Critical heat flux during natural convective boiling on uniformly heated inner tubes in vertical annular tubes submerged in saturated liquid

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Abstract. An experimental study has been made of critical heat flux (CHF) of natural convective boiling on uniformly heated inner tubes in vertical annular tubes. The experiment was performed at a pressure of $P = 0.1$ to $3.1$ MPa for the clearance of $0.4$ to $4.0$ mm, the heated tube diameter of $5$ to $10.6$ mm, the annular tube length of $L = 58$ to $840$ mm and three kinds of liquids. The effects on the CHF are mainly discussed about the pressure in which the density ratio of the test fluid $\rho_v/\rho_l$ varies from $6.24 \times 10^{-4}$ to $0.16$ and of the ratio of $L/D_{he} = 2$ to $500$, where an equivalent heated length, $D_{he}$, serves as a parameter connecting the clearance with the heated tube diameter. The experiment shows that the CHF obtained depends on the ratio of $L/D_{he}$, and then a generalized correlation can be derived predicting the CHF data well.

Kritische Wärmestromdichte beim Sieden unter natürlicher Konvektion an gleichförmig beheizten Innenrohren vertikaler Ringrohre

Zusammenfassung. Die kritische Wärmestromdichte (CHF) beim Sieden unter natürlicher Konvektion an gleichförmig beheizten Innenrohren senkrechter Ringrohre wurde experimentell untersucht, und zwar bei Drücken von $P = 0.1$ bis $3.1$ MPa, Spaltweiten von $0.4$ bis $4.0$ mm, Durchmessern des beheizten Rohres von $5$ bis $10.6$ mm, Längen des Ringrohres von $L = 58$ bis $840$ mm und mit drei Arten von Flüssigkeiten. Die Einflüsse auf die „CHF“ werden hauptsächlich in dem Druckbereich diskutiert, bei welchem das Dichteverhältnis der Testflüssigkeit, $\rho_v/\rho_l$, zwischen $6.24 \times 10^{-4}$ und $0.16$ variiert und das Verhältnis $L/D_{he} = 2$ bis $500$ reicht. Die äquivalente beheizte Länge $D_{he}$ stellt dabei einen Parameter dar, welcher die Spaltweite mit dem Durchmesser des Heizrohres in Beziehung bringt. Die Experimente belegen, daß die erhaltenen CHF-Werte vom Verhältnis $L/D_{he}$ abhängen, woraus sich eine verallgemeinerte Beziehung herleiten läßt, welche die CHF-Daten gut vorausberechnen erlaubt.

Nomenclature

- $D_{he}$: equivalent heated length
- $D_i$: outer diameter of a heated tube
- $D_o$: inner diameter of outer tube
- $g$: gravitational acceleration
- $H_{fg}$: latent heat of evaporation
- $K$: constant ($=0.16$)
- $L$: length of the heated tube or surface in flow direction
- $P$: system pressure
- $q_c$: critical heat flux for saturated boiling
- $s$: clearance of annulus

$\phi$: Kutateladze number

$$\phi = \left(\frac{q_c}{\rho_l H_{fg}}\right)^{1/\gamma} g (\rho_l - \rho_v)/\rho_l$$

$\rho_l$: density of saturated liquid

$\rho_v$: density of saturated vapor

$\sigma$: surface tension

1 Introduction

The critical heat flux (CHF) during ordinary pool boiling on an open heated surface has been studied rather extensively, and then generalized correlations, that are applicable to the critical heat flux data for many kinds of fluids, have been derived by Kutateladze [1], Rohsenow and Griffith [2], Zuber [3], Chang and Snyder [4], Zuber et al. [5], and others. Lienhard and Dhir [6, 7], furthermore, developed hydrodynamics concept proposed by Zuber for the critical heat flux on both large and small heaters, and on finite horizontal flat plates.

On the other hand, researches on the critical heat flux during natural convective boiling in confined channels are 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. In these cases, owing to the complexity of the flow mode, no correlation for the CHF has been evolved that can be applied universally to CHF data for various fluids and conditions.

Under such a condition, Katto [8] proposes a clue for analyzing characteristic of the CHF during natural convective boiling in confined channels with the aid of dimensional analysis. On the basis of his proposal, the CHF can be categorized into four kinds, depending on a geometry of the channels and a flow pattern in the channel. The CHF, for example during the natural convective boiling in vertical uniformly heated tube submerged into the saturated liquid has been measured by Katto and Kawamura [9] for water and R12 under high pressures, by Lehongre et al. [10] for liquid helium (LHe) at atmospheric pressure, and by Monde and Yamaji [11] for water, R113, and R12 under high pressures.
In connection with the CHF in the vertical tubes, the CHF in vertical rectangular and annular channels which are regarded as a similar configuration to the vertical tube, has been widely measured for cryogenic liquids (He, H₂, and N₂) in relation to superconducting devices. Sydoriak and Roberts [12], Lehongre et al. [10], and Vishnev et al. [13] measured the CHF in vertical annular channels, and Ogata et al. [14], Bailey [15], and Jahannes and Mollard [16] measured the CHF in vertical rectangular channels. All of them propose empirical correlations only for their own CHF data. On the other hand, as for the CHF for liquids except for cryogenic liquids and annular channels, Bogaardt et al. [17] measured the CHF for water in a long vertical annular channel and Monde et al. [18] measured the CHF for four different liquids (water, ethanol, R113, and benzene) in vertical rectangular channels at atmospheric pressure. It is pointed out, however, that there are still interesting problems about the CHF characteristics between the vertical tubes, rectangular channels, and annular tubes.

On the other hand, the CHF in a two phase thermosyphon [19–26] has been extensively made as compared with the CHF during the natural convective boiling. Some generalized correlations for the CHF have been derived experimentally and theoretically.

In the present study, in order to elucidate the characteristic of CHF, the CHF has been measured for water, R113, and R22 in vertical uniformly heated tubes (the tube length of \( L = 0.058 \) to \( 0.84 \) m, the heated tube diameter of \( D = 0.005 \) to \( 0.0106 \) m, the clearance of annulus \( s = 0.4 \) to 4.0 mm and \( L/D_{he} = 2 \) to 500) at a pressure of 0.1 MPa for water, of 0.11 to 0.4 MPa for R113, and of 0.7 to 3.1 MPa for R22. A generalized correlation predicting the CHF data will be proposed and then the characteristic of the CHF will be compared with those in vertical rectangles, annuli, and tubes.

### Table 1. Experimental range

<table>
<thead>
<tr>
<th>Test liquid</th>
<th>Water</th>
<th>R113</th>
<th>R22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [mm]</td>
<td>50–840</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter [mm]</td>
<td>5.0, 8.0, 10.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearance [mm]</td>
<td>0.4–4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( L/D_{he} )</td>
<td>2–500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure [bar]</td>
<td>1</td>
<td>1–4</td>
<td>11–31</td>
</tr>
<tr>
<td>( \rho_c/\rho_l )</td>
<td>( 6.24 \times 10^{-4} )</td>
<td>0.00491–0.0179</td>
<td>0.0256–0.16</td>
</tr>
</tbody>
</table>

#### 2 Experimental apparatus and procedure

Figure 1 shows the whole system of the experimental apparatus, consisting of three essential portions; a pressure vessel (see Fig. 2) for storing the saturated liquid at high pressure and settling a test tube in the center position, an electric...