PERGAMON

International Journal of Heat and Mass Transfer 42 (1999) 3189–3194

International Journal of
HEAT and MASS
TRANSFER

Technical Note

Critical heat flux during natural circulation boiling on uniformly heated outer tube in vertical annular tubes submerged in saturated liquid (change in critical heat flux characteristics due to heated equivalent diameter)

Masanori Monde*, Yuichi Mitsutake, Masanori Hayasi

Department of Mechanical Engineering, Saga University, 1 Honjo-machi, Saga-shi, Saga 840-8502, Japan

Received 29 June 1998; received in revised form 18 November 1998

Abstract

Critical heat flux has been measured during natural circulation boiling of water on uniformly heated outer tube in vertical annular tube. The experiment was carried out using water at atmospheric pressure for the clearance of 1.0–4.0 mm, the heated tube diameter of 9–17 mm, and the annular tube length of 100–1000 mm. The similarity of CHF between annular configurations of either inner or outer heated tubes and a simple heated tube can be clearly elucidated based on the characteristics of heated equivalent diameter. The CHF measured for $s=1$ mm can be predicted well by existing correlation for the annular tube and for $s=3$ and 4 mm by existing correlation for the single tube. © 1999 Elsevier Science Ltd. All rights reserved.

---

1. Introduction

One author [1,2] has extensively measured critical heat flux (CHF) during natural circulation boiling in a vertical tube and annular tube with a wide range of density ratio, ρ_l/ρ_g and combination of heated tube length to tube diameter, and proposed the following correlations (1), (2) and (3) to predict the critical heat flux in vertical tube and annular tube.

For the tube [1], the characteristic of CHF can be categorized into two and accordingly the correlations become:

in the case of a small tube:

$$\frac{q_{co}/\rho_g h_{lg}}{\sqrt[4]{\sigma g(\rho_l-\rho_g)/\rho_g^2}} = \frac{0.16}{1+0.025(L/D)} \quad \text{for } D/\sqrt{\sigma/g(\rho_l-\rho_g)}<13 \tag{1}$$

in the case of a large tube:

$$\frac{q_{co}/\rho_g h_{lg}}{\sqrt[4]{\sigma g(\rho_l-\rho_g)/\rho_g^2}} = \frac{0.16}{1+0.003Bo^{1/2}} \quad \text{for } D/\sqrt{\sigma/g(\rho_l-\rho_g)}>13 \tag{2}$$

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

---

* Corresponding author..

0017-9310/99/$ - see front matter © 1999 Elsevier Science Ltd. All rights reserved.
PII: S0017-9310(99)00003-4

Nomenclature

Bo	Bond number $[=L^2/\sigma/g(\rho_l-\rho_s)]$
D_i	inner diameter of outer tube in annulus
d_o	outer diameter of inner tube in annulus
D_{hc}	heated equivalent diameter [=4 (flow area)/heated perimeter]
g	acceleration due to gravity
h_{lg}	latent heat of evaporation
Ku	Kutateladze number $[=q_{co}/\rho_g h_{lg}/\sqrt[4]{\sigma g(\rho_i-\rho_g/\rho_g^2}]$
L	length of heated tube
q	heat flux
q_{co}	critical heat flux
S	clearance of annular passage
ΔT_{sat}	wall superheat

Greek symbols

ρ_g, ρ_l	density of vapor and liquid
σ	surface tension

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

Comparing Eqs. (1) and (3), one may notice that both equations become the same in form except for the factors on L/D or L/D_{he}.

Recently, Islam et al. [3] have measured critical heat flux in a concentric-tube thermosyphon in which an outer tube is heated and a tube inserted serves as a feed of liquid from a liquid reservoir at the top of the thermosyphon and implied that the characteristic of the CHF appears to gradually shift from Eqs. (3) to (1) with increasing the clearance of annular passage through which vapor generated on the outer heated tube flow out. The transition of the CHF from Eqs. (3) to (1) may be attributed to characteristics of heated equivalent diameter, which is defined for the inner or outer tubes heated, respectively as:

for the inner heated tube

$$D_{he}=d_o\left(\left(\frac{D_i}{d_o}\right)^2-1\right)$$

for the outer heated tube

$$D_{he}=\frac{d_o^2}{D_i}\left(\left(\frac{D_i}{d_o}\right)^2-1\right).$$

According to the definition of the heated equivalent diameter, for example, in the case that the outer diameter of inner tube, d_o, becomes close to the inner diameter of outer tube, D_i, namely $d_o \longrightarrow D_i$, under which the clearance of annular passage becomes very narrow, each of the heated equivalent diameters approaches to the same value for either of heated tubes, so that the CHF for both cases may be pre-

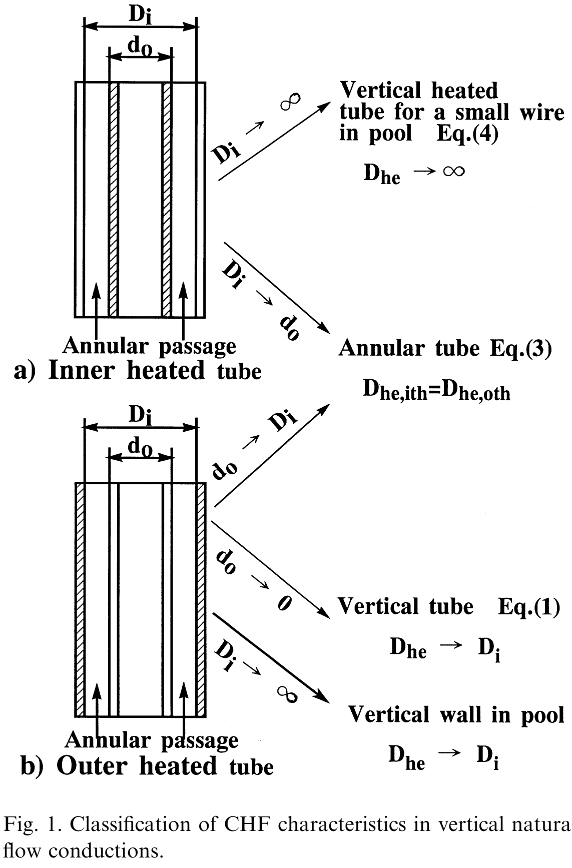

Fig. 1. Classification of CHF characteristics in vertical natural flow conductions.

dicted by Eq. (3), that is, no difference in CHF may be obtained. For the case of a wide annular passage, inversely, both the heated equivalent diameters approach to a different limited value, respectively, that is, the heated equivalent diameter for the inner tube heated becomes infinity, namely $D_{\mathrm{he}} \rightarrow \infty$ so that the flow condition may become similar to pool boiling on vertical heated surface, while the heated equivalent diameter for the outer tube heated approaches to the tube diameter for both limited cases of $d_{\mathrm{o}} \rightarrow 0$ and $D_{\mathrm{i}} \rightarrow \infty$, namely $D_{\mathrm{he}} \rightarrow D_{\mathrm{i}}$. As for flow aspect on the heated tube, in the case of $d_{\mathrm{o}} \rightarrow 0$, its flow configuration becomes close to natural circulation in a vertical tube, while for $D_{\mathrm{i}} \rightarrow \infty$, it approaches to pool boiling on a vertical heated wall, for which no correlation is yet proposed except for a short wall. Therefore, the case of $D_{\mathrm{i}} \rightarrow \infty$ is omitted here since a further study would be required. Flow configurations for these cases can be finally categorized into three different types depending on whether the annular passage has space enough for vapor to flow or not and on which tube is heated as shown in Fig. 1.

Recently, CHF during pool boiling on a vertical heated wire can be proposed by Monde et al. [4] as follows:

$$\frac{q_{\mathrm{co}}/\rho_{\mathrm{g}} h_{\mathrm{lg}}}{\sqrt[4]{\sigma g(\rho_{\mathrm{l}}-\rho_{\mathrm{g}})/\rho_{\mathrm{g}}^{2}}} = \begin{cases} 0.42Bo^{-1/4} & \text{for } Bo<30 \\ 0.18 & \text{for } Bo>30 \end{cases} \tag{4}$$

Eq. (4) was derived for the CHF which occurred under the condition that discontinous coalesced bubbles surrounded the wire and rose along it.

According to trend in the CHF as shown in Fig. 1, the CHF on a vertical heated wire in a large vertical tube may become theoretically similar to that on the vertical wire heated in the pool. As given in Eqs. (2) and (4), there is a great difference in the effect of the Bond number on the CHF. What brings out such a difference, however, is still unknown although a difference may exist in the flow aspect between inward and outward surfaces.

In correlating CHF for forced convection boiling in annulus, incidentally, Katto [5] pointed out based on characteristics of the heated equivalent diameter that when his correlations proposed for uniformly heated tube are extended to CHF for the inner heated tube, the factor only related to an effect of L/D on CHF should be replaced by another one, while for the outer heated tube, his correlations do not need any change, although this result is estimated from a few CHF data.

Deriving correlations for CHF during forced convection boiling in annulus based on that in tube, Shah [6] also pointed out that the heated equivalent diameter played an essential role on CHF in place of hydrodynamic equivalent diameter, and that there is no difference in correlations of the CHF between inner and outer heated tubes except that the tube diameter, D, in the parameter only related to an effect of L/D on CHF is replaced by the heated equivalent diameter, D_{he}, although an accuracy of prediction for annulus slightly deteriorates compared with that for the tube.

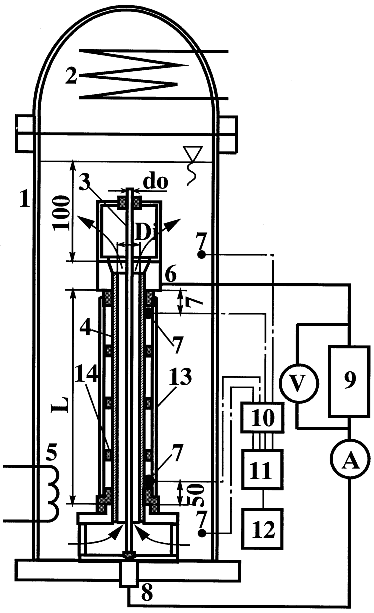

Fig. 2. Experimental apparatus.

In the present study, in order to elucidate the characteristics of the heated equivalent diameter for CHF, the CHF has been measured for water in vertical annulus, in which the outer tube only is heated, at atmospheric pressure. The effect of clearance in annulus on CHF and the estimation mentioned before, will be discussed.

2. Experimental apparatus and procedure

Fig. 2 shows the whole system of experimental apparatus. The test annulus, which was built by setting two different stainless tubes concentrically, is settled at the center of pressure vessel. The outer tube of annulus is directly heated by DC current. The level of test liquid in the vessel was always kept at 150 mm higher than the exit of test tube. Two C-A thermocouples are mounted 7 mm below the exit of the outer tube and 50 mm above from the entrance to measure the surface temperature. A radial heat flow loss from the outer side of the heated surface is insulated less than 1% of electric input by packing air between the outer tube, 4, and the test assembly, 13, and putting the Bakelite, 14,

Table 1
Experimental range

Test liquid	Water		
Pressure (MPa)	0.1		
D_i (mm)	9	12	17
d_o (mm)	3, 5, 7	4, 6, 8, 10	13, 15
S (mm)	1, 2, 3	1, 2, 3, 4	1, 2
L (mm)	100, 250, 500, 1000		

as a spacer. The details of the experimental apparatus are omitted here, because it is the same as that in [2] without the outer heated tube.

The experiment was carried out by increasing the electric input to the outer tube with increments that are less than 5% of each preceding heat flux under the condition that the pressure inside the vessel is kept at atmospheric pressure. The critical heat flux is determined by the following means: when heat flux is increased in increments that are less than 5% 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 0–5%.

The experimental range is summarized in Table 1.

3. Experimental results and discussion

3.1. Boiling curve

Fig. 3, for example, shows boiling curves at two different positions of 7 and 450 mm for $D_i = 12$ mm, $d_o = 8$ mm, and $L = 500$ mm. Two boiling curves clearly show that boiling near the exit reaches a fully-developed boiling from a heat flux less than 10^{-2} MW/m^2, while boiling near the entrance may not appear until about 3×10^{-2} MW/m^2 at which boiling starts due to incipient excursion of the wall temperature. The CHF takes place near the exit since the temperature at the position of 7 mm from the exit first starts rising at a heat flux of 4×10^{-1} MW/m^2. A small decrease in the wall temperature, as shown in Fig. 3, always appears before the CHF condition is reached. This may be caused by an enhancement of heat transfer which results from the heated surface covered with a very thin liquid film. The same phenomenon was observed in annular flow in forced convective boiling [7] in which heat transfer is enhanced and inversely boiling is suppressed by evaporation of thin liquid film.

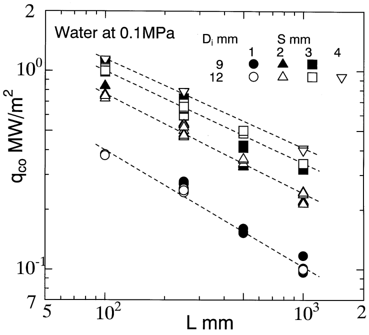

Fig. 4. Relationship between heated length and CHF.

3.2. Position of CHF

As shown in Fig. 3, the CHF first takes place near the exit and then the CHF condition is propagating toward the entrance. A similar result would be

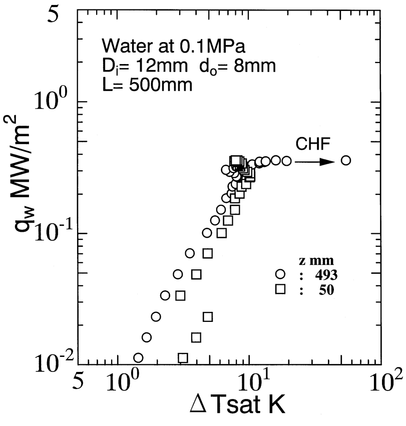

Fig. 3. Boiling curve.

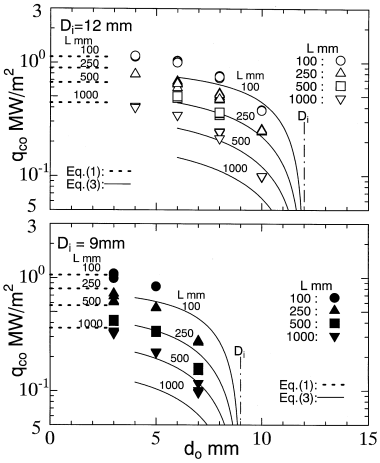

Fig. 5. Effect of inserted tube on CHF.

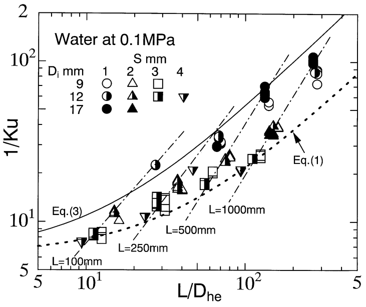

Fig. 6. $1/Ku$ vs L/D_{he}.

obtained for the case of the inner heated tube where the CHF position was identified by rise in the temperature of the heated tube near the exit [2]. There seems to be no difference in point of the CHF occurrence between the outer and inner heated tubes.

3.3. Characteristics of CHF

Fig. 4 shows the CHF values measured for a different tube diameter of $D_i = 9$ and 12 mm plotted against the heated tube length, L. In Fig. 4 a broken line as a reference shows appropriate lines drawn in parallel to the line for the same condition predicted by Eq. (3).

It is found from Fig. 4 that the CHF values linearly decrease with an increase in the heated tube length and then decrease with increasing diameter of the inner tube, that is, a decrease in the clearance of annular passage. This trend agrees with that predicted by Eqs. (1) and (3). In order to make clear the effect of diameter of the inner tube on the CHF and for the comparison of Eqs. (1) and (3), the CHF data are rearranged and plotted against the inner diameter as shown in Fig. 5. A dashed line and a solid line are Eqs. (1) and (3), respectively.

Fig. 5 shows clearly that as the diameter of inner tube becomes smaller, the CHF values gradually approach to Eq. (1), inversely when the inner tube diameter approaches close to the outer tube diameter, the CHF value leaves from Eq. (1) and approaches Eq. (3). This trend with the clearance of annulus is attributed to the characteristic of the heated equivalent diameter mentioned in section 1.

3.4. Correlation of CHF

Fig. 6 shows non-dimensional values of the CHF in order to compare Eqs. (1) and (3) in which the CHF data with the same heated tube length are connected by dotted and dashed lines.

It may be noticed from Fig. 6 that most of the CHF data are predicted well for a small clearance of $S = 1$ mm by Eq. (3), while for a large clearance by Eq. (1). Consequently, the factor in the denominator of Eqs. (1) and (3) may change from $C = 0.025$–0.075 depending on whether the clearance of annular passage is sufficient or not. This trend in CHF due to the clearance can be naturally estimated from the characteristic of the heated equivalent diameter.

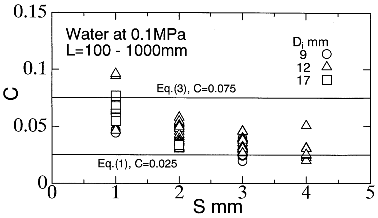

Fig. 7. Effect of clearance on constant in Eqs. (1) and (3).

3.5. Effect of clearance on CHF

Fig. 7 shows the effect of clearance on the factor in the denominator of Eqs. (1) and (3). The value of the factor clearly shifts from $C = 0.025$–0.075 with a certain scattering of data by increasing the clearance. It is not clear at present how the clearance influences the CHF together with which physical properties concern with the CHF or flow condition near the CHF.

4. Similarity of CHF in concentric thermosyphon

Islam et al. [3] measured the CHF in a concentric-tube open thermosyphon in which the inner tube serves as a liquid supplier from a top liquid reservoir to the bottom and outer tube is heated. They mentioned that in the case of a relatively large inner tube diameter being inserted, the flow situation in the thermosyphon becomes similar to that in outer heated tube in the annulus since the annular passage for vapor to escape from the thermosyphon becomes narrow, while the inner tube is large enough for liquid to be supplied to it from the bottom. As a result, the CHF obtained there was pointed out to be predicted well by Eq. (3). In addition, the characteristic of the CHF was also pointed out to gradually change from Eqs. (3) to (1) with an increase of the clearance.

5. Conclusion

The CHF during natural circulation boiling in the vertical annulus in which the outer tube is uniformly heated was measured for water at atmospheric pressure. The key results are:

1. For an annular tube, either of which is heated, the

role of heated equivalent diameter on CHF is important.

2. The characteristic of CHF depends on whether annular space is large or not, as shown in Fig. 1.
3. The CHF can be predicted well for the clearance of $S = 1$ mm by Eq. (3) and of $S \geqslant 3$ mm by Eq. (1).

Acknowledgements

The authors express their appreciation to Mr K. Nakashima for his valuable assistance in making experimental apparatus and Mr Y. Izumi and Mr K. Tsumura for their valuable assistance in collecting data.

References

[1] M. Monde, K. Yamaji, Critical heat flux during natural convective boiling in a vertical uniformly heated tubes submerged in saturated liquid, J. of Heat Transfer 90 (2) (1990) 111–116.

[2] M. Monde, Y. Mitsutake, S. Kubo, Critical heat flux during natural convective boiling on uniformly heated inner tubes in vertical annular tubes submerged in saturated liquid, Wärme- und Stoffübertragung 29 (1994) 271–276.

[3] M.A. Islam, M. Monde, M.Z. Hasan, Y. Mitsutake, Experimental study of CHF in concentric-tube open thermosyphon, Int. J. Heat Mass Transfer 43 (1998) 3691–3704.

[4] M. Monde, T. Inoue, Y. Mitsutake, Critical heat flux in pool boiling on vertical heater, Heat and Mass Transfer 32 (1997) 435–440.

[5] Y. Katto, Generalized correlations of critical heat flux for the forced convection boiling in vertical uniformly heated annuli, Int. J. Heat Mass Transfer 24 (1981) 541–544.

[6] M.M. Shah, A general correlation for critical heat flux in annuli, Int. J. Heat Mass Transfer 23 (1980) 225–234.

[7] J.G. Collier, in: Convective Boiling and Condensation, 2nd ed., McGraw-Hill, 1981, p. 135.