Proceedings of the ASME 2009 2nd Micro/Nanoscale Heat & Mass Transfer International Conference
MNHMT2009
December 18-21, 2009, Shanghai, China

MNHMT2009-18091

CHF of Pool Boiling on Microwires

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ABSTRACT

The present paper reports a new series of experimental data of CHF (critical heat flux) of pool boiling on cylinders. Platinum wires of 30 mm in length are simultaneously used as heaters and thermometers. Their diameters are 0.1, 0.06, and 0.025 mm, respectively. FC-72 and acetone are used as working fluids. The range of the subcooling is from 0 K to about 50 K. The gaps between CHF and MHF (minimum heat flux) become narrower and narrower with the decrease of the heater diameter. But it exists even in the saturated pool boiling on the smallest wire in the present study. The dependence of CHF on the subcooling in acetone differs from that in FC-72 though the data locate in the similar range of Bond number in the two different kinds of working fluids. It indicates that interactions between the influences of the subcooling and size on CHF will be important for the small Bond number, and that there may exist some other parameters, which may be material-dependant, in addition to the Bond number that play important roles in the CHF phenomenon with small Bond number.

Keywords: CHF, subcooling, scaling behavior, micro-wire

INTRODUCTION

Boiling is a very complex and illusive process because of the interrelation of numerous factors and effects as the nucleate process, the growth of the bubbles, the interaction between the heater surface with liquid and vapor, the evaporation process at the liquid-vapor interface, and the transport process of vapor and hot liquid away from the heater surface. It is generally assumed that heat and mass transport in pool boiling process is strongly influenced by buoyancy, which is caused by the great difference in the densities between liquid and vapor at normal gravity environment. Thus, gravity is considered as an important parameter in most physically based or empirical correlations describing the heat transfer of pool boiling. However, for quite a long time, no evidence had been obtained to experimentally check whether the influence of gravity was modeled correctly. Since the end of 1950's, microgravity experiments were initiated which was motivated by the design of space devices. These experiments provide a means to study the influence of gravity on boiling heat transfer and also to separate gravity from gravity-independent factors.

In the past decades, there are several experiments on CHF of pool boiling on cylinders in microgravity, using parabolic aircraft, drop tower, sounding rocket, and space shuttle [1~5]. It is found that the data of CHF on cylinders in microgravity show the same trend as the prediction of the correlation of Lienhard & Dhir [6], although the dimensionless radius, or equivalently the square root of the Bond number, is extended to over two decades of the original lower value of the correlation. It's a strong challenge to the commonly accepted figure on the scaling of CHF in the literature, which is built upon the experimental data obtained in normal gravity.

Thus, in order to reveal the influences of subcooling and cylinder diameter on CHF, a new series of experimental data of CHF on cylinders in normal gravity have been obtained in the present paper.

NOMENCLATURE

Bo	*Bond number defined in Eq. (2), -*
C	*parameter in Eqs. (7) and (8), -*

d	*heater characteristic length, [m]*
g	*gravity, [m/s^2]*
h	*specific enthalpy, [J/kg]*
Ja	$= \rho_l c_{pl} \Delta T_{SUB} / \rho_v h_{lv}$, *Jacob number, -*
K	*Kutateladze number defined in Eq. (1), -*
K^*	$= K(R')/K_\infty$, -
Q	*heat flux, [W/m^2]*
R	*wire or cylinder radius, [m]*
R'	*dimensionless radius defined in Eq. (3), -*
ΔT	*temperature difference, [K]*
ρ	*density, [kg/m^3]*
σ	*surface tension, [N/m]*

Subscripts

CHF	*critical heat flux*
exp	*experimental*
l	*liquid*
pre	*predicted*
sat	*saturated*
sub	*Subcooled*
v	*vapor*
Zuber	*Zuber value with* K*=0.131*
∞	*Large heater*

LITERATURE REVIEW

Several approaches have been attempted to interpret the phenomenon of CHF. Among them, we can recall the *bubble coalescence model* (Rohsenow & Griffith [7]), the *hydrodynamic theory* (Kutateladze [8], Zuber [9], Lienhard & Dhir [6]), the *macrolayer theory* (Haramura & Katto [10]), the *hot spot theory* (Unal et al. [11]), and the *dynamic microlayer theory* (Zhao et al. [12]). Regardless of the modeling approach, CHF data have been often correlated in the so-called Zuber-Kutateladze form

$$\frac{q_{CHF}}{\rho_v^{1/2} h_{lv} \left[(\rho_l - \rho_v) g \sigma\right]^{1/4}} = K \qquad (1)$$

where K is often referred to as Kutateladze number. Generally, if the heater is large with respect to the Taylor wavelength, K is a constant. For small heaters, K is a function of Bond number, which scales buoyancy and capillary forces

$$Bo = \frac{(\rho_l - \rho_v) g d^2}{\sigma} \qquad (2)$$

Here, d denotes the characteristic length of the heater. In the case of cylinders, the radius R is usually used, namely $d=R$.

Pool boiling on cylinders has been extensively studied in the literature. A non-trivial dependence of CHF on the diameter of the cylinder has been reported. As shown in Figure 1 where $K^* = K(R')/K_\infty$, different ranges are identified with the dimensionless radius

$$R' = \sqrt{Bo} = R\sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} \qquad (3)$$

The reported values for these boundaries differ from an author to another: some of them are listed in Table 1.

Table 1. Different values for R'_1, R'_2, and R'_2

Author(s)	R'_1	R'_2
Lienhard & Dhir [6]	0.12	0.03
Mohan Rao & Andrews [13]	0.15	0.02
Shimizu et al. [14]	0.36	0.02
Fujita & Bai [15]	0.5	0.03
Park & Bergles [16]	0.43	0.03
Kutateladze [17]	0.5	

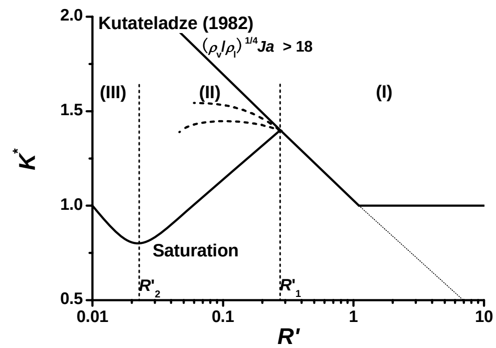

Fig. 1 Scaling of CHF in pool boiling on cylinder

In the range I ($R' > R'_1$), Lienhard-Dhir correlation [6] is commonly accepted

$$K = \begin{cases} 0.123 R'^{-1/4} & (0.15 \le R' \le 1.2) \\ 0.118 & (R' \ge 1.2) \end{cases} \qquad (4)$$

An alternate correlation was proposed by Sun and Lienhard [18]

$$K = 0.117 + 0.297 \exp(-3.44\sqrt{R'}) \quad (R' \ge 0.15) \qquad (5)$$

which is almost as satisfactory as the former one. In deriving Eq. (5), a hydrodynamic mechanism of CHF was presumed, seeking the onset of the instability of vapor jets, of radius $R + \delta$, leaving the heater. The parameter δ, corresponding to a vapor blanket thickness, was estimated by empirical interpolation of a great number of experimental data. A slight modification of Sun-Lienhard correlation was proposed by Hong et al. [19] as

$$K = 0.089 + 1.18 \exp(-2.56\sqrt{R'}) \quad (R' > 0.01 \quad and \quad R' > R'_1) \qquad (6)$$

The scattering of the experimental data of CHF is particularly high for $R' < R'_1$, allowing Lienhard and Dhir [6] to claim that they can no longer be correlated by R' alone in this range. However, for CHF in the range II ($R'_2 < R' < R'_1$),Mohan Rao and Andrews [13] proposed a semi-empirical correlation

$$K = \frac{0.21}{R'}\left[1 + \frac{1}{2(CR')^2}\right]^{-3/4} \qquad (7)$$

$$(0.02 \le R' \le 0.15)$$

based on the hydrodynamic theory. In the above correlation, the parameter C is a constant to take into account the thichness of the so-called vapor blanket around the heater, and to be determined experimentally. A range of C from 1 to 1.5 is proposed.

In the range III ($R' < R'_2$), assuming that there is no difference between the minimum heat flux of film boiling (MHF) and CHF, Mohan Rao and Andrews [13] also proposed a semi-empirical correlation for CHF in this range based on the hydrodynamic theory

$$K = \frac{0.5}{R'}\left(\frac{\rho_v}{\rho_l}\right)^{1/2}\left[1 + \frac{1}{2(CR')^2}\right]^{-1/4} \qquad (8)$$

$$(R' \le 0.02)$$

The hydrodynamics mechanism, however, is generally agreed to be well established only for $R' > 0.15$. The boiling transition in the range III ($R' < R'_2$) is triggered locally by an isolated bubble spreading as a patch: surface tension effects rather than hydrodynamics seem to control the phenomenon. The properties of the material of the heater may play a role in this range.

Usually, the influence of subcooling on CHF is considered as an independent factor with respect to the heater size. You et al. [20], however, found that the subcooling can change the CHF mechanism from dryout to hydrodynamic situations in the case of small Bond number, which agreed with the observation of Kutateladze [17]. As shown in Fig. 1, Kutateladze pointed further out that there exists a strong influence of the subcooling on the scaling behavior of CHF in small dimensionless radius, and that the increasing trend with the decrease of R' can even not alter for $R' < 0.5$, provided $(\rho_v/\rho_l)^{1/4} Ja \ge 18$. If one assumes that

$$K(\Delta T_{sub}, R') = K_{sat,\infty}\begin{pmatrix} 1 + f(\Delta T_{sub}) \\ + g(R') + h(\Delta T_{sub}, R') \end{pmatrix} \quad (9)$$

Then it can be obtained straightway that

$$\begin{cases} h(\Delta T_{sub}, R') \equiv 0 & (R' > R'_1) \\ h(\Delta T_{sub}, R') > 0 & (R' < R'_1) \end{cases} \qquad (10)$$

according to Fig. 1.

Fukuda & Sakurai [21] proposed a correlation to take into account the interaction of subcooling and heater's size

$$K = 0.17\left[1 + \frac{0.39}{R'^{0.6}}\left(\frac{\rho_v}{\rho_l}\right)^{0.81} Ja^{1.5}\right] \qquad (11)$$

$$(0.046 \le R' \le 1.13)$$

where no scaling effect exists in the saturated case. The authors claimed that it can only be applied for the pressure no more than 300 kPa or for the subcooling no higher than about 40 K, where the boiling transition results from the hydrodynamic instability. The CHF due to the Heterogeneous spontaneous nucleation at highly subcooled water at high pressure will be significantly lower than the value derived from the CHF correlation based on the hydrodynamic theory.

A relatively small amount of experimental data is available for CHF in reduced gravity, which are sumarized in Figure 2 (Wan and Zhao [5]). It is shown that the data of CHF on cylinders in microgravity show the same trend as the prediction of the correlation of Lienhard & Dhir [6], although the dimensionless radius, or equivalently the square root of the Bond number, is extended to over two decades of the original lower value of the correlation. It's a strong challenge to the commonly accepted figure on the scaling of CHF in the literature, which is built upon the experimental data obtained in normal gravity. To revisit the influences of the subcooling and the heater size will be helpful for revealing the CHF mechanism in small Bond number.

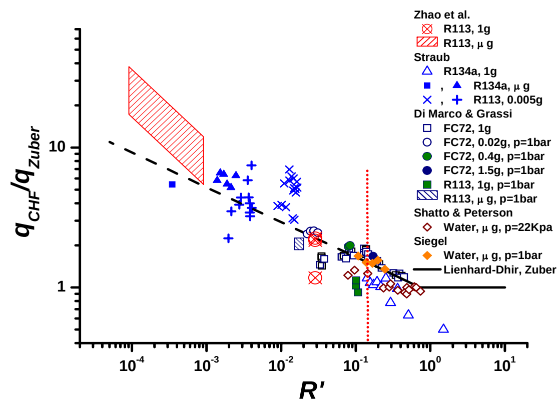

Fig. 2 Scaling of CHF with respect to gravity

EXPERIMENTAL FACILITY

The experimental facility is shown in Figure 3.

The boiling chamber with about 100 mm dia. and 200 mm height is filled with about 1.2 L of degassed working liquid. A condeser is also connected with the chamber to maintain the system pressure as constant, particularly in the saturated cases. The system pressure is kept at about 0.1 MPa. A constant- temperature water bath is used to control the liquid subcooling. The water temperature is measured by a mercury thermometer with an uncertainty of 0.1 °C.

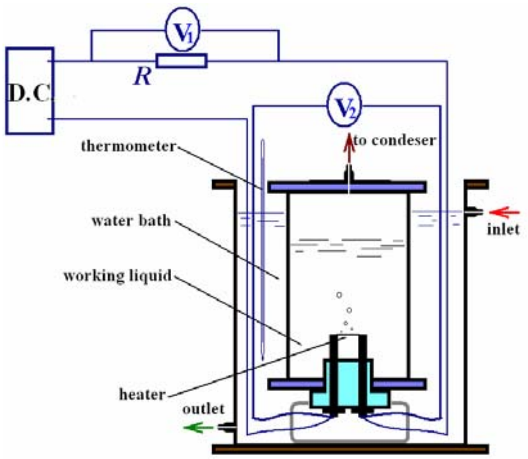

Fig. 3 Schematic representation of the experimental apparatus

Platinum wires of about 30 mm in length are used as the heater. Three diameters, namely 25, 60, and 100 μm, are used. The ends of the wire are soldered with copper poles of 3 mm in diameter to provide a firm support for the wire heater and low resistance paths for the electric current. A D.C. power supply provides the heating power. The heating current is measured by the voltage across the precision resistance *R* of a value of 0.02 Ω and an uncertainty of 1‰ of its value, while the heating voltage is measured directly across the two poles. Two 6.5-digit multimeters are used to sample these voltages. The heater temperature is calculated using the pre-calibrated curve of relation between the resistance and temperature of the wire. Furthermore, the calibration is made again after several runs. It is estimated that the uncertainty of the heater temperature is no mare than 3 °C, while the uncertainty of heat flux is no more than 20 kW/m^2. The measured data points obtained from several preliminary runs locate in a range of ±30% around the prediction by the commonly accepted Kuehn-Goldstein [22] correlation for the single-phase convection (Figure 4), which guarantees the correctness of the present experimental data.

The following degassing procedure is adopted. The working liquid inside the boiling chamber is heated slightly above its boiling point. It is lasted for about one and a half hours. Then cool it again down to the ambient temperature. Repeat the above steps six to nine times in order to remove the gas dissolved in the liquid. Before each experimental run, preheating by water bath will also last for more than one and a half hours to insure a uniform temperature distribution inside the chamber. The heating voltage is then adjusted step-by-step upwards till film boiling appears. Then, the voltage is adjusted downwards till no bubble can be observed. Sometimes, the downward adjustment is cut off in the nucleate boiling region and upward one is begun in order to reach the actual peak value of heat flux, particularly for the smallest wire.

A CCD video camera is used to obtain images of the motion of vapor bubble or film around the heater, which is recorded by a VCR at a speed of 25 fps.

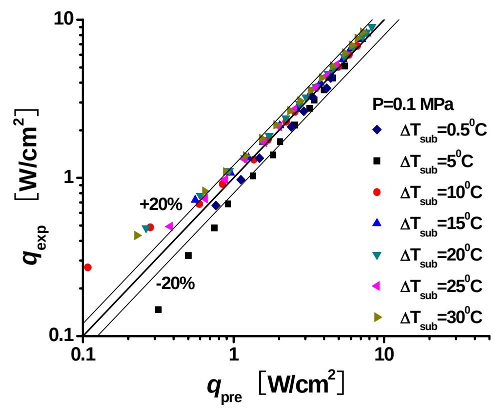

Fig. 4 Comparison between the measured and predicted single-phase convection of FC-72 on the wire of 0.060 mm dia.

RESULTS AND DISCUSSIONS

A) FC-72

In Figure 5, some typical pool boiling curves are shown for different diameters and subcoolins. It is evident that the fully developed nucleate boiling region on smaller wire will become narrower. The similar trend is also observed for the gap between CHF and MHF. But in the present study, even in the saturated pool boiling on the smallest wire, i.e. d=25 μm or equivalently $R' = 0.017$, the gap also exists.

The dependences of CHF on the subcooling are shown in Figure 6. In small Bond number, the data agree well with the predictions of some commonly used linear correlations. It is, however, much evident that the dependence of CHF on the subcooling for the smallest wire differ from that for the others, indicating that there exist some scaling effects for the small Bond number. In other words, interactions between the influences of the subcooling and size on CHF will be important for the small Bond number. The trend, however, doesn't agree with Eq. (11).

The scaling behavior of CHF in pool boiling of FC-72 on platinum wires with different diameters at saturated condition is shown in Figure 7, where some other data obtained by others are also shown for comparing. Generally, satisfactory agreements for larger wires are evident, while some differences exist for the smallest one. It can be concluded that all data in the present study locate in the range I and then can be predicted by hydrodynamic theory with some modification of the effect of the heater size. By the way, the dependence of the subcooling on CHF also suggests the same conclusion according to Kutateladze [17].

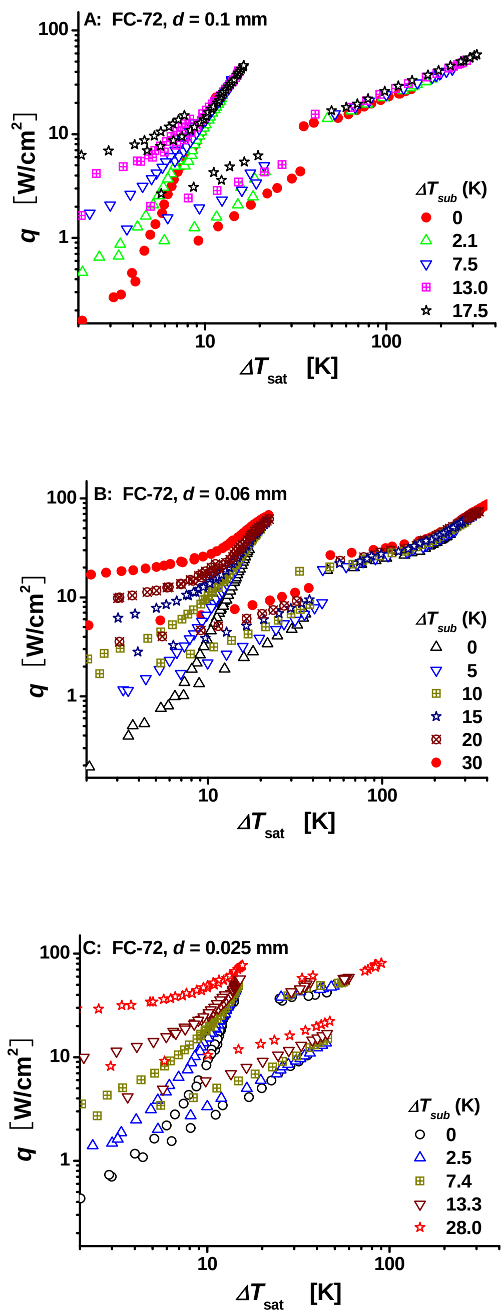

Fig. 5: Typical pool boiling curves of FC-72 on wires with different diameters and subcoolings

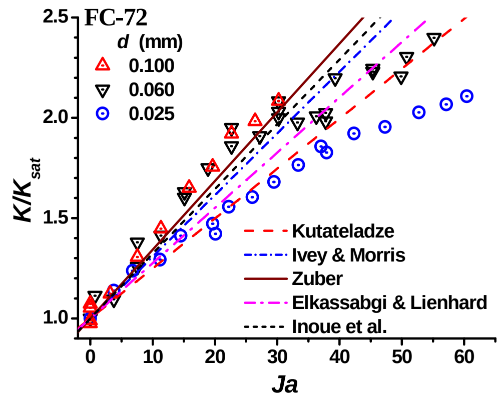

Fig. 6 Dependence of CHF on the subcooling of pool boiling of FC-72

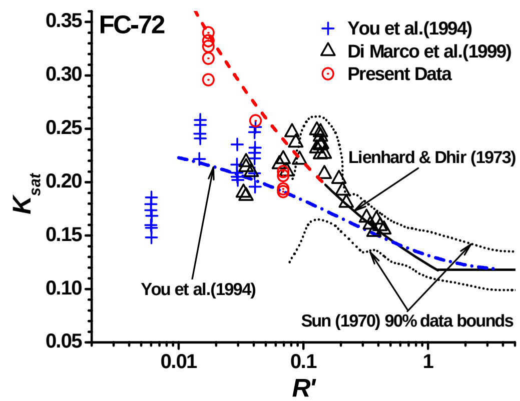

Fig. 7 Scaling behavior of CHF in pool boiling of FC-72

B) Acetone

Some typical pool boiling curves of acetone on wires for different diameters and subcoolings in Figure 8. Similar observations can be obtained as mentioned above in the experiments of FC-72.

It is, however, obvious in some runs that the single-phase convection branch may nearly intersect the film boiling one. But the hysteresis exists for all runs. For example, the boiling curve on the wire of 0.060 mm dia. at the subcooling of 5 K, as shown in Fig. 9, can transit directly from single-phase convection to film boiling with the increase of the heat flux. It will, however, transit form flim boiling to nucleate boiling with the decrease of the heat flux as in normal condition. Decreasing the difference between adjacent steps can result in the normal transition from single-phase convection to nucleate boiling, and then from nucleate boiling to film boiling with the increase of the heat flux, while from film boiling to nucleate boiling with the decrease of the heat flux. The corresponding branches match each other with great satisfaction.

The dependences of CHF on the subcooling in pool boiling of acetone are shown in Fig. 10. The slopes of the curves are much greater than the predictions of the commonly used correlations, which is different from the observation in the case of FC-72.

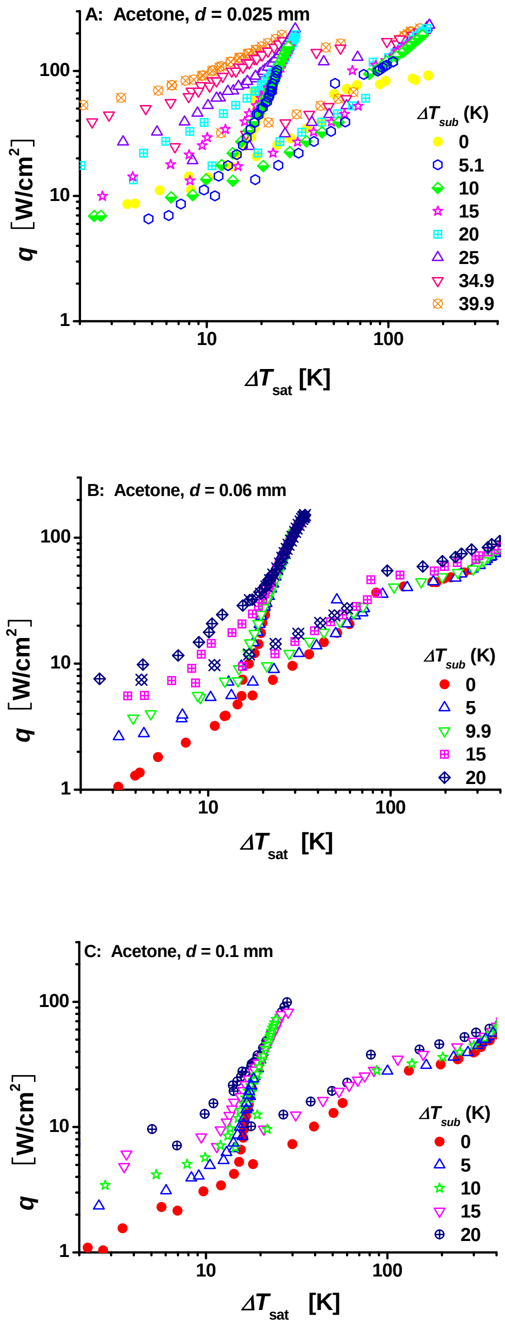

Fig. 8 Typical pool boiling curves of acetone on wires with different diameters and subcoolings

The scaling behavior of CHF in pool boiling of acetone on platinum wires with different diameters at saturated condition is shown in Fig. 11, where some other data obtained by others are also shown for comparing. Generally, satisfactory agreements for larger wires are evident. It can be concluded that all data in the present study locate in the range III. By the way, the dependence of the subcooling on CHF also suggests the same conclusion according to Kutateladze [17].

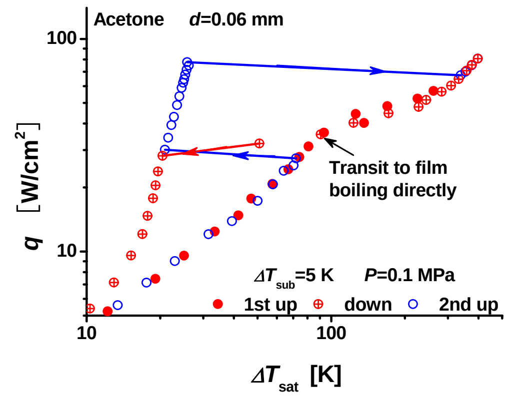

Fig. 9 Comparison of transition directly to film boiling with normal transition from nucleate to film boiling

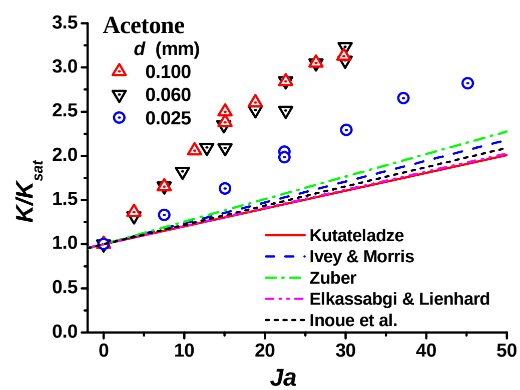

Fig. 10 Dependence of CHF on the subcooling in pool boiling of acetone

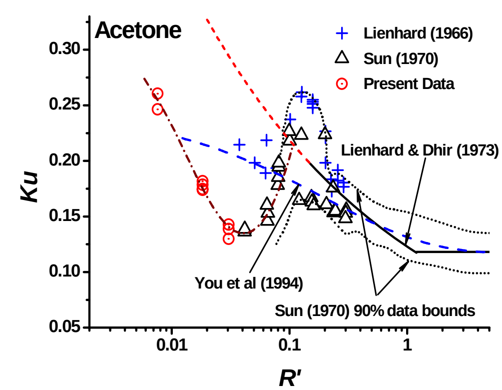

Fig. 11 Scaling behavior of CHF in pool boiling of acetone

It ought to be pointed out here that different scaling behaviors of CHF and different dependences of subcooling on CHF are observed in different working fluids although the dimensionless radius or the Bond number locate in the similar ranges. Thus, interactions between the influences of the subcooling and size on CHF will be important for small Bond number. There may exist some other parameters, which may be material-dependant, in addition to the Bond number that play important roles in the CHF phenomenon for the cases of small Bond number.

SUMMARY

A new serial experimental data of CHF on cylinders at different subcoolings and heater sizes are reported in the present paper. It is found that

1) The fully developed nucleate boiling region on smaller wire will become narrower. The same trend is also observed for the gap between CHF and MHF. But in the present study, even in the saturated pool boiling on the smallest wire, i.e. 25 μm dia., the gap also exists.

2) Different scaling behaviors of CHF and different dependences of subcooling on CHF are observed in different working fluids although the dimensionless radius or the Bond numbers locate in the similar ranges.

3) There may exist some other parameters, which may be material-dependant, in addition to the Bond number that play important roles in the CHF phenomenon for the cases of small Bond number.

ACKNOWLEDGMENTS

The present study is supported financially by the National Natural Science Foundation of China under the grant of 10972225.

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