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Critical heat flux on a uniformly heated cylinder in a cross flow of saturated liquid over a very wide range of vapor-to-liquid density ratio

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Abstract—Experimental studies of critical heat flux (CHF) on a heated cylinder in a cross flow have so far been made within a narrow range of vapor-to-liquid density ratios $\rho_v/\rho_l = 0.0006$–0.005. In the present study, systematic experiments of CHF on a d.c. electrical current-heated, 1 mm diameter cylinder have been performed over a very wide range of $\rho_v/\rho_l = 0.000624$–0.306, employing water at 0.098 MPa, R-113 at 0.098–0.490 MPa, and R-12 at 0.98–3.43 MPa. An empirical generalized correlation, which can predict CHF satisfactorily in saturated boiling over the foregoing wide range of ρ_v/ρ_l, is presented.

1. INTRODUCTION

CRITICAL heat flux (CHF) on a uniformly heated cylinder in a forced cross flow of liquid, that is the CHF in one of the most fundamental boiling systems of external flow type, is an important phenomenon related to the basic study of CHF as well as to the design of heat exchangers such as shell-and-tube type evaporators.

Vliet and Leppert [1] experimented on CHF with nearly saturated water at atmospheric pressure for electrically heated stainless steel wires or tubes of outer diameter $d = 0.254$–4.8 mm and bulk liquid velocity $u = 0.37$–2.9 m s^{-1}. They then postulated CHF to be caused by dryout of liquid which penetrates into the rear portion of a cylinder covered with a massive vapor wake region, and derived the following equation for critical heat flux q_{c0} in a cross flow of saturated liquid:

$$q_{c0} = \frac{1.083k\Delta t_{sat}}{\bar{f}\sqrt{\alpha}}\sqrt{\left(\frac{u}{d}\right)} \qquad (1)$$

where k is the thermal conductivity of liquid, Δt_{sat} the superheat of wall, $\bar{f}$ the fraction of heat transferred directly to vapor while bubbles are on the cylinder surface, α the thermal diffusivity of liquid, u the bulk liquid velocity, and d the cylinder diameter. McKee and Bell [2] carried out experiments with electrically heated stainless steel tubes of comparatively large outer diameter $d = 6.4$–18.0 mm for water at atmospheric pressure and $u = 1.0$–1.7 m s^{-1}, showing that their results of CHF are considerably different in trend of q_{c0} vs d from those of Vliet and Leppert. Cochran and Andracchio [3] carried out experiments with R-113 as well as water at atmospheric pressure for electrically heated nichrome wires of $d = 0.49$–1.81 mm and comparatively low velocity $u = 0.10$–0.81 m s^{-1}, disclosing that when u is low, vapor escape flow takes a configuration of Fig. 1(a) due to the effect of gravity, while when u is sufficiently high, a sheet-like configuration of Fig. 1(b) appears. They regarded equation (1) as applicable to CHF appearing with the sheet-like vapor escape flow of Fig. 1(b).

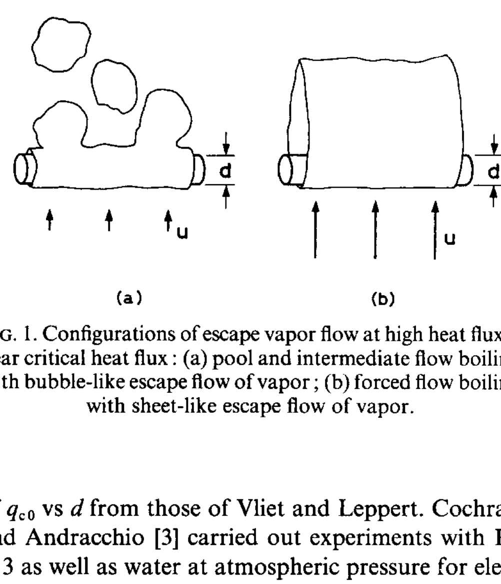

FIG. 1. Configurations of escape vapor flow at high heat fluxes near critical heat flux: (a) pool and intermediate flow boiling with bubble-like escape flow of vapor; (b) forced flow boiling with sheet-like escape flow of vapor.

Lienhard and Eichhorn [4] experimented on CHF with isopropanol at atmospheric pressure employing electrically heated nichrome wires. They analyzed the phenomenon of CHF in a cross flow by introducing a new concept of mechanical energy stability criterion, and derived the following semi-empirical generalized

NOMENCLATURE

d	diameter of cylinder [m]
G	mass velocity of bulk liquid flow, $u\rho_l$ [kg m^{-2} s^{-1}]
H_{fg}	latent heat of evaporation [J kg^{-1}]
ΔH	subcooling enthalpy of bulk liquid [J kg^{-1}]
K	coefficient of equation (7) [—]
m	index of equation (7) [—]
q_c	critical heat flux [W m^{-2}]
q_{c0}	critical heat flux at $\Delta H = 0$ [W m^{-2}]
u	velocity of bulk liquid flow [m s^{-1}].

Greek symbols

ρ_l	density of liquid [kg m^{-3}]
ρ_v	density of vapor [kg m^{-3}]
σ	surface tension [N m^{-1}].

correlation for q_{c0} accompanied by the vapor escape flow configuration of Fig. 1(b), taking account of experimental data of their own for isopropanol together with existing data for water [1, 3, 5], R-113 [3], and methanol [5]

$$\frac{\pi q_{c0}}{\rho_v H_{fg} u} = \frac{1}{169}\left(\frac{\rho_l}{\rho_v}\right)^{3/4} + \frac{1}{19.2}\left(\frac{\rho_l}{\rho_v}\right)^{1/2}\left(\frac{\sigma}{\rho_v u^2 d}\right)^{1/3} \quad (2)$$

where ρ_v is the density of vapor, H_{fg} the latent heat of evaporation, ρ_l the density of liquid, and σ the surface tension. Meanwhile, Yilmaz and Westwater [6] conducted experiments of boiling of R-113 near atmospheric pressure on a steam-heated copper tube of $d = 6.5$ mm for $u = 2.4$–6.8 m s^{-1}, showing that the following relationship holds for their data:

$$\frac{q_{c0}}{\rho_v H_{fg} u} \propto \left(\frac{\sigma}{\rho_v u^2 d}\right)^{0.26}. \quad (3)$$

Hasan *et al.* [7] carried out experiments of CHF in boiling of isopropanol and methanol at atmospheric pressure on an electrically heated, horizontal nichrome wire ($d = 0.51$–1.5 mm) in a cross flow for cases of both upflow ($u > 0$) and downflow ($u < 0$) in a range of $u = -2.4$ to 2.57 m s^{-1}, proving that if the absolute value of u is high enough, the effect of gravity becomes negligibly small making the data for both conditions of $u > 0$ and $u < 0$ identical. They took account of experimental data of their own for isopropanol and methanol at sufficiently high velocities together with existing data in other sources (Vliet and Leppert [1] for water, and Yilmaz and Westwater [6] for R-113), to give the following correlation:

$$\frac{\pi q_{c0}}{\rho_v H_{fg} u} = 0.000919\left(\frac{\rho_l}{\rho_v}\right) + 0.0150\left(\frac{\rho_l}{\rho_v}\right)^{2/3}\left(\frac{\sigma}{\rho_v u^2 d}\right)^{1/3}. \quad (4)$$

This equation is regarded as a revised version of the preceding one, equation (2). Multiplying both sides by $(\rho_v/\rho_l)/\pi$, equation (4) is readily rewritten as

$$\frac{q_{c0}}{G H_{fg}} = 0.000292 + 0.00477\left(\frac{\sigma \rho_l}{G^2 d}\right)^{1/3} \quad (4')$$

where $G = u\rho_l$. Equation (4′) is characteristic in suggesting that q_{c0}/GH_{fg} is a function of $\sigma\rho_l/G^2 d$ only, being independent of ρ_v/ρ_l.

On the other hand, Katto and Haramura [8] analyzed CHF with a concept of critical liquid film thickness δ_c (cf. ref. [9]) on a heated wall of heat flux q, which is given as

$$\frac{\delta_c (q/H_{fg})}{\sigma \rho_v} = 0.00536\left(\frac{\rho_v}{\rho_l}\right)^{0.4}\left(1 + \frac{\rho_v}{\rho_l}\right) \quad (5)$$

and derived generalized correlations of CHF for the two cases of Figs. 1(a) and (b), respectively, with no assistance of empirical constants. Among the above two correlations of CHF, the one for the forced convective case of Fig. 1(b) is written as

$$\frac{q_{c0}}{G H_{fg}} = 0.151\left(\frac{\rho_v}{\rho_l}\right)^{0.467}\left(1 + \frac{\rho_v}{\rho_l}\right)^{1/3}\left(\frac{\sigma \rho_l}{G^2 d}\right)^{1/3}. \quad (6)$$

According to the study of Katto and Haramura [8], the foregoing peculiar data of McKee and Bell [2] for large diameters of $d = 6.4$–18.0 mm is regarded as corresponding to CHF in the situation of Fig. 1(a).

All the experiments of CHF mentioned so far have been conducted at or near atmospheric pressure only, restricting the vapor-to-liquid density ratio to a very narrow range of $\rho_v/\rho_l = 0.006$–0.005; and besides, the bulk liquid velocity u is less than 2.9 m s^{-1} except for the experiment of Yilmaz and Westwater [6], which is a rather special one made with a steam-heated copper tube. Moreover, existing experiments of CHF for subcooled liquid flow, including that of Vliet and Leppert [10], are few, being carried out only for water at or near atmospheric pressure.

With the purpose of broadening the field of vision, therefore, the authors have recently conducted experiments of CHF for $u = 0.59$–7.1 m s^{-1} over a wide range of $\rho_v/\rho_l = 0.006$–0.31 by employing water, R-113 and R-12, as partly reported in refs. [11–13]. This paper reports the result of analyzing CHF data for saturated liquid flow obtained from the foregoing experiments. In order to fix conditions, CHF dealt with in this paper will be restricted to the one on a uniformly heated horizontal cylinder in an upward forced cross flow of saturated liquid.

2. DESCRIPTION OF THE EXPERIMENT

The experimental apparatus employed is schematically illustrated in Fig. 2. Part of the test liquid

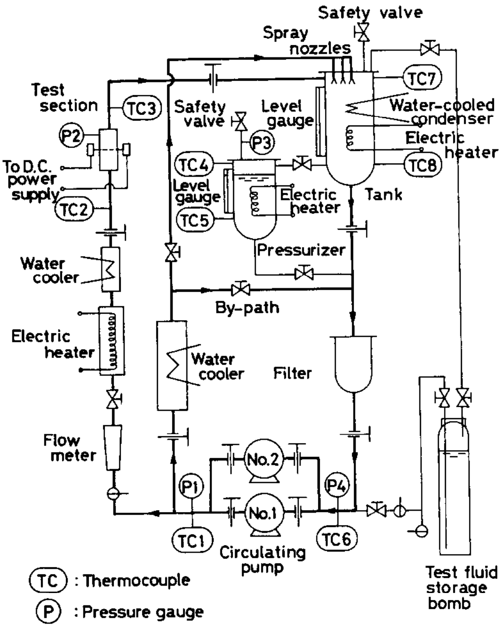

FIG. 2. Experimental apparatus.

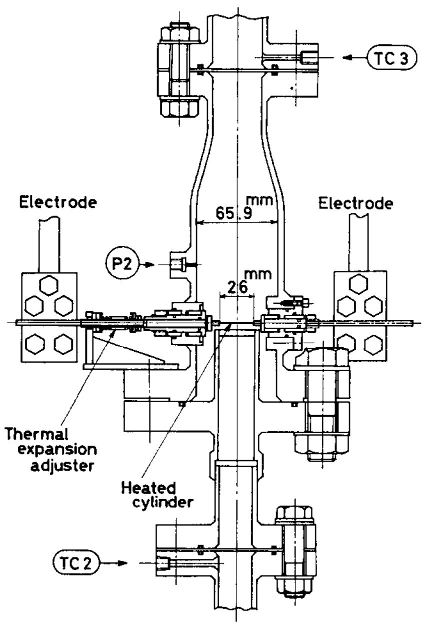

FIG. 3. Test section.

flowing out of circulating pumps is fed, through a turbine flow meter, an electric heater (with eight sheathed heaters regulated by four variable autotransformers), and a water cooler (concentric tubes, counter flow type), to the test section at prescribed values of flow rate and subcooling. System pressure is set at a prescribed value by adjusting the saturation temperature of fluid in a pressurizer.

Details of the test section are illustrated in Fig. 3. A test cylinder located at the center of Fig. 3, that is a stainless steel rod of diameter $d = 1$ mm and length $l = 26$ mm, has been brazed to copper rods on both ends, and is heated by the direct passage of a d.c. current. A thermal expansion adjuster in Fig. 3 is a device designed so as to prevent the bending of the test cylinder due to thermal expansion, satisfying other requirements as well, such as electric insulation, prevention of the leakage of the test fluid, and prevention of the slip out of the left side copper rod pushed by a force due to the pressure difference between the inside and outside. A safety device is also equipped to cut off power input when CHF condition is detected, with a purpose to protect the test cylinder and fluid from excessive temperature rise and thermal decomposition, respectively. The time required from the start of CHF condition up to the cut off of power input is about 0.15 s. A rectangular nozzle exit of 3.6×30 mm is located 5 mm below a test cylinder, providing the cylinder with a uniform upflow of the test liquid. When a test fluid is exchanged for the other one, cleaning and evacuation of the loop are repeated to remove residual substances of air, moisture and the previous test fluid.

Table 1

Fluid	Pressure (MPa)	ρ_v/ρ_l	Velocity, u (m s^{-1})
water	0.098	0.000624	0.95–6.5
R-113	0.098–0.490	0.00473–0.0245	0.59–7.1
R-12	0.98–3.43	0.045–0.306	0.72–7.0

Experiments have been carried out with water, R-113 and R-12 in the ranges shown in Table 1. Part of the experimental data of critical heat flux q_c thus obtained are plotted against the subcooling enthalpy of bulk liquid ΔH in Fig. 4. Roughly speaking, when the value of ρ_v/ρ_l is low ($\rho_v/\rho_l = 0.0006$–0.005) and very high ($\rho_v/\rho_l = 0.15$–0.31), the relation of q_c vs ΔH is linear and approximately linear, respectively. For middle values of ρ_v/ρ_l ($\rho_v/\rho_l = 0.0094$–0.11), however, the relation of q_c vs ΔH is rather complicated, particularly so when the value of G is high, as is seen in Fig. 4. However, it is beyond the scope of this paper to go further into CHF in subcooled boiling, accordingly further details of q_c are omitted here.

3. ANALYSIS OF CHF FOR SATURATED LIQUID FLOW

3.1. *CHF data in saturated boiling*

As can be noted from Fig. 4, the value of critical heat flux q_{c0} for saturated liquid flow ($\Delta H = 0$) is readily determined by extrapolation of $\Delta H \to 0$ for each set of G and ρ_v/ρ_l values. All the data of q_{c0} thus obtained are plotted in Fig. 5 in a generalized form of q_{c0}/GH_{fg} vs $\sigma\rho_l/G^2d$. It will be noted from Fig. 5 that, under a fixed condition of ρ_v/ρ_l, the following relationship holds approximately:

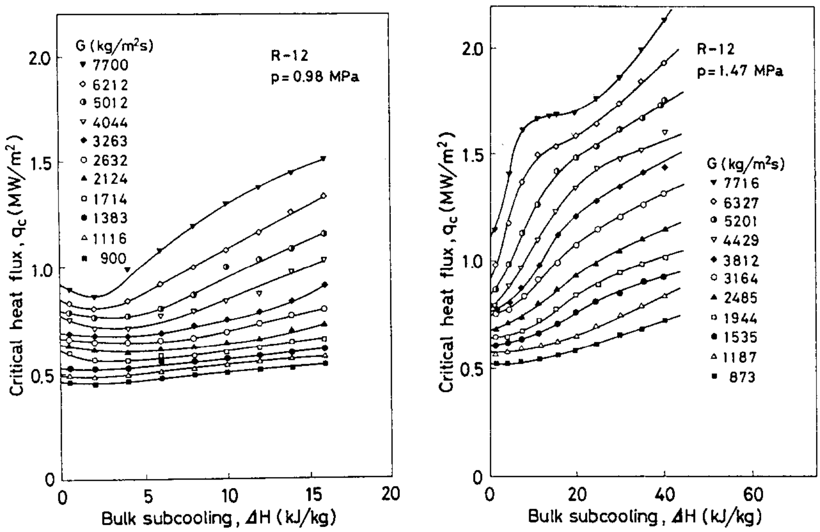

FIG. 4. Examples of experimental data of critical heat flux q_c.

$$\frac{q_{c0}}{GH_{fg}} = K\left(\frac{\sigma\rho_l}{G^2 d}\right)^m \tag{7}$$

where K and m are constants, respectively, depending on the fixed value of ρ_v/ρ_l.

Meanwhile, Fig. 6 which is in a similar form as that of Fig. 5 represents the existing data of water by Vliet and Leppert [1, 10], those of isopropanol by Hasan *et al.* [7], and those of R-113 by Yilmaz and Westwater [6]. The data of methanol by Hasan *et al.* [7] have been omitted from Fig. 5, because of slight irregularities. It will be noted that all of the data in Fig. 6 satisfy the relationship of equation (7).

According to the experimental results of both Figs. 5 and 6, the following interesting facts can be found.

(1) Two independent data groups of water ($\rho_v/\rho_l = 0.000624$) in Figs. 5 and 6 agree fairly well with each other, though they are the data obtained in different experiments and for different cylinder diameters (1.0 mm against 3.18 mm).

(2) The data of isopropanol ($\rho_v/\rho_l = 0.00299$) plotted in Fig. 6 suggests that K and m in equation (7) are functions of ρ_v/ρ_l alone, respectively, independent of the difference of cylinder diameter $d = 0.5$, 0.81 and 1.5 mm.

(3) If the data of isopropanol ($\rho_v/\rho_l = 0.00299$) in Fig. 6 are replotted in Fig. 5, they appear in the vicinity of water data, showing approximate matching with the result of Fig. 5 as to the data variation with changes of ρ_v/ρ_l.

(4) Broken lines in Fig. 6 represent the prediction by equation (4′), indicating that this equation agrees fairly well with the data of water ($\rho_v/\rho_l = 0.000624$) and isopropanol ($\rho_v/\rho_l = 0.00299$); and judging from the result of Fig. 5 including much higher values of

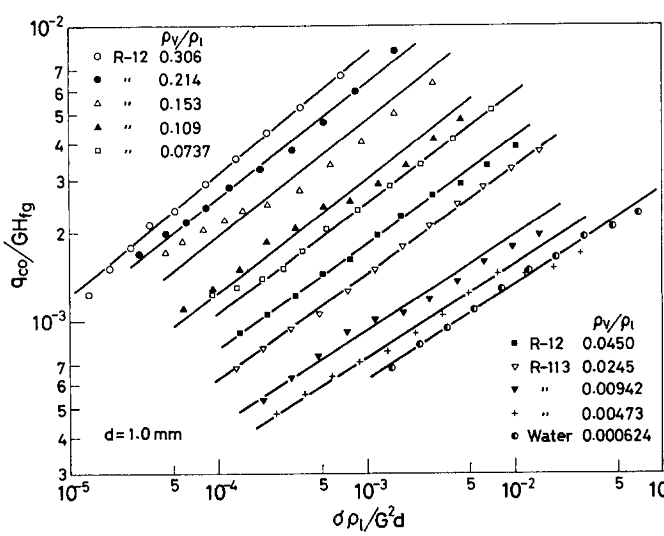

FIG. 5. Correlation of experimental data of critical heat flux q_{c0} for saturated liquid flow obtained in the present work.

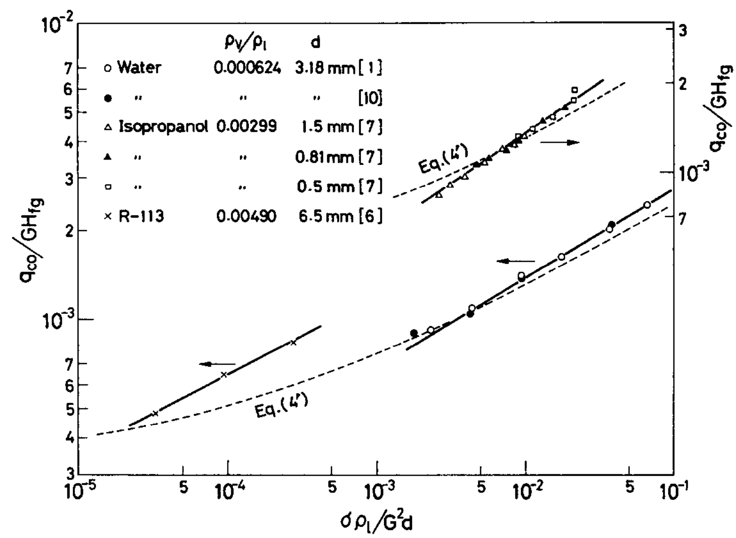

FIG. 6. Correlation of experimental data of critical heat flux q_{c0} for saturated liquid flow from existing sources.

ρ_v/ρ_l, equation (4′) is regarded as applicable within a range of low ρ_v/ρ_l values less than 0.00473 at the highest.

(5) Three data points of R-113 ($\rho_v/\rho_l = 0.00490$, $d = 6.5$ mm) in Fig. 6 are found to give much higher values of q_{c0} than those of R-113 ($\rho_v/\rho_l = 0.00473$, $d = 1.0$ mm) in Fig. 5 in spite of nearly the same value of ρ_v/ρ_l. One may not deny the possibility that this discrepancy is caused by the great difference of diameter, but it seems more likely to depend on the circumstance that the former data are those obtained by Yilmaz and Westwater [6] with a steam-heated copper tube, which provides a condition for the wall temperature considerably different from that of an electrical current-heated cylinder.

3.2. *Generalized correlation of q_{c0} data*

Values of K and m in equation (7) can be readily determined from every straight line drawn along each data group in Figs. 5 and 6. K and m thus obtained are plotted as functions of ρ_v/ρ_l, respectively, in Fig. 7, where two thick solid lines represent the following equations derived empirically so as to fit the data of K and m, respectively:

$$K = 0.00588 + 0.500(\rho_v/\rho_l)^{1.11} \quad (8)$$

$$m = 0.42(\rho_v/\rho_l)^{0.0428}. \quad (9)$$

It will be noted from the result of Fig. 7: (i) that both equations (8) and (9) agree surprisingly well with experimental data over a very wide range of ρ_v/ρ_l, in spite of simple expressions; (ii) that a relative change of the value of m with changes of ρ_v/ρ_l ratio is very small as against that of the value of K; and (iii) that K has an interesting character that it is kept nearly constant when ρ_v/ρ_l is very low, whereas it increases nearly in proportion to ρ_v/ρ_l when ρ_v/ρ_l is very high.

On the other hand, if equation (6) is compared with equation (7), it immediately gives

$$K = 0.151(\rho_v/\rho_l)^{0.467}[1+(\rho_v/\rho_l)]^{1/3} \quad (10)$$

$$m = 1/3. \quad (11)$$

These two equations are represented by broken lines in Fig. 7, indicating that they do not agree so well with experimental data. However, rough coincidence can be assumed of the foregoing two equations and experimental data over a wide range of $\rho_v/\rho_l = 0.0005$–0.4. This may suggest that a simple model from which equation (6) is derived (cf. ref. [8] for details) has something valid in principle about fluid behaviors near the heated surface.

4. CONCLUSIONS

(1) Employing three kinds of test fluids, experiments of CHF on a d.c. electrical current-heated, 1 mm diameter cylindrical heater in a forced cross flow of $u = 0.59$–7.1 m s^{-1} have been performed in a range of ρ_v/ρ_l values extending from 0.000624 to 0.306.

(2) The obtained data of q_{c0} are found to match the existing data for low ρ_v/ρ_l values ($\rho_v/\rho_l = 0.000624$–0.00299); and the following generalized correlation has been derived empirically, showing good agreement with the data over a wide range of $\rho_v/\rho_l = 0.0005$–0.4

$$\frac{q_{c0}}{GH_{fg}} = K\left(\frac{\sigma\rho_l}{G^2 d}\right)^m$$

where

$$K = 0.00588 + 0.500(\rho_v/\rho_l)^{1.11}$$

and

$$m = 0.42(\rho_v/\rho_l)^{0.0428}.$$

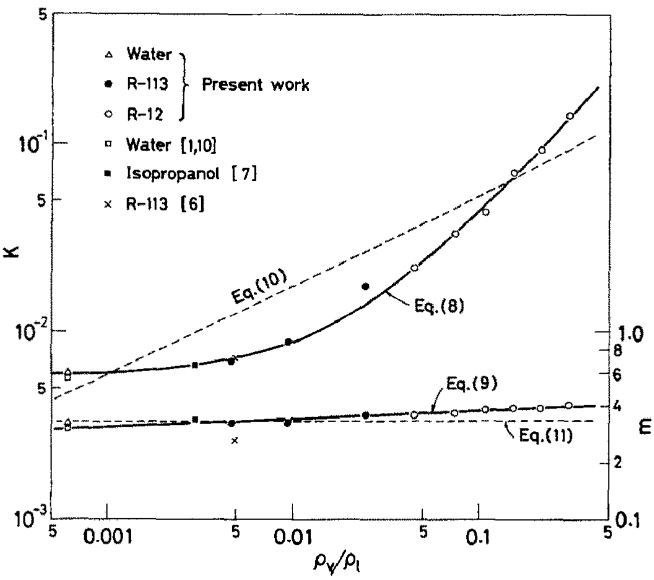

FIG. 7. Values of K and m plotted against vapor/liquid density ratio ρ_v/ρ_l.

(3) A semi-empirical correlation, equation (4′), is regarded as applicable within a range of low ρ_v/ρ_l ratios less than 0.00473 at the highest.

(4) A theoretical correlation of q_{c0}, equation (6), which is based on the concept of critical liquid film thickness, does not agree so well with experimental data, but still shows rough coincidence with the data over a wide range of $\rho_v/\rho_l = 0.0005$–0.4.

(5) Three data points of R-113 for $d = 6.5$ mm in Fig. 6 are inconsistent with other data. This discrepancy seems to be caused by the difference in heating conditions: that is, steam heating for the above data points against electrical current heating for all other data.

(6) Interesting results of Fig. 7 for cylinders in a cross flow suggest the need to make a similar study of q_{c0} for flat plate heaters in a parallel flow, which is different from the former system in having no wake region.

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FLUX THERMIQUE CRITIQUE SUR UN CYLINDRE UNIFORMEMENT CHAUFFE PLACE DANS UN ECOULEMENT FRONTAL DE LIQUIDE SATURE, POUR UN LARGE DOMAINE DE QUALITE DE VAPEUR

Résumé—Des études expérimentales de flux thermique critique (CHF) sur un cylindre chaud placé dans un écoulement frontal ont été menées ultérieurement pour un domaine restreint du rapport de masse volumique vapeur–liquide, soit ρ_v/ρ_l = 0,0006–0,005. Dans la présente étude, des expériences systématiques du CHF sur un cylindre chauffé par courant électrique continu, et de 1 mm de diamètre, ont été faites pour un très large domaine de ρ_v/ρ_l, soit 0,000624–0,306, avec eau à 0,098 MPa, R-113 à 0,098–0,490 MPa et R-12 à 0,98–3,43 MPa. On présente une formule générale empirique qui peut prédire CHF de façon satisfaisante dans l'ebullition saturée pour un large domaine de ρ_v/ρ_l.

DIE KRITISCHE WÄRMESTROMDICHTE EINES GLEICHMÄSSIG BEHEIZTEN, MIT GESÄTTIGTER FLÜSSIGKEIT QUERANGESTRÖMTEN ZYLINDERS IN EINEM SEHR GROSSEN BEREICH DES VERHÄLTNISSES VON DAMPF- ZU FLÜSSIGKEITSDICHTE

Zusammenfassung—Experimentelle Untersuchungen der kritischen Wärmestromdichte eines beheizten querangeströmten Zylinders wurden bisher nur in einem sehr kleinen Bereich des Verhältnisses aus Dampf- und Flüssigkeitsdichte ρ_v/ρ_l = 0,0006–0,005 durchgeführt. In dieser Arbeit wurde die kritische Wärmestromdichte an einem Gleichstrom-beheizten Zylinder mit 1 mm Durchmesser über einem sehr großen Bereich von ρ_v/ρ_l = 0,000624–0,306 systematisch untersucht. Es wurde Wasser bei 0,098 MPa, R113 bei 0,098–0,490 MPa und R12 bei 0,98–3,43 MPa benutzt. Eine verallgemeinerte Korrelation wird vorgestellt, mit der die kritische Wärmestromdichte beim gesättigten Sieden im oben genannten Bereich von ρ_v/ρ_l genügend genau berechnet werden kann.

КРИТИЧЕСКИЙ ТЕПЛОВОЙ ПОТОК НА ПОВЕРХНОСТИ РАВНОМЕРНО НАГРЕТОГО ЦИЛИНДРА В ПОПЕРЕЧНОМ ПОТОКЕ НАСЫЩЕННОЙ ЖИДКОСТИ В ШИРОКОМ ДИАПАЗОНЕ ИЗМЕНЕНИЯ ОТНОШЕНИЯ ПЛОТНОСТЕЙ ПАРА И ЖИЦКОСТИ

Аннотация—Проведено экспериментальное изучение величины критического теплового потока на поверхности поперечно обтекаемого нагретого цилиндра в широком диапазоне изменения отношения плотности жидкости к плотности пара ρ_v/ρ_l = 0,0006–0,005. В работе описываются результаты систематических экспериментов по определению величины критического теплового потока на поверхности цилиндра диаметром 1 мм и нагреваемого постоянным электрическим током в широком диапазоне изменения ρ_v/ρ_l = 0,000624–0,306. Рабочими жидкостями являются вода при 0,098 МПа, R-113 при 0,098–0,490 МПа и R-12 при 0,98–3,43 МПа. Приводится эмпирическая обобщающая зависимость, которая позволяет удовлетворительно рассчитать критический тепловой поток при кипении насыщенной жидкости в указанном диапазоне изменения ρ_v/ρ_l.