28. CHF CORRELATIONS RELATED TO THE CORE COOLING OF A RESEARCH REACTOR

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ABSTRACT

Critical heat flux (CHF) at low flow condition can become important in a research reactor under a number of accident conditions. Regardless of the initial stages of these accidents, a similar condition, which is basically the decay heat removal by natural convection boiling, can develop. Under such conditions, burnout may occur even at a very low heat flux. In view of this, the low-flow CHF has been studied to provide a better understanding of the dryout behavior.

The experimental results under atmospheric pressure indicate that a CHF can occur at much lower heat flux than pool-boiling CHF or than predicted by the conventional correlations. This fact indicates that a special care should be taken in analyzing the boiling phenomenon which occurs when the coolant flow is very low in a low pressure system.

INTRODUCTION

In order to design or to allow possible correction of a system to overcome the occurrence of burnout, critical heat flux (CHF) under various conditions must be known. Critical heat flux for water flowing in a vertical rectangular channel is important in relation to the core cooling of MTR-type research reactors. Most of the CHF correlations developed so far for rectangular channels are applicable only to systems at high flow rate and positive subcooling at the burnout position as shown in Table 1. This is because the main emphasis in reactor safety has been directed to more drastic accident conditions.

However, it is noted that accidents which lead to the decay heat removal by natural convection have much higher probability than those of severe accidents extensively studied so far. The decay heat removal by natural convection can become important under a number of different accident conditions such as loss-of-heat sink (LOHS), loss-of-flow (LOF) and loss-of-coolant accidents (LOCA) in various types of liquid cooled nuclear reactors. Regardless of the initial stages of these accidents, a similar condition, which is basically the decay heat removal by natural convection boiling, can develop. Under such conditions, burnout may occur at a low heat flux.

In addition to this, a flow reversal condition is encountered in many MTR-type research reactors during a flow transient after shutdown. During this period, the coolant flow becomes so low that if the flow rate is mismatched with the decay heat removal, a CHF may occur.

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Table 1. Applicable ranges of critical heat flux correlations.

<table>
<thead>
<tr>
<th></th>
<th>Mirshak et al.</th>
<th>Zenkevich et al.</th>
<th>Bernach</th>
<th>Labuntsov</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Dia. (mm)</td>
<td>5.33 - 11.7</td>
<td>4.06 - 11.9</td>
<td>&lt; 30.5</td>
<td>______</td>
</tr>
<tr>
<td>Heated length (cm)</td>
<td>48.3 - 61.0</td>
<td>18.5 - 160</td>
<td>______</td>
<td>______</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>1.8 - 6</td>
<td>105 - 220</td>
<td>0.3 - 211</td>
<td>1 - 200</td>
</tr>
<tr>
<td>Subcooling (°C)</td>
<td>5 - 75</td>
<td>&gt; 10</td>
<td>0 - 182</td>
<td>0 - 240</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>1.52 - 13.7</td>
<td>______</td>
<td>0.09 - 47.6</td>
<td>0.7 - 45.0</td>
</tr>
<tr>
<td>Mass Velocity (kg/m²s)</td>
<td>______</td>
<td>&gt; 270</td>
<td>______</td>
<td>______</td>
</tr>
</tbody>
</table>

Among the CHF correlations for vertical rectangular channels, the Macbeth correlation\(^7\) and the Katto correlation\(^8\) are applicable to both high and low flow rates. They are, however, based on the experimental data at higher pressures than expected under such conditions mentioned above. The data on the CHF for low-flow-rate/low-pressure conditions are lacking, and no correlation is available at present. This is partly because various flow instabilities due to boiling may have significant effects on the CHF at low pressure\(^9\)-\(^11\).

In view of the above, an experimental study has been performed recently for the CHF at low-flow/low-pressure conditions. This report describes the experiment briefly and provides the results obtained from it and some considerations on the CHF correlations for the safety analysis of research reactors.

PREVIOUS WORKS

As mentioned above, the CHF correlations\(^1\)-\(^4\) widely used for research reactors are applicable when the flow rate is high and the subcooling at the burnout position is positive. It is noted that under such conditions, burnout occurs due to vapor-blanketing on the heated wall. The guidebook\(^12\) published by the International Atomic Energy Agency (IAEA) in 1980, however, extrapolated the CHF at low velocities based on the Mirshak correlation\(^1\) and the Labuntsov correlation\(^4\) suggesting that the CHF approaches to the pool-boiling CHF at very low coolant velocities.

On the other hand, the CHF at low flow rate may be deduced also from the Macbeth correlation\(^7\) and the Katto correlation\(^8\), although they are applicable only to higher pressure conditions. As pointed out by Katto, their correlations at low flow rate predict the CHF caused by the permanent dryout of the liquid film on the heated wall. Therefore, the CHF occurs at high quality by this mechanism. According to these correlations, the CHF at a very low flow rate is roughly proportional to the mass velocity, contrary to the suggestion by the IAEA guidebook\(^12\).

Recently, Monde et al.\(^13\) obtained the CHF during natural convection boiling in vertical rectangular channels submerged in saturated liquid and heated from one side. Their data were correlated by the following equation:

\[ Q_{\text{CHF}} = f(\text{mass velocity}) \]
where \( q_c \) : the critical heat flux, \( \rho_v \), \( \rho_l \) : the densities of the vapor and the liquid, respectively, \( h_f \) : the latent heat of vaporization, \( \Delta \rho \) : the difference of the densities of two phases, \( \sigma \) : the surface tension, \( g \) : gravity, \( L_h \) : heated length, \( s \) : thickness of the channel. Equation (1) suggests that the CHF at very low flow rates becomes independent of the flow rate and approaches to a certain value which is generally much smaller than pool-boiling CHF.

It is well known that for a vertical channel with a complete blockage, the CHF occurs due to flooding. In this case, liquid flows down from the top and the vapor generated in the heated section flows upward. When the heat flux becomes sufficiently high, the high vapor flow remarkably reduces the liquid penetration into the heated section, thus causing a dryout. The CHF can be calculated by using the flooding correlation of Wallis and is given by

\[
q_c = \frac{C^2 h_f \rho_v g \Delta \rho D}{A_h^2 \left[ 1 + \left( \frac{\rho_v}{\rho_l} \right)^{2/3} \right]^2}
\]

where \( D \) : hydraulic equivalent diameter, \( A \) : flow area, \( A_h \) : heated area, \( C \) : constant = 0.725 to 1 depending on the entrance geometry.

In addition to these, Mishima and Ishii recently observed in an internally heated annulus that the CHF at low mass velocity occurred due to the flow regime transition from churn to annular flow. Based on the criterion for the flow regime transition, the CHF was calculated by

\[
q_c = \left( \frac{A}{A_h^2} \right) h_f \left[ G \Delta h_f \right] + \left( 1/C_0 - 0.11 \right) \frac{\rho_v g \Delta \rho D}{A_h^2 \left[ 1 + \left( \frac{\rho_v}{\rho_l} \right)^{2/3} \right]^2}
\]

where \( G \) : mass velocity, \( \Delta h_i \) : inlet subcooling. \( C_0 \) is the distribution parameter given by

\[
C_0 = 1.2 - 0.2 \frac{\rho_v}{\rho_l}
\]

The second term in Eq.(3) is almost equal to the flooding CHF predicted by Eq.(2) at low pressures, thus Eq.(3) approaches to Eq.(2) at very low mass velocity. On the other hand, when the mass velocity and the inlet subcooling is high, the second term in Eq.(3) can be neglected. This indicates that the exit quality at burnout is very low in contrast to the high-quality CHF correlations and that the CHF given by Eq.(3) can be much lower than predicted by those correlations.

The predictions by the above correlations are compared for a research reactor condition in Fig.1.
In this figure, $q^*$ and $G^*$ are non-dimensional critical heat flux and mass velocity, respectively, and defined by the following equations:

\begin{align}
q^* &= \frac{q}{(h_{fg} \sqrt{\lambda p g \Delta \rho})}, \\
G^* &= \frac{G}{(\sqrt{\lambda p g \Delta \rho})}, \\
\lambda &= \sqrt{\frac{\sigma}{(g \Delta \rho)}}.
\end{align}

Using Eq. (5) the pool-boiling CHF correlation\textsuperscript{17-18} can be written in a simple form as follows,

$$q^* = 0.16.$$  

It can be seen from Fig. 1 that at low pressure with typical geometrical conditions for research reactors, the flooding CHF is remarkably lower than the pool-boiling CHF as well as the high-quality CHF\textsuperscript{7-8}.

**EXPERIMENTAL**

**Test Procedure**

The test loop consisted of a test section, an upper and a lower plenum, a downcomer (water tank), a bypass, a circulating pump, flow control valves, three turbine flowmeters and a pipeline connecting these components as shown in Fig. 2.

Two types of rectangular test sections were fabricated for the experiment. The cross section of the first test section is shown in Fig. 3. The flow channel is 2.4 mm in thickness and 40 mm in width. A 30 mm-wide, 350 mm-long stainless steel heater is mounted on one wall. The opposite wall consists of a transparent Pyrex plate which enables us to observe the flow regime. Ten Chromel-Alumel thermocouples are spot-welded onto the inside of the heater at an interval of 35 mm along the centerline. These thermocouples are connected to burnout detectors which actuate a relay to switch off the power to the test section as soon as the heater temperatures rise beyond a preset value due to the occurrence of burnout.

The flow channel of the second test section has the same dimension as the first one but is heated from a pair of
parallel heaters on both sides of the channel. The heaters are fabricated in the same manner as described above.

The power to the test section was supplied by a 20V, 1200A, dc power supply and heat input was calculated from the voltage drop across the test section and that across the on-line shunt rated at 15V/1500A.

The loop was filled with ion-exchanged water. To avoid over pressure in the loop, the vent valve on top of the water tank was left open during the test. Thus all the measurements were carried out under atmospheric pressure.

The inlet water flow rate was adjusted by the valves in the inlet pipe. The flow orientation can be set either upward or downward by using the valves in the pipeline.

The temperatures at the end of the heater, the inlet flow rate and the voltages from the power supply were recorded by a strip chart. A large abrupt increase in the temperature trace was observed at the occurrence of burnout.

Experimental Results

Test Section Heated from One Side

The critical heat fluxes measured in the test section with one heater are shown in Fig.4. The abscissa represents the mass velocity, which is positive for upward flow and negative for downward flow. The figure shows that there is a minimum in the CHF at complete bottom blockage and low downward flow. The visual observation indicated that this minimum CHF occurred due to flooding and is correlated by the following equation similar to Eq.(2),

\[ q_f = \frac{0.7Ah_f \sqrt{g \Delta \rho w}}{A_h [1 + (\rho_g/\rho_l)^{1/2}]^2} \quad (9) \]

where \( w \) : width of the flow channel, \( q_f \) : CHF due to flooding. For a downward flow, we need to take account of the effect of inlet subcooling, hence Eq.(9) becomes

\[ q_c = q_f [1 + 2.9 \times 10^5 (\Delta h_l/h_{fg})^{0.5}] \quad (10) \]

The minimum CHF in the downward flow appears at mass velocities up to about -200kg/m².s. This is because the vapor bubbles are stagnated in the heated section by the downward liquid flow at that mass velocity. The critical mass velocity which causes the bubble stagnation can be estimated as follows. The bubble drift velocity \( V_{bj} \) in the churn-turbulent flow regime is \( 16 \)

![Fig.4 Critical heat flux for the test section heated from one side.](image-url)
\( V_{gj} = (C_0 - 1) j + \sqrt{g/\rho} (\rho g \Delta \rho / \rho_1)^{1/2}, \) \hspace{1cm} (11)

where \( j \): volumetric flux of the vapor liquid mixture. With the condition that bubble velocity is zero, one obtains for the critical mass velocity \( G_c \),

\[ G_c = -\sqrt{2}(\rho_1^2 \rho g \Delta \rho)^{1/2}/C_0. \] \hspace{1cm} (12)

The distribution parameter \( C_0 \) for a rectangular channel is given by \( C_0 = 1.35 - 0.35V/P_{\rho g/\rho_1}. \) \hspace{1cm} (13)

Using these equations, the critical mass velocity for the present test section becomes \(-159\) kg/m²s which roughly agrees with the observation. Below the critical mass velocity, the vapor flows upward against the liquid flow, leading to a flooding burnout. On the other hand, beyond the critical mass velocity, the vapor bubbles are forced downward and the CHF increases with increasing mass velocity (downward). In this region the flow looks like annular flow but the boiling boundary oscillates violently. Thus the CHF occurs as soon as the exit equilibrium quality exceeds zero. Hence, the CHF in this region can be estimated by

\[ q_c = \Delta h_i G/A_h \] \hspace{1cm} (14)

when the mass velocity is positive, the CHF increases monotonically with increasing mass velocity. The influence of the inlet subcooling is not clear in this case. Then the CHF can be tentatively correlated by

\[ q_c = q_f + 1.46 \times 10^{-3} h_{fg} G, \] \hspace{1cm} (15)

which is similar to Eq.(3).

**Test Section Heated from Both Sides**

The measured CHF in the test section heated with two heaters is shown in Fig. 5. In this case, although the range of the tested flow rate is narrower than in the case with one heater because of the limitation on the power supply, the CHF seems to behave as in the case with one heater. Then the minimum CHF occurs due to flooding and is correlated by

\[ q_f = \frac{0.5A_h \sqrt{\rho g \Delta \rho w}}{A_h [1 + (\rho / \rho_1)^{1/2}]^2}. \] \hspace{1cm} (16)

If one takes account of the effects of inlet subcooling, one may use Eq.(10) together with Eq.(16). Equation (16) gives lower CHF than Eq.(9). This is mainly because the inlet restriction at the upper end is larger in the test section with

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**Fig. 5** Critical heat flux for the test section heated from both sides.
two heaters. It is noted, however, that the geometrical condition at the upper end of the coolant channel in a research reactor is more like that in the test section with one heater. Furthermore, the CHF due to flooding may be the same with the other conditions unchanged, because the flooding phenomenon depends only on the total power input to the heated section. Hence it is recommended to use Eq.(9) for research reactors.

When the mass velocity becomes higher in downward flow, the inlet flow oscillates just as observed in the test section with one heater, and the CHF can be correlated by Eq.(14).

The CHF for upward flow in this case is tentatively correlated by

$$q_c = q_f + 1.6 \times 10^{-3} h_f G$$  
(17)

where \(q_f\) is given by Eq.(16).

**DISCUSSION**

The experimental results above described are compared to the conventional correlations. The comparisons are made in terms of the non-dimensional CHF and mass velocity defined by Eqs.(5) and (6), respectively. Figures 6 and 7 demonstrate the non-dimensional plots of the CHF data at fixed inlet subcooling for the test section heated from one side and the comparison to the other correlations. The Kutateladze correlation\(^1\) for high flow CHF at low pressure is also used in the comparison. The Mirshak correlation\(^2\) and the Labuntsov correlation\(^3\) are used beyond their applicable ranges, postulating that when exit equilibrium quality is positive, the subcooling at the burnout position is zero. The bold lines in the figures represent the transition boundary from the churn to annular flow. The criterion for the transition in a rectangular channel is calculated by combining Eqs.(3) and (9), therefore,

$$q_c = q_f + \Delta h G/A_H$$  
(18)

![Fig. 6 Non-dimensional plot of CHF data at inlet temperature 30°C for the test section heated from one side in comparison with several CHF correlations.](image)

![Fig. 7 Non-dimensional plot of CHF data at inlet temperature 85°C for the test section heated from one side in comparison with several CHF correlations.](image)
It can be seen from these figures that neither pool-boiling CHF correlations\(^7\)\(^-\)\(^8\) nor high-quality CHF correlations\(^7\)\(^-\)\(^8\) can reproduce the CHF at low mass velocity which is much lower than predicted by those correlations.

In the upward flow, the CHF is close to the transition boundary from the churn to annular flow, Eq.(18), at high inlet subcooling, while it is between the high-quality CHF and the churn-annular flow transition boundary at low inlet subcooling. At very low flow rate, the CHF approaches to the flooding CHF, Eq.(9). The Monde correlation\(^13\) for natural convection boiling CHF also agrees well with the flooding CHF. At high mass velocities, the CHF curve appears to merge with the Labuntsov correlation\(^4\). The Mirshak correlation\(^1\) should be properly used for downward flow because it is obtained from the downflow experiment.

In the downward flow, the CHF at low mass velocities can be correlated by two lines calculated by Eqs.(10) and (14), representing the flooding CHF and the condition that the exit equilibrium quality is zero, respectively. At high mass velocities, the Mirshak correlation\(^1\) will hold.

The same discussion can be followed for the CHF with two heaters as shown in Fig.8. Slightly different constants were obtained in the resultant correlations between one-side and both side heating. The CHF for upward flow, Eqs.(15) and (17) may depend on the heater geometry. However, for the burnout due to flooding, the CHF may be the same with the other conditions unchanged as noted before.

The reason for the discrepancy between the experimental data and the high quality CHF correlations\(^7\)\(^-\)\(^8\) is not known at present. However, it is pointed out that the CHF at low flow rate is very sensitive to various parameters such as the system pressure, the geometry of the channel, inlet valve throttling, the pump characteristics. Particularly at low pressures, the flow easily becomes unstable due to boiling, which may result in a premature burnout\(^9\)\(^,\)\(^11\). Therefore, further studies are needed to know the general criteria to tell which mechanism causes a burnout at a given condition.

**SUMMARY AND CONCLUSIONS**

As previously described, the CHF obtained from the experiment with rectangular channels under low-flow-rate/low-pressure conditions appeared to be much lower than predicted by conventional correlations. The minimum CHF occurred at a complete bottom blockage and at mass velocities less than \(G\) given by Eq.(12) in downward flow which causes a bubble stagnation in the heated section. Attention
should be paid to this fact because a similar condition may develop in a research reactor prior to the flow reversal after the shutdown of the reactor. Furthermore, it is noted that a complete top blockage has not been tested in this experiment, although it is more likely to occur in a research reactor and may lead to more pessimistic consequences than the bottom blockage.

Based on the above discussions, the following recommendations are made for the CHF correlations for rectangular channels at low pressure.

In a downward flow,
(1) the Mirshak correlation\(^1\) is relevant at high flow rate,
(2) the CHF at intermediate flow rate can be determined by the condition that the exit equilibrium quality is zero, resulting in Eq.(14),
(3) the CHF at low mass velocities less than \(G_c\) given by Eq.(12) occurs due to flooding and is correlated by Eq.(10).

In an upward flow,
(1) the Labuntsov correlation\(^2\) or the Kutateladze correlation\(^3\) can be used at high flow rate,
(2) the CHF at low flow rate is tentatively correlated by Eqs.(16) and (18), which may be modified depending on the geometry. The lower boundary may be given by Eq.(18) corresponding to the churn-annular flow transition.

It should be noted here that these results are obtained for steady inlet-flow condition and may be valid also for a slow transient. However, under a rapid transient conditions, it is probable that no burnout occurs even if the steady-flow CHF condition is exceeded.

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