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International Journal of Heat and Mass Transfer 45 (2002) 4133–4139

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Critical heat flux of natural circulation boiling in a vertical tube Effect of oscillation and circulation on CHF

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Received 21 September 2001; received in revised form 22 March 2002

Abstract

An experimental study has been made to elucidate an effect of oscillated flow induced near critical heat flux (CHF) and natural circulated flow of vapor and liquid in a vertical tube on the CHF. The experiment has been carried out for the condition of heated tube length of $L = 100$–1000 mm, tube diameter of $D = 4$–9 mm and the CHF is measured under the condition that the exit of the unheated tube connecting the heated tube is extruded into a vapor chamber to prevent a liquid flowing into the heated tube from the top. The experiment reveals that the CHF for $D = 7$ and 9 mm and any tube length from 100 to 1000 mm becomes identical to that for the case of the tube top in the liquid, while the CHF for $D = 4$ and 5 mm is smaller than that for the case of the tube top in the liquid due to no liquid supply from the top. It is found that the oscillation induced near the CHF increases the CHF. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Critical heat flux; Phase change; Natural convection boiling; Vertical tube; Natural circulation

1. Introduction

Critical heat flux (CHF) during natural convective boiling in confined channels, such as a tube and an annulus, is important as a fundamental study of the CHF phenomenon as well as for its application to industrial problems related to superconducting devices and a cooling of microelectric devices. The CHF is recently recalled to play an essential role in predicting a safety cooling of PWR and BWR reactors after its hypothetical coolant accident and its loss of coolant accident happened such as three mile island-2 (TMI-2) accident. On the other hand, a two-phase thermosyphon, which is another type of confined flow, is widely applied to cool an electric device. The CHF for the thermosyphon is considered as a result of constraint of liquid supply to the heated tube due to a counter-current flow of vapor and liquid [1–3]. Therefore, in order to improve the CHF of the thermosyphon, Islam et al. [4] inserted a tube into the thermosyphon to avoid a counter-current flow of liquid and vapor at the exit of the thermosyphon. They succeeded in improving the CHF about eight times at an optimum operation. The CHF in a confined channel is generally considered to closely relate to flow condition, although the flow mode becomes very complicated.

Authors [5,6] have extensively measured the CHF during natural circulation boiling in a vertical tube and annular tube with a wide range of density ratio, ρ_l/ρ_g and ratio of heated tube length to tube diameter. The following correlations Eqs. (1)–(3) are proposed to predict the CHF in vertical tube and annular tube.

For the tube [5], the characteristic of CHF can be categorized into two and accordingly the correlations become:

in the case of a small tube;

$$\frac{q_{co}/\rho_g h_{lg}}{\sqrt[4]{\sigma g(\rho_l - \rho_g)/\rho_g^2}} = \frac{0.16}{1 + 0.025(L/D)}$$

$$\text{for } D/\sqrt{\sigma/g(\rho_l - \rho_g)} < 13 \qquad (1)$$

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0017-9310/02/$ - see front matter
PII: S0017-9310(02)00130-8

Nomenclature

D	tube diameter
D_{ori}	diameter of orifice
D_{he}	heated equivalent diameter [= 4(flow area)/heated perimeter]
g	acceleration due to gravity
h_{lg}	latent heat of evaporation
j_g	superficial vapor velocity $[= 4(L/D) \times (q/\rho_g h_{lg})]$
Ku	Kutateladze number $[= (q_{co}/\rho_g h_{lg})/(\sqrt[4]{\sigma g(\rho_l - \rho_g)/\rho_g^2})]$
L	length of heated tube
q_{co}	critical heat flux
q_w	surface heat flux
ΔT_{sat}	wall superheat
ρ_g, ρ_l	density of vapor and liquid
σ	surface tension

in the case of a large tube;

$$\frac{q_{co}/\rho_g h_{lg}}{\sqrt[4]{\sigma g(\rho_l - \rho_g)/\rho_g^2}} = \frac{0.16}{1 + 0.003 Bo^{1/2}}$$

$$\text{for } D/\sqrt{\sigma/g(\rho_l - \rho_g)} > 13 \quad (2)$$

For the annular tube with an inner tube heated [6], its characteristic appears in a single mode independent of $D_{he}/[\sigma/g(\rho_l - \rho_g)]^{1/2}$ and the correlation becomes:

$$\frac{q_{co}/\rho_g h_{lg}}{\sqrt[4]{\sigma g(\rho_l - \rho_g)/\rho_g^2}} = \frac{0.16}{1 + 0.075(L/D_{he})} \quad (3)$$

Comparing Eqs. (1) and (3), one may notice that both Eqs. (1) and (3) become the same in form except for the factors on L/D or L/D_{he}. Recently, Monde et al. [7] made it clear the reason that characteristics of the CHF are different between the tube and annular tube and its correlation changes from Eqs. (1)–(3) based on characteristics of heated equivalent diameter.

Incidentally, the CHF data, which are used to derive Eq. (1), are obtained under the oscillation of liquid and vapor in a confined channel, since the experiment to measure them has been usually done under the condition that the exit of confined channel is set below a level of saturated liquid as shown in Fig. 1(a). A similar oscillation [8] was experienced under the same experimental condition as the present one, that has its frequencies to vary from 1.0 to 1.3 Hz for the tube length of $L = 460$ mm and from 0.4 to 1.0 Hz for $L = 960$ mm in the range of the tube diameter of $D = 2$–10 mm. Therefore, the CHF would be strongly influenced by the oscillation and a liquid supply from the top of the tube.

In the present study, in order to elucidate the effect of the oscillation and a liquid supply on the CHF, we measured the CHF under the condition that the exit of the heated tube is extruded into the vapor chamber as shown in Fig. 1(b) by which liquid is prevented from flowing into the heated tube from the top and is surely circulated from the bottom to the top and that the oscillation is suppressed by mounting an orifice at the inlet

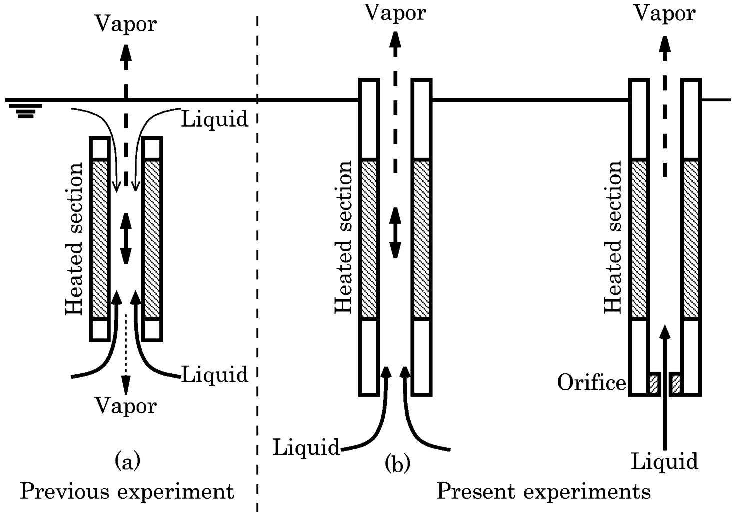

Fig. 1. Flow configurations of vapor and liquid in tube.

of the heated tube. These effects on the obtained CHF will be discussed here.

2. Experimental apparatus and procedure

Fig. 2 shows the whole system of experimental apparatus and its details are referred in Monde and Yamaji [5]. The tested tube is settled at the center of a pressure vessel. The tube is directly heated by DC current and its actual heated length can be appropriately set by changing the position of electrode (Fig. 3).

The level of test liquid in the vessel was always kept at 150 mm higher than the exit of heated tube. Only one thermocouple is mounted at a position of 7 mm just below from the exit of the actual heated tube to monitor the surface temperature. The position of 7 mm was chosen to avoid an end effect. The heat flux was calculated with a relative accuracy higher than 0.1% from the electric input. The radial heat flow loss from the outer side of the heated tube is estimated to be less than 1% of electric input. This estimation is resulted from the following

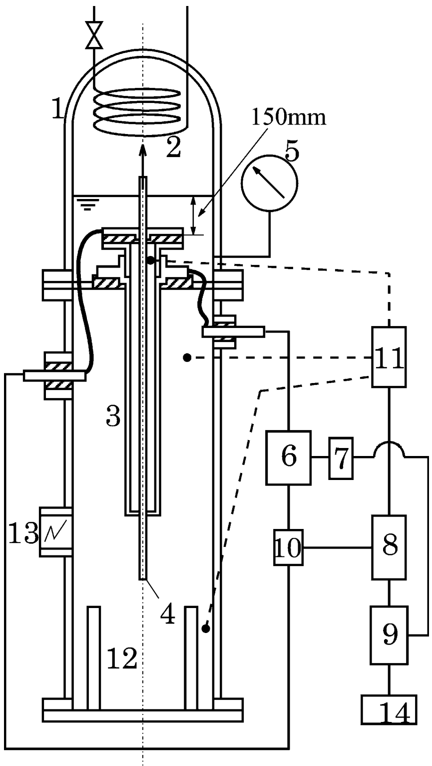

Fig. 2. The schematic of experimental apparatus: (1) pressure vessel, (2) cooler, (3) test section, (4) orifice, (5) pressure gage, (6) DC power supply, (7) GPIB programmer, (8) digital thermometer, (9) GPIB, (10) fixed resistor, (11) ice box, (12) auxiliary heater, (13) window, (14) CPU.

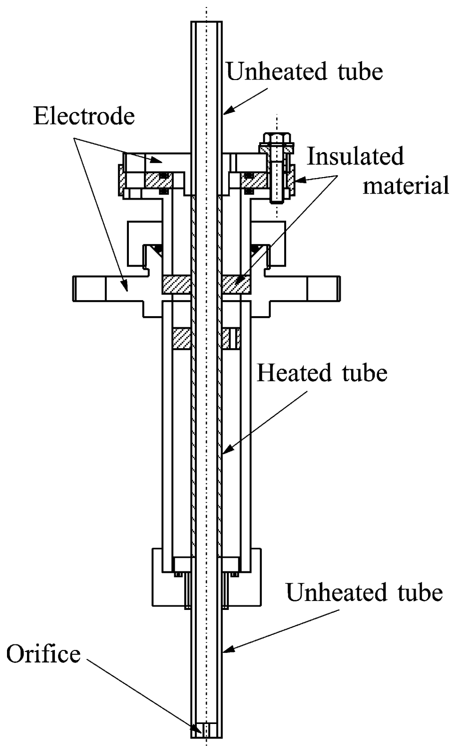

Fig. 3. Details of heated tube.

reasons: the temperature difference between saturated liquid and the outer side of the heated tube is usually less than 20 K before the occurrence of CHF and then boiling heat transfer on the tube wall becomes extremely high. The axial heat loss from the end of tube to the electrode is also limited close near the electrode from a calculation for heat transfer in a finned surface and then can be ignored except for the part near the electrode. The level of test liquid in the vessel was always kept for any length of the heated tube at 150 mm higher than the exit of the actual heated tube, while for the case of the extruded tube the unheated tube is always extruded at 200 mm higher than the liquid level. By settling the extruded tube, a liquid supply from the top of the tube is totally prevented. Whereas, a 500 mm length of unheated tube is additionally attached to prevent some vapor flowing out from the bottom of the tube due to an oscillation of liquid and vapor. In addition to this, an orifice is mounted at the entrance of the unheated tube to suppress the oscillation there. The bottom end is kept free to absorb a thermal expansion of the heated tube.

The experiment is carried out by increasing the electric power supply to the outer tube with increments that are less than 5% of each preceding heat flux under the condition that the pressure inside vessel is kept at a designated pressure. The steady state condition can be

Table 1
Experimental range

Fluid	Water
P (MPa)	0.1
L (mm)	100, 250, 500, 1000
D (mm)	4, 5, 7, 10
D_{ori} (mm)	1–5
$(D_{ori}/D)^2$	1/16, 1/9, 1/4

reached within a few minute after setting the heat flux, since heat capacity of the outer tube is rather small compared with heat input and heat transfer coefficient of evaporation is large enough. The CHF is determined by the following means: when heat flux is increased in increments that are less than 2% of each preceding heat flux, and finally a point is reached where the tube temperature monitored runs away. At this point, the CHF is determined with an uncertainty of 0–2%. The experimental range is summarized in Table 1.

3. Experimental result and discussion

3.1. Boiling curve

Fig. 4 shows typical boiling curves for the heated lengths of $L = 100$ and 500 mm in $D = 7$ mm and $P = 0.1$ MPa. These boiling curves are obtained at the position of 7 mm from the top of the heated tube. Each arrow in Fig. 4 indicates the occurrence of the CHF. A broken line is one predicted by Eq. (1) and a light solid line is the Nishikawa and Fujita [9] correlation for pool boiling as a reference.

For the case of $L = 100$ mm, the surface temperature is increased with an increase in heat flux and then suddenly runs away at a heat flux at which the CHF takes place as shown by the arrow. The feature of the occurrence of CHF can be considered to be similar in trend to that in ordinary pool boiling. For the case of $L = 500$ mm, on the other hand, there is an inflection point at which the trend in increase in the surface temperature with an increase in heat flux is significantly changed that a small increase in heat flux leads to a large rise in the surface temperature, but a steady state is still attained and then after some increments of heat flux, and then the CHF condition is finally reached. The same tread is always observed for all the tube diameter of $L = 250$, 500 and 1000 mm. The heat flux at the reflection point is named as the advancing CHF and briefly is given as Adv. CHF in figures, here.

Fig. 5 also shows typical boiling curves for $D = 7$ mm, $L = 500$ mm and $P = 0.1$ MPa, when an orifice is mounted at the entrance of the tube to suppress an oscillation of liquid and vapor caused at the CHF. It is seen from Fig. 5 that at a heat flux below the advancing CHF, a similar boiling takes place for any orifice and then no difference in boiling feature between with the orifice and without the orifice appears at a heat flux less than the advancing CHF. However, after the advancing CHF, the trend in the boiling curve dramatically changes resulting from constraint of flow rate due to the orifice. A small increase in heat flux makes the CHF occur as shown in Fig. 5 so that the CHF is very close to the advancing CHF.

It should be mentioned finally that the advancing CHF does not appear only for $L = 100$ mm in the range

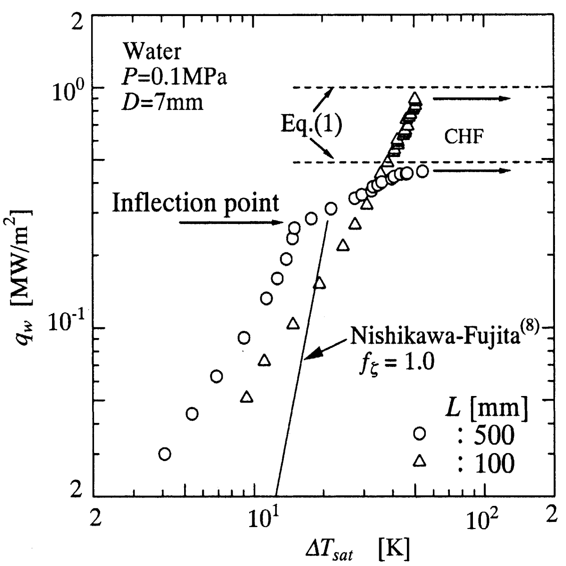

Fig. 4. Boiling curves without orifice.

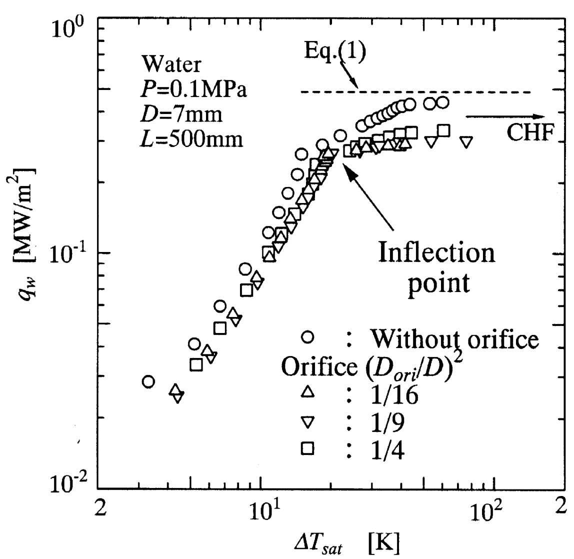

Fig. 5. Boiling curves with orifice.

of $(D_{ori}/D)^2$ of 1 to 1/16, although for the other heated length it is always observed.

3.2. Occurrence of CHF and flow situation

The boiling curve and the CHF are measured under the flow condition as shown in Fig. 1(b) that the exit of the tube is extruded into the vapor chamber for which no liquid is supplied through the top of the tube. However, when comparing flow situations between 1(a) and (b), we notice that the difference is only whether a liquid can be possible to flow into the tube through its top or not. Therefore, flow situation for the extruded condition seems to be similar to one for the submerged one and is guessed that an oscillatory flow would be generated at about 1 Hz over the entire tube without the orifice.

In comparison of boiling curves in Figs. 4 and 5, the CHF for $L = 100$ mm would be occurred under the condition that a liquid always exists enough to cover the heated tube. On the other hand, in the case of $L \geqslant 250$ mm, a sufficient liquid exists on the heated tube as $L = 100$ mm until the advancing CHF, but after the advancing CHF it seems to be not enough to cover the heated surface where the flow beneath the measuring point would become mist flow. The CHF is approaching the advancing CHF with decreasing the diameter of the orifice. This fact may be attributed to a suppression of the flow oscillation as well as liquid supply due to the orifice.

3.3. Effect of heated tube diameter on CHF

Fig. 6 shows the value of the measured CHF plotted against the heated tube diameter for $L = 500$ mm. In Fig. 6, a solid line is Eq. (1) for $L = 500$ mm with an error band of ±20%.

It is seen from Fig. 6 that without the orifice the CHF for $D = 7$ and 10 mm agrees well with Eq. (1), while the CHF for $D = 4$ and 5 mm becomes smaller than that predicted by Eq. (1). Recalling the position of the tube top as shown in Fig. 1, the agreement between the measured CHF and Eq. (1) implies that no liquid is supplied through the top of the tube for $D = 7$ and 10 mm even though the top is submerged into the saturated liquid. On the other hand, a decrease in the CHF value for $D = 4$ and 5 mm is attributed to a constraint of liquid supply from the top. Therefore, it is concluded that whether some liquid is supplied through the top or not, depends on the tube diameter even though the top of the tube is set under the level of the liquid and this critical value appears between 4 and 6 mm.

The result that the CHF is approaching the advancing CHF by mounting the orifice as shown in Fig. 6, means that the oscillatory flow is constrained by the orifice leading to reduction of liquid supply.

3.4. Effect of heated tube length on CHF

Fig. 7 shows the value of the CHF measured for $D = 5$ mm plotted against the heated length. Fig. 7 also shows Eq. (1) with an error range of −20% by a broken line.

It is found from Fig. 7 that the CHF data always become smaller than that predicted by Eq. (1), especially the CHF for $L = 100$ mm being more than 20%. This reason comes from no liquid supply through the top of the tube.

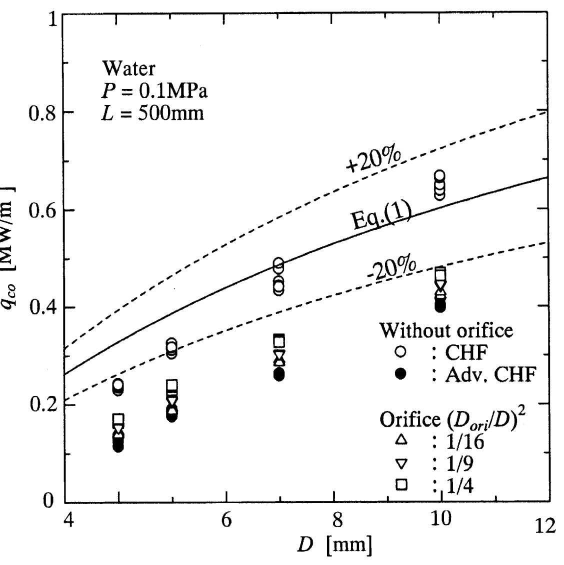

Fig. 6. Comparison of q_{co} with D.

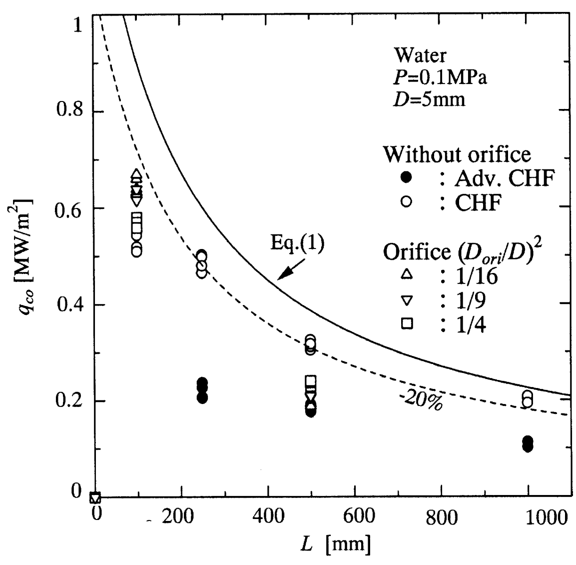

Fig. 7. Comparison of q_{co} with L.

As for an effect of the orifice, the CHF for $L = 500$ mm is equally decreased independent of the size of the orifice and then its values almost agree with its advancing CHF. For $L = 100$ mm, its CHF value seems to inversely increase with a decrease in the size of orifice. This trend would become more remarkable for a smaller heated tube. The reason is not clear, yet.

3.5. Correlation of CHF

Fig. 8 shows the reciprocal of the Kutateladze number, $1/Ku$, calculated from the measured CHF plotted against L/D. The solid line in Fig. 8 is Eq. (1) and also several data surrounded by circles correspond to the CHF for $D = 4$ and 5 mm.

Fig. 8 shows that the CHF data for $D = 7$ and 10 mm can be predicted well by Eq. (1), while those for $D = 4$ and 5 mm are more than 20% smaller than that by Eq. (1). For the case of the tube submerged into the liquid, the decrease in the CHF value depends on whether liquid is supplied through the top of the tube or not as already mentioned in Sections 3.3 and 3.4.

3.6. Flow situation at the top of submerged tube

Comparing flow behavior near the CHF between submerged and extruded tubes, we can guess from Fig. 8 that some amount of liquid can flow into the submerged tube of $D = 4$ and 5 mm from the top of the tube, while no liquid flows into the tube for the tube diameter of $D = 7$ and 10 mm, even though the tube is submerged. In order to find this reason, we try to calculate superficial velocity at the tube exit at the CHF point and plot it against the tube diameter as shown in Fig. 9. Some curves in Fig. 9 are obtained by using the CHF values predicted for each tube length by Eq. (1). The value of $D_\sigma = \lambda_T/\pi = [\sigma(\rho_f - \rho_g)]^{1/2} = 5.02$ mm just corresponds to a reduced value calculated from the Taylor Instability wave length. The solid symbol indicates the CHF data for the tube diameters smaller than $D_\sigma = 5.02$ mm. It may be of interest to note from Fig. 9 that the superficial velocities for the tube diameters smaller than about $D_\sigma = 5.02$ mm largely decreases from the line predicted by Eq. (1) with a decrease in the tube diameter. Especially, this trend becomes marked for a shorter tube length. For the submerged tube, the decrease in the superficial velocity makes the interface disturbed by vapor flow near the tube exit more stable, resulting into larger amount of liquid supply there. In other words, for the tube diameter smaller than $\lambda_T/\pi = 5.02$ mm, a stable interface would be established on the tube rim from which some amount of liquid would be supplied into the tube. Therefore, the CHF for the extruded tube for which no liquid flows into from the top end becomes smaller than that for the submerged tube. On the other hand, for the tube diameter larger than $\lambda_T/\pi = 5.02$ mm, the stable interface cannot be sustained on the tube rim, yet. Consequently, no liquid penetrates into the tube through its rim, resulting into no difference in the CHF value between the submerged and the extruded tubes.

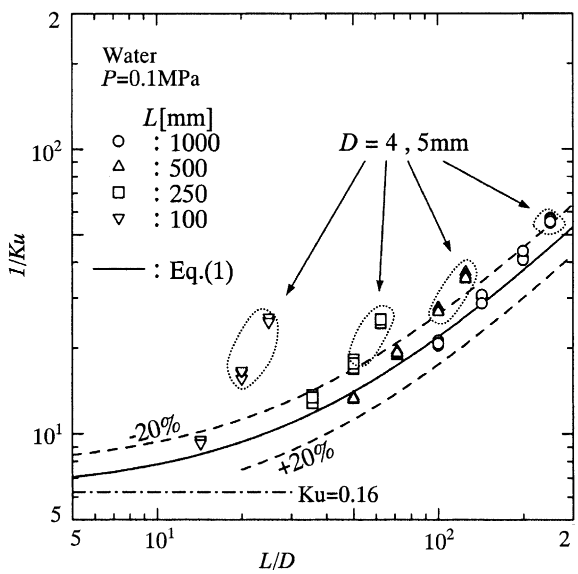

Fig. 8. Comparison of $1/Ku$ with L/D.

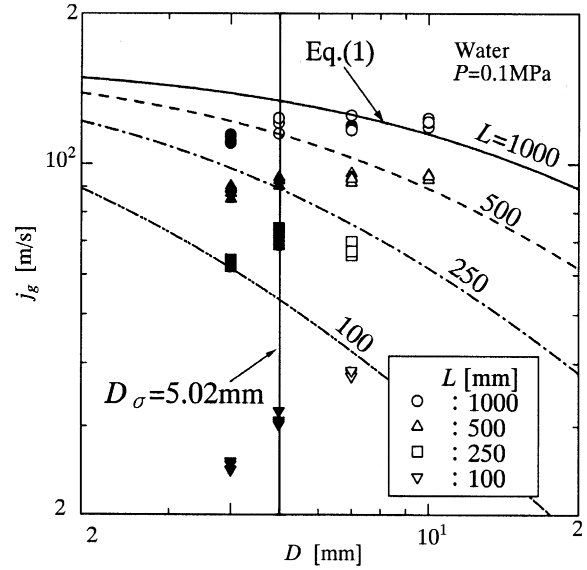

Fig. 9. Comparison of j_g with D.

3.7. Effect of orifice on CHF

Fig. 10 shows the reciprocal of the Kutateladze number, $1/Ku$, for $L = 500$ and 100 mm plotted against

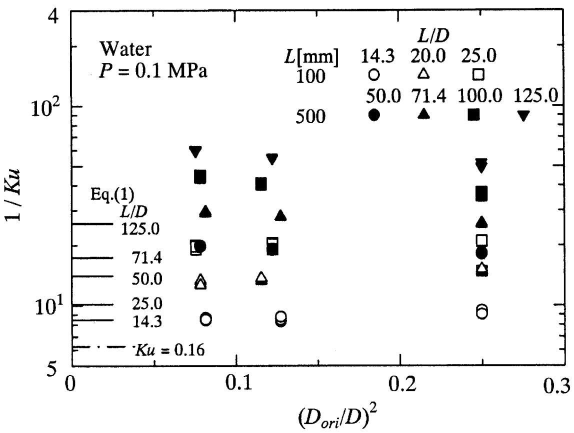

Fig. 10. Plot of $1/Ku$ vs. $(D_{ori}/D)^2$ for constant value of L/D.

$(D_{ori}/D)^2$ to depict an effect of orifice on the CHF and also shows the prediction by Eq. (1) for comparison.

It is found from Fig. 10 that the value of the CHF for $L/D \geqslant 20$ is slightly decreased by an effect of the orifice in the range of $0.0625 \leqslant (D_{ori}/D)^2 \leqslant 0.25$ and this effect become more significant for the larger value of L/D, while the CHF only for $L/D = 100/7$ ($= 14.3$) is hardly influenced by the orifice in the present range. The CHF value with the orifice is approaching the advancing CHF without the orifice as shown in Fig. 6. This fact implies that an increase from the advancing CHF to the CHF would be accomplished by a liquid supply due to an oscillatory flow in the tube. The installation of the orifice may suppress this oscillation to make the CHF decrease until the advancing CHF. Incidentally, although it is not clear why the CHF for $L/D = 100/7$ behaves different trend compared with the other cases, one possibility is that the area of the orifice is still enough to supply the liquid into the heated tube from the two reasons that the CHF values are the same between with and without the orifice and no liquid for $D = 4$ mm is supplied from the top of the tube as mentioned before.

4. Conclusions

The CHF has been measured under the condition that both liquid and vapor co-currently upward flow through the heated tube by artificially extruding the tube exit into the vapor chamber and the following results are obtained:

1. For the tube diameter of $D \geqslant 7$ mm, the CHF can be predicted by Eq. (1) and cannot be influenced by the position of the tube exit being submerged or extended.
2. For the tube diameter of $D \geqslant 7$ mm, both liquid and vapor always flow co-currently through the heated tube independent of the position of the tube exit.
3. For the tube diameter of $D \leqslant 5$ mm, the CHF for the case of the tube exit outside liquid becomes smaller than that predicted by Eq. (1) for the submerged exit condition due to a constraint of liquid supply from the tube exit.

Acknowledgements

The authors express appreciation to Mr. K. Nakashima for his valuable assistance in making experimental apparatus and also Mr. T. Shimomura for his valuable assistance in making experimental apparatus and collecting data.

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