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Two-mode boiling on a horizontal heating wire: effects of liquid subcoolings

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Abstract

The steady-state boiling curves of methanol boiled on an electrically heated tungsten wire, including the nucleate boiling curve, the film boiling curve, and the equilibrium line located in between are reported with liquid subcooling as a parameter. As liquid subcooling increases, the critical heat flux becomes greater, the film boiling mode more efficient, and the equilibrium line shifts upwards. A lower liquid temperature results in a more stable nucleate boiling mode. However, at a very high liquid subcooling, the steady-state boiling curves are not influenced by the liquid subcooling.

Nomenclature

d wire diameter, [mm]
I_E equilibrium current, [amp]
$I_{E,cal}$ calculated equilibrium current, [amp]
$I_{E,exp}$ experimental equilibrium current, [amp]
$I_{E,sat}$ equilibrium current at saturated condition, [amp]
$I_{E,sub}$ equilibrium current at subcooled condition, [amp]
q heat flux, [W/m^2]
q_{CHF} critical heat flux, [W/m^2]
T wall superheat, [K]
T_{SUB} liquid subcooling, [K]

1. Introduction

Under certain conditions, boiling of different modes can coexist on the same heating element. In pool boiling with an electrically heated wire, steady state and unsteady state two-mode boiling (nucleate and film boiling) had been studied [1–7]. The important conclusions drawn from these works are as follows: (a) there are infinitely many 'average' transition boiling curves and one 'true' transition curve under a specific heater/fluid combination, with the former being mainly determined by the heating method and the disturbances existing in the boiling processes; (b) an 'equilibrium line' exists in each wire boiling system dividing both the nucleate and film boiling respectively into stable and metastable regimes; (c) an 'equal-area rule' can be employed in determining the equilibrium line, with the two ends of the wire locating at respectively nucleate and film boiling. The intersections between the equilibrium line and the boiling curves denote the separating points dividing the *stable* and *metastable* regimes.

The points separating stable and metastable regimes on the boiling curve are important in practice. The critical points such as the critical heat flux (CHF) and minimum heat flux (MHF) points indicate the absolutely unstable points at which the system cannot tolerate infinitesimal disturbance. These critical points can be well described by classical hydrodynamic theory [8]. On the other hand, a heater under metastable nucleate boiling mode (i.e. the nucleate boiling curve below CHF and above the intersection between equilibrium line and nucleate boiling curve) can tolerate a finite-magnitude disturbance to prevent burnout. If a large enough disturbance is introduced, however, the heater would still transit into film boiling. This is the so-called 'non-hydrodynamic' aspect of burnout [9]. Furthermore, if the heater is under stable nucleate boiling mode (i.e. the nucleate boiling curve below the intersection between equilibrium line and nucleate boiling curve), no transition to film boiling would occur regardless of the disturbances magnitude. That is, the operation is absolutely stable and safe. Similar conclusions could also be applied to the film boiling curve.

Lu and Lee [2] noted that the nucleate boiling curve, the film boiling curve, and the steady-state transition

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boiling curve, the equilibrium line, form the 'steady-state boiling curves' of the system, which determines the stability characteristics of the boiling processes. Lee and Lu [3] had reported the effects of heating wires (tungsten, tantalum, molybdenum and titanium of 0.3–1.55 mm), boiling liquids (methanol, acetone, iso-propanol, and iso-butanol) and heating methods on the steady-state and unsteady-state boiling curves. They employed the equal-area concept to interpret the boiling data, and to estimate the location of equilibrium line (discussed later). Recently, Lin and Lee [10] had identified the stable and metastable regimes on nucleate and film boiling curves of an indirectly conductive heating surface for methanol flow boiling.

This study is a continuation of Lee and Lu's work on wire boiling. The focus is upon the effects of subcoolings on the steady-state boiling curves of liquids boiled on an electrically heated tungsten wire. Notably, the applied electric current along the equilibrium line is a constant, termed as the equilibrium current. The equilibrium current can serve as an index for the relative stability between nucleate and film boiling modes of the boiling process.

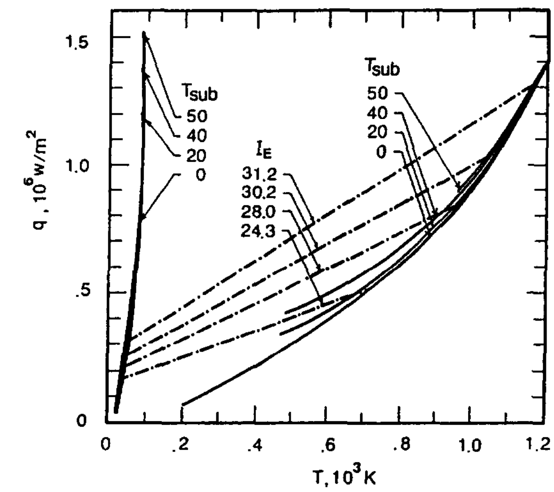

Fig. 1. Steady-state boiling curves under saturated and subcooled conditions. 0.51 mm wire, methanol.

2. Experimental

Pool boiling has been conducted in a pool with a horizontal tungsten wire of diameters 0.51 and 1.55 mm. The working liquids are methanol, acetone, iso-propanol and iso-butanol, with purity over 99% *w/w*. Metal wire was hung between two electrodes through which a DC current was passed for heating. A 1 kW auxiliary heater was installed at the bottom of the vessel to preheat liquid. Heat flux and wall superheat can be calculated from the electric current and voltage drop data. Detailed descriptions about the pool (including a schematic drawing of experimental setup), the experimental methods, the data reduction procedures, and the determination of equilibrium line can be found in Lu and Lee [2].

Average heat flux and average wall superheat data can be calculated on the basis of the voltage drop and the electric current across the wire. The maximum errors in heat flux and wall superheat measurements were estimated as 2.7% and 4.4%, respectively.

3. Results and discussion

Figure 1 shows the steady-state boiling curves for methanol boiling on a 0.51 mm W wire. Nucleate and film boiling curves are depicted as the solid curves. For each pair of nucleate boiling curve and film boiling curve, there is a unique equilibrium line, depicted as the dot-dashed curve in the figure. An increasing liquid subcooling shifts the CHF point, indicating a wider operation range for nucleate boiling, and raise the film boiling heat flux at lower wall superheat. These findings are consistent with the literature results [11]. The combined effect is to shift the whole boiling curves, including the nucleate boiling curve, the film boiling curve, and the 'true' transition boiling curve upwards; hence giving a higher equilibrium line to fulfil the equal-area criterion. (Note: Discussion on the *true* transition boiling curve and the *average* transition boiling curve is provided in [3]). The corresponding equilibrium current data, denoted as the symbol I_E in the figure, increases accordingly. A larger I_E denotes to a more stable nucleate boiling mode. Restated, a higher I_E indicates a wider nucleate boiling curve which is absolutely stable and safe. We can observe from the figure that the intersections between the equilibrium line and the film boiling curve move upwards and rightwards. This results in a wider metastable film boiling regime, thereby exhibiting a less stable feature.

Steady-state boiling curves for acetone, iso-propanol and iso-butanol boiled on 0.51 mm W wire have a similar trend as noted in Fig. 1, and are not shown here for brevity's sake. Comparisons between these results reveal that the nucleate boiling curves of four liquids are close. The film boiling heat transfer efficiency follows the sequence: iso-propanol > iso-butanol > methanol > acetone, which is consistent with conventional film boiling theory [12]. However, the difference is within 10%. The combined effects give a similar equilibrium current. That is, the relative stability between nucleate and film boiling modes is roughly the same.

Figure 2 depicts the experimental results for iso-propanol boiled on a 1.55 mm wire. The results for the other liquids are similar to Fig. 1. The basic characteristics of the boiling on a 1.55 mm wire are similar to those on a 0.51 mm wire, except that (i) the corresponding CHF is

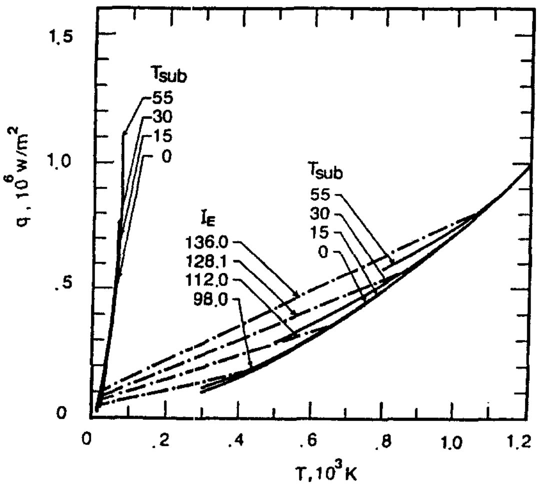

Fig. 2. Steady-state boiling curves under saturated and subcooled conditions. 1.55 mm wire, iso-propanol.

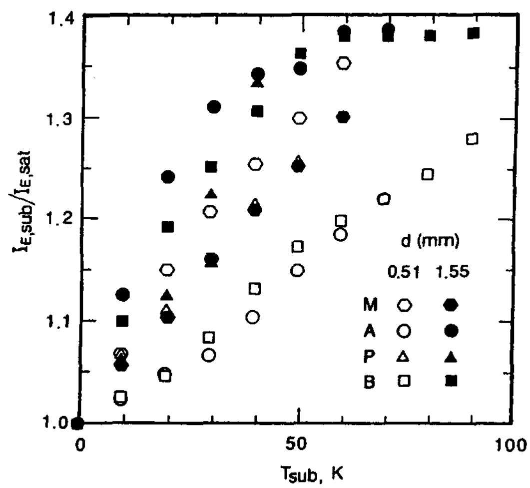

Fig. 3. Ratio of $I_{E,sub}/I_{E,sat}$ versus T_{sub} plot. M: methanol, A: acetone, P: iso-propanol, B: iso-butanol.

lower; (ii) the film boiling is less efficient. The combined effects shift the equilibrium line to a lower position. As a result, nucleate boiling (film boiling) on a wire of greater diameter is less (more) stable than that on a wire of smaller diameter.

To employ the equal-area criterion for estimating I_E requires the knowledge about the 'true' transition boiling curve, which is generally not available for a boiling wire. Lee and Lu [3] had proposed a method on the basis of the scheme by Weber [13]: the weighted influences of

Table 1
Experimentally obtained I_E ($I_{E,exp}$) and calculated I_E ($I_{E,cal}$) data

		MeOH		i-BuOH		i-PrOH		Acetone	
d, mm	T_{sub}, K	$I_{E,exp}$	$I_{E,cal}$	$I_{E,exp}$	$I_{E,cal}$	$I_{E,exp}$	$I_{E,cal}$	$I_{E,exp}$	$I_{E,cal}$
0.51	0	24.3	26.7	25.7	25.1	26.2	26.7	24.6	25.7
0.51	10	—	—	—	—	—	—	26.0	26.0
0.51	15	—	—	—	—	27.0	28.0	26.8	27.1
0.51	20	28.0	27.3	—	—	—	—	—	—
0.51	25	—	—	—	—	—	—	27.8	27.9
0.51	30	—	—	27.3	28.3	—	—	—	—
0.51	40	30.2	29.1	—	—	—	—	29.4	29.3
0.51	45	—	—	—	—	29.6	29.9	—	—
0.51	50	31.2	30.1	—	—	—	—	—	—
0.51	55	—	—	—	—	30.5	30.9	—	—
0.51	65	—	—	31.0	30.70	—	—	—	—
0.51	70	—	—	—	—	31.9	32.0	—	—
0.51	100	—	—	33.4	33.1	—	—	—	—
1.55	0	106.0	105.6	100.8	99.7	98.0	97.4	98.6	101.7
1.55	15	—	—	—	—	112.0	109.8	—	—
1.55	20	—	—	—	—	—	—	111.0	112.3
1.55	25	—	—	122.2	122.3	—	—	—	—
1.55	30	123.0	119.0	—	—	128.1	126.0	—	—
1.55	40	128.0	127.4	—	—	—	—	131.7	125.0
1.55	55	—	—	—	—	136.0	137.8	—	—
1.55	60	138.0	131.6	137.0	133.0	—	—	—	—
1.55	80	—	—	138.0	136.6	—	—	—	—

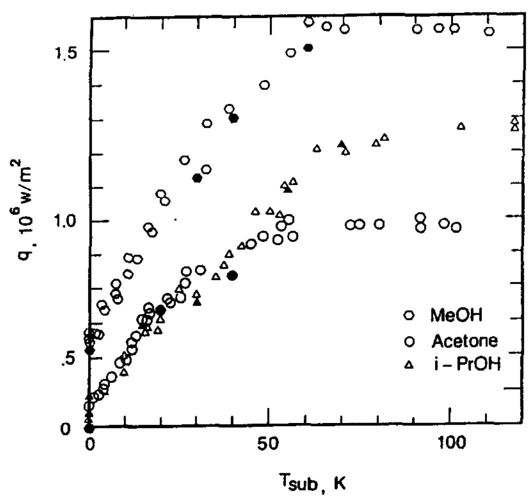

Fig. 4. Ratio of $q_{CHF,sub}/q_{CHF,sat}$ versus T_{sub} plot. Open symbols: data from [14]. Close symbols: this work.

perturbations along nucleate and film boiling curves nearby the equilibrium line would compensate out each other. Their method is employed, herein, to calculate the equilibrium currents according to experimental boiling curves together with the heater properties. The results are listed in Table 1. The agreement with experimental results is satisfactory.

The ratio of the equilibrium currents under subcooled and saturated conditions, $I_{E,sub}/I_{E,sat}$, are depicted against T_{sub} in Fig. 3. The ratio increases from 1.0 to 1.3–1.4 at low to moderate subcoolings. At elevated subcoolings, however, the ratio tends to level off and reaches a plateau value. This corresponds to the dependence of CHF on subcooling observed by Elkassabgi and Lienhard [14]. A comparison is made in Fig. 4. We noted in experiments that under high enough subcooling both the CHF and the film boiling curves become less influenced by liquid temperature. As a result, according to the equal-area criterion, the equilibrium current approaches a constant, plateau value. The relative stability between nucleate and film boiling mode is not a function of subcooling at very high liquid subcooling.

4. Conclusions

This work has investigated the effects of liquid subcooling on two-mode boiling on a horizontal heating wire immersed in a pool. At a low to moderate liquid subcooling, the critical heat flux becomes greater, the film boiling mode more efficient, and the equilibrium line shifting upwards, indicating a more stable nucleate boiling mode at elevated subcoolings. However, as the liquid subcooling becomes very high, the steady-state boiling curves are not influenced by the liquid subcooling.

Acknowledgement

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