN, FTN, F, and a part of FT. Note that in this work the convection is grouped into nucleate boiling, and is omitted in this list. We explored the nature of the stability of the regime between the upper and lower branches. The fin is initially heated in the air to some point with a high base temperature and a low base heat flux, which is located somewhere between the two stable branches. Methanol with a prescribed temperature is then poured into the chamber to quench the fin. If other stable steady state(s) are in the middle regime, the change in the initial conditions might attract the operation to it (them). Nevertheless, no middle steady states have been found. This partially proves the unstable nature of the whole middle regime.

The experimentally stable and unstable fin boiling curves with different fin aspect ratios resemble the zones of stable and unstable fin boiling. Figures 5 and 6 display such a "map" based on the saturated methanol boiling of $L/D = 2$, 4, 6 and 8, respectively. Especially the zones open in the direction of a higher base heat flux and base superheat. The fin aspect ratio only slightly influences the upper steady-state branch, the USS regime; however, the lower branch (LSS regime) markedly shifts with the fin aspect ratio. The preceding observations are qualitatively consistent with the theoretical predictions of Lin and Lee (1996). If operating at the USS regime, nearly the same base heat flux can be achieved, regardless of the fin aspect ratio, if the base superheat is fixed. In addition, a larger aspect ratio can prevent the fin from transiting easily to the LSS regime, which is recommended for safety reasons. However, the fin effectiveness, that is, the ratio between the heat flux from the wall with the fin and the heat flux from the wall without the fin, quickly levels off as fin length increases. To achieve an optimal boiling fin design, a compromise between the fin performance and the material's cost should be made.

Effects of liquid subcooling

Figure 7 presents the boiling curves for saturated and subcooled methanol ($\Delta T_{sub} = 10$ and 20 K) on an $L/D = 2.0$ fin. Higher liquid subcooling leads to a slight shift in the stable N and TN modes; however, the maximum heat flux attainable is enhanced by 50% when increasing liquid subcooling by 20 K. The F mode with a higher base temperature is a weak function of liquid subcooling. Nevertheless, the F mode with a lower base temperature and the FT mode in the lower steady-state branch shift upwards, implying a more efficient heat transfer under higher liquid subcooling. These observations closely correspond to the generally accepted liquid subcooling effects on the pool boiling of liquid without a fin. Restated, a higher liquid subcooling has only a secondary effect on the nucleate boiling curve and the film boiling with a higher superheat. It can substantially increase the CHF and MHF, however, which results in a more efficient transition boiling mode and film boiling mode with a lower superheat (Lee, 1998). Furthermore, except for the shift in the corresponding boiling curves, all stability characteristics in subcooled methanol fin boiling resemble those in saturated boiling, which are not repeated here for brevity.

The subcooled methanol boiling curves with fins of various aspect ratios resemble the USS, LSS, and the unstable regimes. Figure 8 depicts these regimes. Notably, the USS regimes shift upwards and leftwards as liquid subcooling increases, reflecting a more efficient boiling transfer. Although

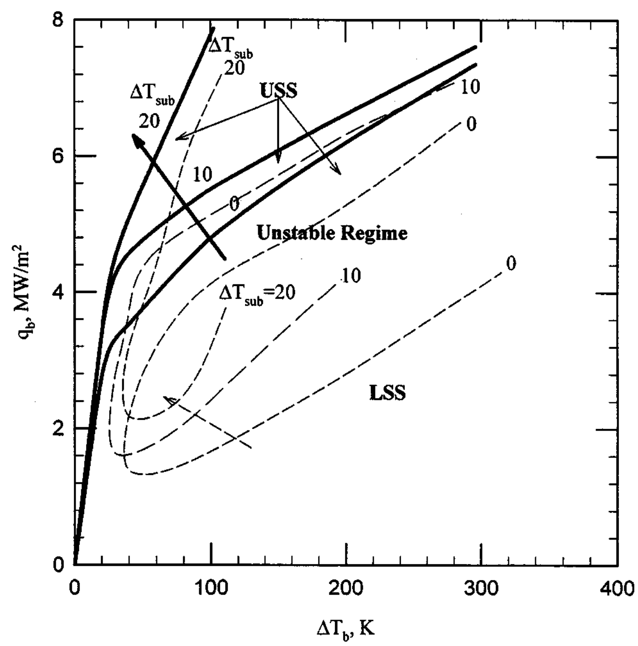

Figure 8. Experimental fin boiling plot with associated stability characteristics.

Saturated and subcooled methanol. Dashed curves enveloped regime: unstable regime; regime between bold curve and dashed curve: USS, upper steady-state regime; regime below the dashed curve enveloped regime: LSS, lower steady-state regime.

the unstable regime shifts along with the USS regime, the corresponding unstable area on the plot shrinks accordingly. Consequently, in light of the heat-transfer performance and the associated stability characteristics, we recommend a higher liquid subcooling during operation.

In sum, this experimental work under saturated and subcooled conditions has verified the theoretical findings in Lin and Lee (1996). According to our results, a fin designed in the stable region can function well and transport more than ten times of heat flux than that from a flat plate. However, if a fin is designed in the unstable region, even though the corresponding analytical steady-state solutions are available in the literature, the fin cannot function properly and may cause subsequent device burnout. Moreover, increasing liquid subcooling causes the shift in various boiling regimes, but does not influence the basic stability characteristics of fin boiling.

Conclusions

This work investigates straight pin fin boiling. Theoretical analysis on fin stability reported in Lin and Lee (1996) is experimentally verified. Theoretically predicted large regimes with rather high fin efficiencies, including most film + transition (FT) and transition (T) boiling regimes, are essentially unstable and should be avoided in fin design. Both saturated and subcooled methanol boiling are considered as well.

Notation

q_b = base heat flux, MW/m^2
η = fin efficiency
ΔT_b = base superheat temperature, K
ΔT_{CHF} = superheat temperature at CHF, K
ΔT_{MHF} = superheat temperature at MHF, K

Literature Cited

Haley, K. W., and J. W. Westwater, "Boiling Heat Transfer from a Single Fin to a Boiling Liquid," *Chem. Eng. Sci.*, **20**, 711 (1965).

Kern, D. Q., and A. D. Kraus, *Extended Surface Heat Transfer*, McGraw-Hill, New York (1972).

Kraus, A. D., "Sixty-Five Years of Extended Surface Technology," *Appl. Mech. Rev.*, **41**, 321 (1988).

Lai, F. S., and Y. Y. Hsu, "Temperature Distribution in a Fin Partially Cooled by Nucleate Boiling," *AIChE J.*, **13**, 817 (1967).

Lee, D. J., "Two-Mode Boiling on a Horizontal Heating Wire: Effects of Liquid Subcoolings," *Int. J. Heat Mass Transfer*, **41**, 2925 (1998).

Liaw, S. P., and R. H. Yeh, "Fins with Temperature Dependent Surface Heat Flux—I. Single Heat Transfer Mode," *Int. J. Heat Mass Transfer*, **37**, 1509 (1994a).

Liaw, S. P., and R. H. Yeh, "Fins with Temperature Dependent Surface Heat Flux—II. Multi-Boiling Heat Transfer," *Int. J. Heat Mass Transfer*, **37**, 1517 (1994b).

Liaw, S. P., and R. H. Yeh, "Analysis of Pool Boiling Heat Transfer on a Single Cylindrical Fin," *J. Chin. Soc. Mech. Eng.*, **11**, 448 (1990).

Lin, W. W., "Stability and Entropy Generation of Boiling Heat Transfer Systems," PhD Diss., National Taiwan Univ., Taipei (1998).

Lin, W. W., and D. J. Lee, "Boiling on a Straight Pin Fin," *AIChE J.*, **42**, 2721 (1996).

Lin, W. W., and D. J. Lee, "Boiling on Plate Fin and Annular Fin," *Int. Commun. Heat Mass Transfer*, **25**, 1169 (1998a).

Lin, W. W., and D. J. Lee, "Boiling on a Straight Pin Fin with a Temperature-Dependent Thermal Conductivity," *Heat Mass Transfer* (1998b).

Sen, A. K., and S. Trinh, "An Exact Solution for the Rate of Heat Transfer from a Rectangular Fin Governed by Power Law-Type Temperature Dependence," *ASME J. Heat Transfer*, **108**, 457 (1986).

Unal, H. C., "Determination of the Temperature Distribution in an Extended Surface with a Non-Uniform Heat-Transfer Coefficient," *Int. J. Heat Mass Transfer*, **28** (1985).

Unal, H. C., "An Analytic Study of Boiling Heat Transfer from a Fin," *Int. J. Heat Mass Transfer*, **30**, 341 (1987).

Yeh, R. H., and S. P. Liaw, "An Exact Solution for Thermal Characteristics of Fins with Power-Law Heat Transfer Coefficient," *Int. Commun. Heat Mass Transfer*, **17**, 317 (1990a).

Yeh, R. H., and S. P. Liaw, "Theoretical Study of a Fin Subject to Various Types of Heat Transfer," *Tatung J.*, **20**, 59 (1990b).

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