CRITICAL HEAT FLUX OF FORCED FLOW BOILING IN A NARROW ONE-SIDE HEATED RECTANGULAR FLOW CHANNEL

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Critical Heat Flux of Forced Flow Boiling in a Narrow One-side Heated Rectangular Flow Channel

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The present work deals with the critical heat flux (CHF) under subcooled flow boiling in a narrow one-side uniformly heated rectangular flow channel. The range of interest of parameters such as pressure, flow velocity and subcooling is around 0.1 MPa, 5–15 ms⁻¹ and 50° C, respectively. The rectangular flow channel used is 50 mm long, 12 mm in width and 0.2 to 3 mm in height. Test conditions were selected by combination of the following parameters: Gap = 0.2–3.0 mm (Dyy = 0.3934–4.8 mm); flow length, 50.0 mm; water mass flux, 4.94–14.82 Mgm⁻²s⁻¹ (water flow velocity, 5–15 ms⁻¹); exit pressure, 0.1 MPa; inlet temperature, 50° C; inlet coolant subcooling, 50° C. Over 40 CHF stable data points were obtained. CHF increased with the gap and flow velocity in a non-linear fashion. HTC increased with flow velocity and decreasing gap. Based on the experimental results, an empirical correlation was developed, indicating the dependence of CHF on the gap and flow velocity. All of data points predicted within ±18% error band for the present experimental data. On the other hand, another similitude-based correlation was also developed, indicating the dependence of Boiling number (Bo) on Reynolds number (Re) and the variable of Gap/La, where La is a characteristic length known as Laplace capillary constant. For the limited present experimental data, all of data points were predicted within ±16%.

Keywords: CHF, One-side Heated Rectangular Channel, Boiling Curve, Burnout, Gap Effect, Forced Convection, CHF Correlation, Prediction

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* Shanghai Nuclear Engineering Research & Design Institute (SNERDI)
片面加熱矩形流路における強制対流限界熱流束

日本原子力研究所東海研究所原子炉工学部

鄭 利民*・井口 正・呉田 昌俊

秋本 誠

（1997年 7月16日受理）

本研究は、片面一様加熱の矩形流路において強制対流サブクール沸騰条件下的限界熱流束（CHF）を扱ったものである。本研究では、圧力、冷却水流速、冷却水サブクール度を試験条件とし、それぞれ0.1MPa、5-15m/s、50℃とした。試験に用いた流路は、縦0.2-3.0mm、横2mmの矩形流路で、横方向流路壁を片面加熱した。流路の垂直方向（冷却流れ方向）加熱長さは50mmである。試験は、流路縦寸法をパラメトリックに変えて行い、40点を超える試験データを得た。

CHFは、流路縦寸法及び冷却水流速の増加とともに、非直線的に増加した。熱伝達率は、流路縦寸法の減少及び冷却水流速の増加とともに、増加した。試験結果に基づき、流路縦寸法及び冷却水流速の効果を表すCHF相関式を開発した。本相関式によれば、予測値と試験データは±18%の範囲で一致した。一方、冷却水流速効果の尺度としてレイノルズ数（Re）、流路縦寸法効果の尺度として流路縦寸法とラプラス定数（La）の比を用いて、CHFを無次元化したボイリング数（Bo）との関係を数式化することにより、CHFを予測する相関式を開発した。本相関式によれば、予測値と試験データは±16%の範囲で一致した。
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1. INTRODUCTION

Subcooled flow boiling has been widely investigated in the past. As well known, forced convection subcooled boiling involves a local-boiling liquid, whose bulk temperature is below the saturation, flowing over a surface exposed to a high heat flux, and is one of the most efficient techniques of removing high heat fluxes. However, successful use of subcooled flow boiling with high heat fluxes requires avoiding the critical heat flux (CHF). The occurrence of CHF, for the case of heat flux controlled systems, results in a significant increase in the wall temperature well above that at which serious damage or "burnout" of heating surface occurs.

The present work deals with CHF under subcooled flow boiling in a narrow one-side uniformly heated rectangular flow channel. The range of interest of parameters such as pressure, flow velocity and subcooling is around 0.1 MPa, 5–15 m/s and 50°C, respectively. The rectangular flow channel used is 50 mm long, 12 mm in width and 0.2 to 3 mm in height. The present paper reports the results of the experimental investigation of CHF under the experimental conditions mentioned above. The effects due to the variation of geometric and thermal-hydraulic parameters (gap, flow velocity) on the heat transfer and CHF are also presented together with comparison of the experimental data with existing correlations.
2. SUMMARY OF PREVIOUS WORKS

CHF condition in subcooled boiling of water has been investigated by numerous researchers \[1,2,3,4,5\]. Some test facilities were developed to perform forced convective, subcooled boiling heat transfer and pressure drop studies. Available correlations and models have been established based on the experimental data for the prediction of CHF in subcooled flow boiling in the range of interest of fusion reactors thermal–hydraulic conditions, i.e. high inlet liquid subcooling and flow velocity and small diameter and length in round tubes.

Previous experimental conditions and results are shown as follows:


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference 1</th>
<th>Reference 2</th>
<th>Reference 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flux (Mg/m²s⁻¹)</td>
<td>5.0 to 50.0</td>
<td>2.0 to 90.0</td>
<td>11.0 to 40.0</td>
</tr>
<tr>
<td>Exit Pressure (MPa)</td>
<td>0.1 to 2.2</td>
<td>0.1 to 8.4</td>
<td>0.6 to 2.5</td>
</tr>
<tr>
<td>Subcooling (°C)</td>
<td>0 to 150.0</td>
<td>90.0 to 230.0</td>
<td>50.0 to 136.0</td>
</tr>
<tr>
<td>Length-to-diameter</td>
<td>1.0 to 100.0</td>
<td>10.0 to 200.0</td>
<td>about 40</td>
</tr>
<tr>
<td>Max. CHF (MW/m²)</td>
<td>350.0</td>
<td>3.3 to 224</td>
<td>60.6</td>
</tr>
</tbody>
</table>

CHF increased with increasing subcooling and mass flux in a non-linear fashion. For exit pressure of 0.2 to 2.2 MPa, CHF is only weakly dependent on pressure, and a slight decrease in the CHF value is noted. Over a diameter range from 0.3 to 3 mm, CHF is increased by a factor of two with decreasing diameter; the effect of decreased diameter is a function of mass flux and subcooling. The effect of length-to-diameter ratio was studied by performing experiments for values ranging from 1 to 200. Increases in CHF are only noted for length-to-diameter ratios less than 10 \[2\].

With the aim of establishing the bounds of validity of existing predictive tools for the calculation of CHF in subcooled flow boiling, four correlations (Levy, Westinghouse, modified–Tong, and Tong–75) and three models (Weisman and Ileslamlou, Lee and Mudawar and Katto) have been statistically analysed using 24 data sets by Celata \[3\]. Among the correlations, a very good agreement with experimental data is shown by the modified–Tong correlation characterized by a very good statistics (76.5% of predictions are within ±25% error band) and by an r.m.s. error of 21.2%. Westinghouse correlation provides a fairly good prediction, even though below the performance of modified–Tong correlation. Other correlations show a fairly good agreement with many experimental data, but are unreliable when used very far from the recommended applicable ranges as shown below. Among the models, a very good prediction of experimental data is provided by the Katto model which is characterized by good statistics (72.3% of predictions are within ±25% error band) and by a r.m.s. error of 24.5%.
Among the tens of predictive tools available in literature, the modified-Tong and Westinghouse correlations and Katto model seem to be reliable predictive tools for the calculation of the CHF in subcooled flow boiling\textsuperscript{[1,2,3,4,5]}. The applicable ranges and calculated r.m.s. errors\textsuperscript{[3]} for the promising correlations are summarized as follows:

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Westinghouse</th>
<th>modified-Tong</th>
<th>Tong-75</th>
<th>Katto</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flux (Mgm(^{-2})s(^{-1}))</td>
<td>0.3 to 11.0</td>
<td>2.2 to 40.0</td>
<td>0.7 to 6.0</td>
<td>0.35 to 40.6</td>
</tr>
<tr>
<td>Exit Pressure (MPa)</td>
<td>5.7 to 20.0</td>
<td>0.1 to 5.0</td>
<td>7.0 to 14.0</td>
<td>0.1 to 19.6</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>0.3 to 25.4</td>
<td>2.5 to 8.0</td>
<td>3.0 to 10.0</td>
<td>1.14 to 11.07</td>
</tr>
<tr>
<td>Subcooling (°C)</td>
<td>0 to 126.0</td>
<td>15.0 to 190.0</td>
<td>0 to 117.5</td>
<td></td>
</tr>
<tr>
<td>Length-to-diameter</td>
<td>21.0 to 365.0</td>
<td>12.0 to 40.0</td>
<td>5.0 to 100.0</td>
<td>1.0 to 100.0</td>
</tr>
<tr>
<td>CHF (MWm(^{-2}))</td>
<td>1.25 to 12.5</td>
<td>4.0 to 60.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r.m.s. error (%)</td>
<td>27.7</td>
<td>21.2</td>
<td>55.6</td>
<td>24.5</td>
</tr>
</tbody>
</table>
3. TEST DESCRIPTION

3.1 Description of Apparatus

The experimental facility and equipments used for this CHF experiment are as follows:

- **Power source**: DC power supply (Current : 1500 A, Voltage : 50 V)
- **CHF test facility** (including hydraulic loop, test section, etc.):
  
  | Pressure         | 0.1 MPa |
  | Max. Temperature | 100 °C  |
  | Max. Flow rate   | 40 l/min |
- **Analyzing recorder** (YOKOGAWA AR1100A)

A schematic diagram of the test facility employed is shown in Fig. 3.1-1. Major components installed in this test facility are as follows:

- Heat exchanger
- Preheater
- Feedwater pump (circulating pump)
- Flow regulator (including three flow meters):
  
  | Large flow rate (l/min): | 0 to 38 |
  | Intermediate flow rate (l/min): | 0 to 12.6 |
  | Small flow rate (l/min): | 0 to 4.24 |
- Test section (Rectangular channel):
  
  | Length (mm): | 50.0 |
  | Width (mm): | 12.0 |
  | Effective heated width (mm): | 10.0 |
  | Gap (mm): | 0.1, 0.2, 0.5, 1.0, and 3.0 |
  | Designed copper film thickness (μm): | 9.0 |

The loop is made of stainless steel and is filled with tap water passed through deionizing particulate resin beds. Temperature, pressure, and flow measuring instrumentation are installed. The feedwater pump is connected to a flow regulator (including three flow meters) to maintain stable flow conditions. And each flow meter is installed to measure the water flow rate for a certain flow rate condition. The test section is always vertically oriented with water flowing upwards, even though other test section orientations and flow directions are possible. The test section is connected to copper feed clamps, by means of which it is possible to transfer the electric current to the test section. The power is computed by evaluating the product of the voltage drop across the test section and the current flowing through the copper film of the test section. Pressure taps are placed just upstream of the inlet of the test section. The static pressure is measured by pressure transducer. The pressure at the exit of the test section is atmospheric pressure. The bulk fluid temperature is measured just upstream \( T_{\text{in}} \) and downstream \( T_{\text{out}} \), after suitable mixing of the liquid, of the test section using thermocouples. The measurement of \( T_{\text{in}} \) and \( T_{\text{out}} \) together with the water mass flow rate, allows the computation of the thermal power delivered to the fluid by the heat...
balance in the coolant. Downstream of the test section, the fluid flows into the heat exchanger (fluid-to-fluid cooled tank) and preheater, where the fluid is cooled down and regulated to 50°C, towards the feedwater pump.

3.2 Test Condition, Test Procedure, and Measurement

Present test conditions are listed as follows.

(1) Pressure (MPa): 0.1
(2) Inlet temperature (°C): 50.0
(3) Flow velocity at test section inlet (m/s): 5.0, 7.5, and 10.0
(4) Test section geometric parameters:
   • Rectangular channel
   • Length (mm): 50.0
   • Width (mm): 12.0
   • Effective heated width (mm): 10.0
   • Gap (mm): 0.1, 0.2, 0.5, 1.0, and 3.0
   • Designed copper film thickness (μm): 9.0

Before CHF experiment, the fluid in the loop was preheated until its temperature increases and reaches a desired value (50°C). Then CHF experiment was started.

In CHF experiment, all of the parameters are continuously monitored using digital and analogue displays, and each variation is recorded. The experimental procedure consists of the following actions. First, the mass flow rate is set up using the manual control of the pump. Secondly, the mass flow rate is regulated to a desired value by using the manual control of the opening ratio of the bypass valve. Once flow rate and exit pressure are steady, power is added to the test section. And then the power is increased gradually by increasing the current and voltage across the test section. After each increment, small adjustment is made in the flow rate, so that the inlet flow conditions correspond to the desired ones. The procedure mentioned above is repeated until burnout occurs, evidenced by test section destruction and detected by the sharp drop in the electrical power.

In the present CHF experiments, eight parameters are recorded into the floppy disc with the analyzing recorder. These are as follows.
   • Volumetric flow rate;
   • Electric voltage across the test section;
   • Electric current of the test section;
   • Electric power of the test section;
   • Inlet coolant temperature of the test section;
   • Outlet coolant temperature of the test section;
   • Electric voltage across the test section node No.1;
   • Electric voltage across the test section node No.2.
Note: The node No.1 is just located nearby and upstream of the exit of the test section, and node No.2 is just located nearby and upstream of the node No.1 of the test section. The flow length for each node (node No.1 or No.2) is 10 mm. (See Fig. 3.1-1)

3.3 Description of Data Processing

During CHF experiments, the experimental data except for the inlet and outlet coolant temperature are recorded in the units of electric voltage. Therefore, it is necessary to do some unit conversion calculation in order to restore the physical values of these parameters.

In order to restore the experimental parameters, some programs (AR2OA, READO and WRITEO) are developed and used to convert the experimental data recorded on the floppy disc into the physical values of the experimental parameters and to produce some additional necessary parameters. In this way, all of the necessary experimental parameters can be obtained. These are as follows.

- Time (s);
- Volumetric flow rate (l/min);
- Electric voltage across the test section (V);
- Electric current of the test section (A);
- Electric power of the test section (kW);
- Inlet coolant temperature of the test section (°C);
- Outlet coolant temperature of the test section (°C);
- Electric voltage across the test section node No.1 (V);
- Electric voltage across the test section node No.2 (V);
- Average film temperature of the test section (°C);
- Film temperature for the test section node No.1 (°C);
- Film temperature for the test section node No.2 (°C).

The method of calculating copper film temperature (average, node No.1 and No.2) is described in Section 4.3.

After these necessary parameters are obtained, the plots which needed for analyzing experimental data can be made with plotting program.

The detailed method of data processing is described in Appendix.
Fig. 3.1-1 Schematic diagram of CHF test facility and test section
4. PRELIMINARY ANALYSIS ON DATA RELIABILITY AND UNCERTAINTY

In order to analyze the experimental results, it is necessary to evaluate the reliability and uncertainty of some important parameters, such as heat flux, film temperature and so on.

4.1 Energy Balance

As known, there are two ways to calculate the average heat flux $q''$ based on the experimental data. One is to calculate the heat flux $q''$ with the electric parameters, i.e. the heat flux $q''$ is equal to the current times the voltage over the heat transfer area. The other is to calculate the heat flux $q''$ with the thermal–hydraulic parameters, i.e. the heat flux $q''$ is equal to the mass flow rate times the enthalpy rise over the heat transfer area. Figure 4.1–1 shows the comparison between both heat fluxes (HEATFLUXA and HEATFLUXB are the predicted heat fluxes with electric and thermal–hydraulic parameters respectively). It is shown that the difference in the heat flux with the two methods mentioned above is about 10% for the present experiment.

4.2 Heat Flux and CHF Data

As mentioned, the test section is always vertically oriented with water flowing upwards and the film of the test section is uniformly heated in the experiment. Thus, the burnout should take place at the exit of the test section. Experimental CHF is calculated by using the electric parameters of the node No.1 which is just located nearby and upstream of the exit of the test section, i.e. CHF is equal to the current times the voltage over the heat transfer area. Based on the above evaluation on the energy balance, it is estimated that the uncertainty of calculating heat flux with thermal–hydraulic parameters is about 10%. Because the measured electric parameters are more accurate than measured thermal–hydraulic parameters, the uncertainty of experimental CHF should be very limited. Although it is impossible to specify the uncertainty of the experimental CHF, it is considered that the uncertainty must be much less than 10%.

4.3 Film Thickness, Temperature and Heat Transfer Coefficient

As mentioned, both electric voltage $V$ and current $I$ of test section film are measured for two nodes and the whole test section in CHF experiment. It means both voltage and current of the test section film for each node and section can be obtained from the experimental data. Therefore, the electric resistance $R$ and specific resistance $\rho_e$ of the test section film for a certain node or section can be calculated by the following equations [(4.3–1) and (4.3–2)].
\[ R = \frac{V}{I} \quad (4.3-1) \]

where:

- \( R \): Electric resistance (\( \Omega \));
- \( V \): Voltage (V);
- \( I \): Current (I).

\[ \rho_e = 1.0 \times 10^8 \text{ RS/L} \quad (4.3-2) \]

\[ S = b \delta \quad (4.3-3) \]

where:

- \( \rho_e \): Specific resistance (\( \mu\Omega \cdot \text{cm} \));
- \( R \): Electric resistance (\( \Omega \));
- \( S \): Cross section area of the test section film (m\(^2\));
- \( b \): Width of the test section film (m);
- \( \delta \): Thickness of the test section film (m);
- \( L \): Length of a certain node or test section (m).

The copper film temperature \( T_{\text{film}} \) can be looked up from the Material Property handbook (see Fig. 4.3–1 attached) in which it shows that the specific resistance \( \rho_e \) is varied along with the temperature \( T_{\text{film}} \). Thus, the test section film temperature \( T_{\text{film}} \) can be calculated.

But in the actual calculation, the calculated film temperature may be mismatch with the actual value due to the manufacture/fabrication tolerances. Therefore, it is necessary to calibrate the initial film temperature in order to determine the actual geometric parameters of the test section film especially for the thickness of the film.

In order to determine the actual film thickness of the test section, a number of measured parameters are taken as reference parameters such as inlet and outlet coolant temperature of the test section. And at first, it is assumed that the film temperature of the test section is only a little bite (for example, about 2 degree centigrade) greater than the local fluid temperature within the early stage of the experiment while given heat flux is very low and no boiling takes place. Therefore, the assumed film temperature can be obtained (i.e. \( T_{\text{film}, \text{assumed}} = T_{\text{fluid, measured}} + 2 \)). Thus, for a certain node or section, specific resistance \( \rho_{e, \text{assumed}} \) of the test section film can be looked up from the Material Property handbook. On the other hand, the electric resistance \( R \) of the test section film can be calculated by the equation (4.3–1). Therefore, the thickness of the test section film can be calculated by using equation (4.3–4), which is derived from equations (4.3–2) and (4.3–3). In this way, the mean film thickness \( \delta \) of the certain test
section within the short time can be calculated with the following equation (4.3–5).

\[ \delta_i = \frac{\rho_e, \text{ assumed}, \ i \cdot L}{1.0 \times 10^8 \ R_i \cdot b} \]  

(4.3–4)

\[ \delta = \frac{1}{n} \sum_{i=1}^{n} \delta_i \]  

(4.3–5)

where:

- \( \rho_e, \text{ assumed}, \ i \) : Specific resistance looked up from assumed \( T_{\text{film, assumed}} \) (\( \mu \Omega \cdot \text{cm} \));
- \( L \) : Length of a certain node or test section (m);
- \( R_i \) : Electric resistance for a certain time (\( \Omega \));
- \( b \) : Width of the test section film (m);
- \( \delta \) : Mean film thickness within the early stage of experiment (m);
- \( \delta_i \) : Calculated film thickness for a certain time (m);
- \( i \) : Number of the experimental data set for a certain time (–);
- \( n \) : Total number of the experimental data sets selected within the early stage of the experiment (–).

In this way, the film thickness \( \delta \) can be calculated under the assumed temperature \( T_{\text{film, assumed}} \). Therefore, the transient film temperature can be calculated by using calculated film thickness \( \delta \) in equation (4.3–3).

In order to evaluate the dependency of the calculated film thickness on assumed \( T_{\text{film, assumed}} \), the sensitive analysis was performed by assuming \( T_{\text{film, assumed}} \) as follows.

\[
\begin{align*}
T_{\text{film, assumed}} &= T_{\text{fluid}} + \Delta T \\
\Delta T &= 2, 4, 6, 8, 10, \ldots
\end{align*}
\]  

(4.3–6)

Table 4.3–1 shows the result of the calculated film thickness at a given heat flux \( q^* \) and \( \Delta T \). It is known that the calculated film thickness is almost kept as a constant as far as \( \Delta T \) is less than 10° C. The superheat \( \Delta T \) of the film is considered to be less than 10° C while the heat flux is very low and no boiling takes place. This is known from most of previous boiling curves, for example McAdams one. Thus, the assumption of 2° C in \( \Delta T \) is reasonable and acceptable for calculating the film
thickness of the test section.

Table 4.3–1 Film thickness varied with the assumed ΔT

<table>
<thead>
<tr>
<th>Film Thickness (μm)</th>
<th>ΔT (°C)</th>
<th>Variation in Film Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>4.6778</td>
<td>4.7086</td>
</tr>
<tr>
<td>Node 1</td>
<td>5.3480</td>
<td>5.3832</td>
</tr>
<tr>
<td>Node 2</td>
<td>5.4277</td>
<td>5.4635</td>
</tr>
</tbody>
</table>

Further, the sensitivity of $T_{\text{film, assumed}}$ on $T_{\text{film}}$ and heat transfer coefficient (HTC) was also evaluated. As shown in the Fig. 4.3–2, for the extreme case (i.e. ΔT = 10° C), the maximum uncertainty of 6% in $T_{\text{film}}$ due to $T_{\text{film, assumed}}$ is estimated to be the calculation error. For the present CHF experiment, the fluid temperature $T_{\text{fluid}}$ ranges from 50 to 65° C and the film temperature $T_{\text{film}}$ is about 130° C as the film burnout takes place. Thus, as the film burnout takes place, the minimum temperature difference between the film and fluid is about 65° C, and maximum error in the film temperature calculation is 8° C (=130×0.06). As known, heat transfer coefficient (HTC) is equal to heat flux $q''$ over the temperature difference between the film and fluid, i.e.

$$HTC = \frac{q''}{(T_{\text{film}} - T_{\text{fluid}})} \quad (4.3-7)$$

where

- HTC : Heat transfer coefficient; Wm$^{-2}$° C$^{-1}$
- $q''$ : Heat flux; Wm$^{-2}$
- $T_{\text{film}}$ : Film temperature; ° C
- $T_{\text{fluid}}$ : Fluid temperature; ° C

Therefore, an uncertainty in heat transfer coefficient (HTC) due to the uncertainty of $T_{\text{film}}$ is estimated to be about 12%, as follows.

Uncertainty = (Uncertainty in $T_{\text{film}}$)/(Δ$T_{\text{film}}$) = 8/65 = 12%
Run No 186; Gap = 3.0mm, Length = 50mm, Q = 21.6 ℓ/min

**Fig. 4.1-1 Heat flux vs. time**

**Fig. 4.3-1 Copper specific resistance varied with temperature**
Run no. 186: Gap = 3.0mm, Length = 50mm, Q = 21.6 ℓ/min

Fig. 4.3-2 Film temperature vs. time
5. TEST RESULT EVALUATION

5.1 General Result

In the present experiments, test conditions were selected by combination of the following parameters: gap=0.2–3.0 mm; flow length=50.0 mm; water mass flux=4.94–14.82 Mgm⁻²s⁻¹ (water flow velocity, 5–15 ms⁻¹); exit pressure=0.1 MPa; inlet temperature=50°C; inlet subcooling=50°C. Tests were carried out in order to verify the influence of a single parameter on CHF, i.e. variation of only one parameter with the other conditions being fixed. Experimental results are summarized in Table A-4.1, listing a total of 34 tests. The CHF condition is defined as the heat flux corresponding to burnout, i.e. destruction of the test section film.

Some of the experimental data were not collected in Table A-4.1, because premature burnouts or unstable CHFs were experienced. For those cases, test section film was observed to have failed prematurely or the burnout point was well upstream from the exit of the test section.

Experimental results of CHF are shown in Fig. 5.1-1, where CHF is plotted against the gap of the test section; in Fig. 5.1-2, where CHF is plotted against flow velocity. Experimental results of HTC are also shown in Fig. 5.1-3, where HTC (corresponding to film burnout) is plotted against the gap of the test section; in Fig. 5.1-4, where HTC (corresponding to film burnout) is plotted against flow velocity. Under the experimental conditions mentioned above, the highest value of CHF is 12.9 MWm⁻². Experimental results of Boiling number (Bo) are shown in Fig. 5.1-5, where Bo is plotted against Reynolds number (Re) and Gap/La. Gap/La is a non-dimensional length, where La is a characteristic length known as Laplace capillary constant, i.e. \( La = \left( \sigma / g (\rho_f - \rho_g) \right)^{0.5} \) (detailed description is given in Section 5.4). The non-dimensional length Gap/L is usually considered as an indicator for developing length. Therefore, it is widely used to indicate the degree of developing or steadiness. On the other hand, La is considered as an indicator of bubble size. For example, the bubble size generated with evaporation is described by Fritz [6] as

\[ R_b = k La \]

where \( R_b \) is bubble size, and \( k \) is an empirical factor. Thus, the non-dimensional number Gap/La is considered as an indicator of the ratio of the gap of the flow channel to the bubble size.

Examples of the boiling curves obtained in the present experiments are shown in Fig. 5.1-6. The experimental boiling curves can be classified into three types. These are as follows:

1. Typical boiling curve, which is a bend line, as shown in Fig. 5.1-6A;
2. Unclear typical boiling curve, which is a slight bend line, as shown in Fig. 5.1-6B;
(3) Non-typical boiling curve, which is a straight line, as shown in Fig. 5.1–6C.

The type of boiling curve depends on the experimental conditions. The observation results on the type of boiling curves are listed in Table 5.1–1. The typical boiling curve, where there is a crisis between forced convective heat transfer region and subcooled nucleate boiling heat transfer region, is observed under larger gap and lower flow velocity. On the other hand, non-typical boiling curve, where boiling curve tends to a straight line, is observed under smaller gap and/or larger flow velocity, demonstrating that the convective heat transfer effect becomes more significant.

Table 5.1–1 Observation results on type of boiling curves

<table>
<thead>
<tr>
<th>Gap (mm)</th>
<th>Flow velocity (ms⁻¹)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.0</td>
<td>7.5</td>
<td>10.0</td>
<td>15.0</td>
</tr>
<tr>
<td>0.2</td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>△ O</td>
<td>△ O</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>△ O</td>
<td>O</td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: × : Non-typical boiling curve was observed;  
△ : Unclear typical boiling curve was observed;  
O : Typical boiling curve was observed.

5.2 Gap and Flow Velocity Effect on CHF

Figures 5.1–1 and 5.1–2 illustrate dependency of CHF on gap and flow velocity. CHF increased with gap, and the slope was an increasing function of the flow velocity. For each value of gap, CHF increased with the flow velocity.

Figures 5.2–1 and 5.2–2 illustrate dependency of CHF on gap and flow velocity in log-scale. It was found that the experimental CHF almost varied with gap and flow velocity in log-linear fashion. The effects of gap and flow velocity on the experimental CHF can be described with the following relationship.

\[
\text{CHF}_{\text{exp}} \sim \text{Gap}^m \quad (5.2-1) \\
\text{CHF}_{\text{exp}} \sim \text{Vel}^a \quad (5.2-2)
\]
where

\[
\begin{align*}
\text{CHF}_{\text{exp}} & : \text{Experimental CHF; MWm}^{-2} \\
\text{Gap} & : \text{Gap of the test section; mm} \\
\text{Vel} & : \text{Flow velocity; ms}^{-1}
\end{align*}
\]

and \(m\) and \(n\) are experimentally determined exponents.

The exponents of \(m\) and \(n\) varies within the following ranges for the present experimental data.

\[
\begin{align*}
0.1541 < m < 0.2214 \\
0.3093 < n < 0.5645
\end{align*}
\]

Figure 5.2–3 illustrates dependency of Boiling number (Bo) on the Reynolds number (Re) and the variable of Gap/La in log scale. It was found that the experimental Bo almost varied with the Reynolds number (Re) and the variable of Gap/La in log–linear fashion. It is shown that Boiling number (Bo) increases with decreasing Reynolds number (Re), and it increases with the variable of Gap/La. The effects of Re and Gap/La on Bo can be described with the following relationship.

\[
\begin{align*}
\text{Bo}_{\text{exp}} & \sim \text{Re}^o \\
\text{Bo}_{\text{exp}} & \sim (\text{Gap/La})^p
\end{align*}
\]

where

\[
\begin{align*}
\text{Bo}_{\text{exp}} & : \text{Experimental Boiling number, q''}_{\text{CHF}}/(\text{Gh}_{fg}); (-) \\
\text{Re} & : \text{Reynolds number, GD}_{by}/\mu; (-) \\
\text{G} & : \text{Mass flux; kgm}^{-2}\text{s}^{-1} \\
\text{h}_{fg} & : \text{Latent heat; Jkg}^{-1} \\
\text{D}_{by} & : \text{Channel equivalent hydraulic diameter; m} \\
\mu & : \text{Fluid dynamic viscosity; kgm}^{-1}\text{s}^{-1} \\
\text{Gap} & : \text{The gap of the test section; m} \\
\text{La} & : \text{Characteristic length or Laplace capillary constant, } [\sigma/\text{g}(\rho_l-\rho_g)]^{1/2}; \text{ m}
\end{align*}
\]

and \(o\) and \(p\) are experimentally determined exponents.

(Note : detailed description is given in Section 5.4)

The exponents of \(o\) and \(p\) varie within the following ranges for the present experimental data.

\[
\begin{align*}
-0.691 < o < -0.3655 \\
0.6822 < p < 0.7497
\end{align*}
\]
5.3 Gap and Flow Velocity Effect on HTC

Figures 5.1–3 and 5.1–4 illustrate the dependency of HTC on gap and flow velocity. HTC increased with decreasing gap, and increased with flow velocity for each value of gap.

5.4 Empirical Correlation of CHF Data

Numerous types of CHF correlations have been proposed for subcooled forced convective boiling. The major types are empirical, similitude–based, analytical, tabular, and graphical. For the given range of experimental data upon which these correlations are based, CHF can usually be predicted with reasonable accuracy. But most of the correlations are based on the CHF experiments with tubes. Conversely, no correlations have been developed specifically for the CHF experiments with the narrow one–side uniformly heated rectangular flow channel, and a new correlation is needed

In order to develop the correlation, the experimental data listed in Table A–4.1 were used. As known, five parameters of flow velocity, exit subcooling, pressure, diameter (gap) and length–to–diameter ratio are the predictor variables for CHF. But in the present experiment, inlet subcooling, pressure and flow length were fixed at 50°C, 0.1 MPa and 50.0 mm, respectively. Therefore, only flow velocity and gap were the real predictor variables.

(1) Empirical Correlation

The first step of the process was to assume a log–linear relationship between CHF and each of the primary variables:

\[
CHF = A_0 \left(\frac{\text{Gap}}{\text{Gap}_0}\right)^a \left(\frac{\text{Vel}}{\text{Vel}_0}\right)^b
\]  

where

\[
\text{Gap}_0 = 3 \text{ mm};
\]
\[
\text{Vel}_0 = 15 \text{ m/s};
\]
\[
\text{CHF} : \text{MWm}^{-2};
\]

and \( A_0, a \) and \( b \) are experimentally determined coefficient and exponents respectively.

Regression was performed by taking the logarithm of this expression, giving

\[
\log(CHF) = \log(A_0) + a\log(\text{Gap}/\text{Gap}_0) + b\log(\text{Vel}/\text{Vel}_0)
\]  

\[ (5.4-2) \]
After the regression calculation, the final correlation is as follows:

\[ \text{CHF} = 9.5765(\text{Gap}/3)^{0.1878} (\text{Vel}/15)^{0.4369} \]  \hspace{1cm} (5.4-3)

where

- CHF : Predicted CHF with this empirical correlation; MWm\(^{-2}\)
- \( A_0 = 9.5765 \text{ MWm}^{-2} \);
- \( a = 0.1878 \);
- \( b = 0.4369 \);
- Gap : The gap of the test section, mm;
- Vel : Flow velocity passing through the test section; ms\(^{-1}\)
- Gap\(_0\) = 3 mm;
- Vel\(_0\) = 15 ms\(^{-1}\).

A scatter plot that compares the predicted CHF with the experimental data is given in Fig. 5.4-1. The correlation was considered satisfactory. For the present experimental data, all of data points were predicted within ±18% error band.

Parametric plot was constructed that exhibits the predicted CHF levels as a function of each of the two primary variables, with satisfactory results. In Fig. 5.4-2, predicted CHF is plotted as a function of gap and flow velocity which vary from 0.2 to 3 mm and 5 to 15 ms\(^{-1}\), respectively. The tendency is similar to that observed in the experimental results shown in Figs. 5.1-1 and 5.1-2, as well as in previous studies. That is, CHF increases with gap and flow velocity in a non-linear manner.

(2) Similitude–based Correlation

Another way of the process was to assume a log-linear relationship between Boiling number (Bo) and each of the primary variables:

\[ \text{Bo} = A_1 \text{Re}^c (\text{Gap}/\text{La})^d \]  \hspace{1cm} (5.4-4)

with

\[ \text{La} = [\alpha/g(\rho_f - \rho_g)]^{0.5} \]  \hspace{1cm} (5.4-5)
where

\[ \text{Bo} : \text{Boiling number}, \frac{q''_{\text{CHF}}}{(G \mu)}; (-) \]
\[ \text{Re} : \text{Reynolds number}, \frac{GD}{\mu}; (-) \]
\[ \text{Gap} : \text{The gap of the test section}; \text{m} \]
\[ \text{La} : \text{Characteristic length or Laplace capillary constant}; \text{m} \]
\[ \sigma : \text{Surface tension}; \text{Nm}^{-1} \]
\[ g : \text{Gravitational acceleration}; \text{ms}^{-2} \]
\[ \rho_f : \text{Saturated liquid density}; \text{kgm}^{-3} \]
\[ \rho_g : \text{Saturated vapor density}; \text{kgm}^{-3} \]
\[ q''_{\text{CHF}} : \text{Critical heat flux}; \text{Wm}^{-2} \]
\[ G : \text{Mass flux}; \text{kgm}^{-2}s^{-1} \]
\[ h_{fg} : \text{Latent heat}; \text{Jkg}^{-1} \]
\[ D_{hy} : \text{Channel equivalent hydraulic diameter}; \text{m} \]
\[ \mu : \text{Fluid dynamic viscosity}; \text{kgm}^{-1}s^{-1} \]

and \( A_1, c \) and \( d \) are experimentally determined coefficient and exponents respectively.

As described in Section 5.1, \( \text{Gap/La} \) is a non-dimensional length, which is considered as an indicator of the ratio of the gap of the flow channel to the bubble size.

After the regression calculation, the final correlation is as follows:

\[ \text{Bo} = 0.1457 \text{Re}^{-0.5283} (\text{Gap/La})^{0.716} \]

(5.4–6)

where

\[ \text{Bo} : \text{Predicted Boiling number}; (-) \]
\[ A_1 = 0.1457; \]
\[ c = -0.5283; \]
\[ d = 0.716; \]
\[ \text{Re} : \text{Reynolds number}, \frac{GD}{\mu}; (-) \]
\[ \text{Gap} : \text{The gap of the test section}; \text{m} \]
\[ \text{La} : \text{Characteristic length or Laplace capillary constant, m}. \]

The predicted-to-experimental Bo ratio is plotted against Re and the variable of \( \text{Gap/La} \) in Fig. 5.4–3. The correlation was considered satisfactory. For the present experimental data, all of data points were predicted within \( \pm 16\% \) error band.

In addition, it was found from the above correlation that the value of exponent of Reynolds number (Re) \((-0.5283)\) is close to that value specified in modified–Tong correlation \((-0.5)\).
Fig. 5.1-1 CHF vs. the gap of the test section

Fig. 5.1-2 CHF vs. flow velocity
Fig. 5.1-3 Heat transfer coefficient vs. the gap of the test section

Fig. 5.1-4 Heat transfer coefficient vs. flow velocity
Fig. 5.1-5  Boiling number (Bo) vs. Re and Gap/La
RUN NO. 237 : GAP = 1.0 mm, LENGTH = 50 mm, Q = 3.40 L/min
Fig. 5.1–6A Typical boiling curve

RUN NO. 226 : GAP = 0.5 mm, LENGTH = 50 mm, Q = 2.70 L/min
Fig. 5.1–6B Unclear typical boiling curve

RUN NO. 260 : GAP = 0.2 mm, LENGTH = 50 mm, Q = 2.16 L/min
Fig. 5.1–6C Non-typical boiling curve
Fig. 5.2-1 CHF vs. the gap of the test section

Fig. 5.2-2 CHF vs. flow velocity
Fig. 5.2-3 Boiling number (Bo) vs. Re and Gap/La
Fig. 5.4-1 Scatter plot for CHF correlation
Fig. 5.4-2 Predicted & experimental CHF vs. the gap and flow velocity
Fig. 5.4-3 Scatter plot of predicted-to-experimental Bo ratio for Similitude-based correlation
6. ASSESSMENT OF EXISTING EMPIRICAL CORRELATIONS ON CHF

As there are no data in the range of interest, suitable and reliable correlations for the prediction of subcooled CHF are limited. The only possibility is to use available correlations that are recommended for ranges of validity completely different from the present data and evaluate the possibility of using them with a certain reliability outside the proposed ranges. Two empirical correlations have been selected for comparison.

**Westinghouse** [3]

\[ q''_{\text{CHF}} = (0.23 \times 10^6 + 0.094G)(3 + 0.01 \Delta T_{\text{sub}})[0.435 + 1.23 \exp(-0.0093L/D)] \]
\[ \{1.7 - 1.4 \exp[-0.532((h_f-h_{in})/h_{fg})^{3/4} (\rho_g/\rho_f)^{1/3}]\} \]

(6-1)

where

\[ q''_{\text{CHF}} \] : Critical heat flux; BTUft\(^{-2}\)hr\(^{-1}\)
\[ G \] : Mass flux; lbft\(^{-2}\)hr\(^{-1}\)
\[ \Delta T_{\text{sub}} \] : Fluid subcooling; °F
\[ L \] : Channel flow length; cm
\[ D \] : Channel diameter; mm
\[ h_f \] : Saturated liquid enthalpy; Jkg\(^{-1}\)
\[ h_{in} \] : Inlet fluid enthalpy; Jkg\(^{-1}\)
\[ h_{fg} \] : Latent heat; Jkg\(^{-1}\)
\[ \rho_g \] : Saturated vapor density; kgm\(^{-3}\)
\[ \rho_f \] : Saturated liquid density; kgm\(^{-3}\)

recommended in the ranges

\[ 0.2 \times 10^6 < G < 8 \times 10^6 \text{ lbft}^{-2}\text{hr}^{-1} \ (0.3 < G < 11 \text{ Mgm}^{-2}\text{s}^{-1}), \]
\[ 800 < P < 2750 \text{ psia} \ (5.7 < P < 20.0 \text{ MPa}), \]
\[ 21 < L/D < 365, \]
\[ 0 < \Delta T_{\text{sub}} < 228 \text{ °F} \ (0 < \Delta T_{\text{sub}} < 126 \text{ °C}), \]
\[ 0.4 \times 10^6 < q''_{\text{CHF}} < 4 \times 10^6 \text{ BTUft}^{-2}\text{hr}^{-1} \ (1.25 < q''_{\text{CHF}} < 12.5 \text{ MWm}^{-2}). \]

**Modified–Tong** [3]

\[ B_0 = C \text{Re}^{-0.5} \]  

(6-2)

with

\[ C = (0.216 + 4.74 \times 10^{-2}P)\Psi \]
\[ \Psi = 0.825 + 0.986x_{\text{ex}} \] if \( x_{\text{ex}} > -0.1 \)
\[ \Psi = 1 \] if \( x_{\text{ex}} < -0.1 \)
\[ \Psi = 1/(2 + 30x_{\text{ex}}) \] if \( x_{\text{ex}} > 0 \) (exit saturated conditions)
where

\[ \begin{align*}
    B_0 & : \text{Boiling number, } q''_{\text{CHF}}/(Gh_{fg}); (-) \\
    \text{Re} & : \text{Reynolds number, GD}/\mu; (-) \\
    q''_{\text{CHF}} & : \text{Critical heat flux; Wm}^{-2} \\
    G & : \text{Mass flux; kgm}^{-2}\text{s}^{-1} \\
    h_{fg} & : \text{Latent heat; Jkg}^{-1} \\
    D & : \text{Channel diameter; m} \\
    \mu & : \text{Fluid dynamic viscosity; kgm}^{-1}\text{s}^{-1} \\
    x_{\text{ex}} & : \text{Exit fluid quality; (-)} \\
    P & : \text{Pressure; MPa.}
\end{align*} \]

recommended in the ranges

\[ \begin{align*}
    2.2 < G < 40 \text{ Mgm}^{-2}\text{s}^{-1}, 0.1 < P < 5.0 \text{ MPa}, 2.5 < D < 8.0 \text{ mm}, 12 < L/D < 40, \\
    15 < \Delta T_{\text{sub}} < 190^\circ \text{C}, 4.0 < q''_{\text{CHF}} < 60.6 \text{ MWm}^{-2}
\end{align*} \]

A comparison of predictions obtained by using Westinghouse correlation with present experimental data is shown in Figs. 6-1 and 6-2. In the predictions, equivalent hydraulic diameter \(D_{hy}\) was specified as the channel diameter \(D\). In Fig. 6-1, experimental and predicted CHF are plotted versus gap and flow velocity; and in Fig. 6-2, experimental-to-predicted CHF ratio is plotted versus gap and flow velocity. It is shown that the predicted CHF increased with flow velocity in a linear manner as known with Equation (6-1), where the flow velocity effect is indicated by the term of \((0.23\times10^6 + 0.094G)\). On the other hand, it is almost kept as a constant with the gap for a certain flow velocity as known with Equation (6-1), where the gap effect is indicated by the term of \([0.435 + 1.23\exp(-0.0093L/D)]\). The ratio of the experimental to the predicted CHF with Westinghouse correlation ranges from about 2.0 to 4.5 under the experimental conditions. There is a large deviation in comparison with the value shown in Chapter 2. Systematic trend of the gap and flow velocity effects on experimental-to-predicted CHF ratio was observed. Experimental-to-predicted CHF ratio increased with gap and it increased with decreasing flow velocity. Thus, Westinghouse correlation couldn't properly predict the effects of both the gap and flow velocity on CHF for the present data, and modification seems necessary for reflecting both effects on CHF.

And another comparison of predictions obtained by using modified-Tong correlation with present experimental data is shown in Figs. 6-7 and 6-8. In the predictions, equivalent hydraulic diameter \(D_{hy}\) was specified as the channel diameter \(D\). In Fig. 6-7, experimental and predicted CHF are plotted against the gap and flow velocity; and in Fig. 6-8, experimental-to-predicted CHF ratio is plotted against gap and flow velocity. It is shown that the predicted CHF increased with flow velocity as known with Equation (6-2), where the flow velocity effect is indicated by the term of both Boiling number \(Bo\) and Reynolds number \(Re\). On the other hand, it increased with decreasing gap for a certain flow velocity as known with Equation (6-2), where
the gap effect is indicated by the term of Reynolds number (Re) and exit quality ($x_{ex}$). The ratio of the experimental to the predicted CHF with modified-Tong correlation ranges from about 0.2 to 0.8 under the experimental conditions. There is a large deviation in comparison with the value shown in Chapter 2. Systematic trend of the gap and flow velocity effects on experimental-to-predicted CHF ratio was not found so far. Thus, modified-Tong correlation couldn’t properly predict the effects of both gap and flow velocity on CHF for the present data, and modification seems necessary for reflecting both effects on CHF.

Sensitivity calculations were also performed by using the different channel diameter with the above two empirical correlations in order to explain the reason of the deviation. The equivalent hydraulic diameter($D_{hy}$), the equivalent heated diameter($D_{heated}$) and half gap($0.5\text{Gap}$) were specified respectively. The value of channel diameter specified for each case is listed in Table 6–1. The predicted results with Westinghouse correlation are shown in Figs. 6–1 to 6–6. It was found that there is almost no any effects on the predicted CHF with Westinghouse correlation by specifying the different channel diameter. This is because the gap effect is indicated by the term of $[0.435 + 1.23\exp(-0.0093L/D)]$ with Equation (6–1) and effect of the variable L/D on this term is very small for the present experiment. The predicted results with modified-Tong correlation are shown in Figs. 6–7 to 6–12. There is a crisis of the predicted CHF along with the gap for a certain flow velocity, where the exit fluid becomes saturated (i.e. $x_{ex}=0$). The left side of that point is saturated fluid region, and the right side of that point is the subcooled fluid region. It was found that the predicted CHF decreased and the ratio of the experimental to the predicted CHF increased (ranges from about 0.25 to 1.5) when the equivalent heated diameter($D_{heated}$) was specified. The deviation is still large even though it becomes smaller in comparison with $D_{hy}$ case. And the predicted CHF increased and the ratio of the experimental to the predicted CHF decreased (ranges from about 0.12 to 0.5) when the half gap($0.5\text{Gap}$) was specified. Systematic trend of the gap and flow velocity effects on experimental-to-predicted CHF ratio was not found so far.

Table 6–1 The value of channel diameter specified for each case

<table>
<thead>
<tr>
<th>Gap (mm)</th>
<th>D (mm)</th>
<th>L/D (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_{hy}$</td>
<td>$D_{heated}$</td>
</tr>
<tr>
<td>3.0</td>
<td>4.800</td>
<td>14.40</td>
</tr>
<tr>
<td>1.0</td>
<td>1.846</td>
<td>4.80</td>
</tr>
<tr>
<td>0.5</td>
<td>0.960</td>
<td>2.40</td>
</tr>
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<td>0.2</td>
<td>0.393</td>
<td>0.96</td>
</tr>
<tr>
<td>0.1</td>
<td>0.198</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Note : D : Channel diameter; L : Channel flow length, 50.0 mm.
From above results, it can be noticed that Westinghouse correlation provides a systematic underprediction, and modified-Tong correlation gives a systematic overprediction of the present experimental CHF data except for larger gap in $D_{\text{heated}}$ case. As mentioned, these correlations were developed based on the CHF experiments with the round tubes, but the test section used at present experiment is a narrow one-side heated rectangular flow channel. This might be the reason why there is a large difference between experimental and predicted CHF. Anyway, these correlations need to be modified to predict CHF for the present experiments. Modifications must be made for both terms of indicating flow velocity and geometry effects for a narrow one-side heated flow channel.
QCHF vs. GAP [WH & Exp. (V=5-15m/s), D=Dhy]

QCHF vs. VELOCITY [WH & Exp. (V=5-15m/s), D=Dhy]

Fig. 6-1 Experimental & predicted CHF vs. the gap and flow velocity for Westinghouse correlation (D = Dhy)
Fig. 6-2 Experimental-to-predicted CHF ratio vs. the gap and flow velocity for Westinghouse correlation (D = D_{hy})
QCHF vs. GAP [WH & Exp. (V=5-15m/s), D=Dheated]

\[\text{CHF (W/M*2)}\]

QCHF vs. VELOCITY [WH & Exp. (V=5-15m/s), D=Dheated]

\[\text{CHF (W/M*2)}\]

Fig. 6-3 Experimental & predicted CHF vs. the gap and flow velocity for Westinghouse correlation \((D = D_{heated})\)
Fig. 6-4 Experimental-to-predicted CHF ratio vs. the gap and flow velocity for Westinghouse correlation (D = \( D_{\text{heated}} \))
Fig. 6-5 Experimental & predicted CHF vs. the gap and flow velocity for Westinghouse correlation (D = 0.5Gap)
Fig. 6-6 Experimental-to-predicted CHF ratio vs. the gap and flow velocity for Westinghouse correlation (D = 0.5Gap)
Fig. 6-7 Experimental & predicted CHF vs. the gap and flow velocity for modified-Tong correlation ($D = D_{hy}$)
Fig. 6–8 Experimental-to-predicted CHF ratio vs. the gap and flow velocity for modified-Tong correlation (D = $D_{hy}$)
QCHF vs. GAP [Tong & Exp. (V=5-15m/s), D=Dheated]

QCHF vs. VELOCITY [Tong & Exp. (V=5-15m/s), D=Dheated]

Fig. 6-9 Experimental & predicted CHF vs. the gap and flow velocity for modified-Tong correlation (D = D_{heated})
Fig. 6–10 Experimental-to-predicted CHF ratio vs. the gap and flow velocity for modified-Tong correlation ($D = D_{heated}$)
QCHF vs. GAP [Tong & Exp. (V=5–15m/s), D=0.5Gap]

CHF (MW/M²) vs. GAP (MM)

QCHF vs. VELOCITY [Tong & Exp. (V=5–15m/s), D=0.5Gap]

CHF (MW/M²) vs. VELOCITY (M/S)

Fig. 6–11 Experimental & predicted CHF vs. the gap and flow velocity for modified-Tong correlation (D = 0.5Gap)
Fig. 6-12 Experimental-to-predicted CHF ratio vs. the gap and flow velocity for modified-Tong correlation (D = 0.5Gap)
7. CONCLUSION

The experimental work was carried out with the narrow one-side uniformly heated rectangular flow channel. The rectangular flow channel used is 50 mm long, 12 mm in width and 0.2 to 3 mm in height. Test conditions were selected by combination of the following parameters: $\text{Gap} = 0.2$–$3.0$ mm ($D_{hy} = 0.3934$–$4.8$ mm); flow length = $50.0$ mm; water mass flux = $4.94$–$14.82$ Mgm$^{-1}$s$^{-1}$ (water flow velocity, $5$–$15$ ms$^{-1}$); exit pressure $= 0.1$ MPa; inlet temperature $= 50^\circ$C; inlet subcooling $= 50^\circ$C. CHF increased with gap and flow velocity in a non-linear fashion. HTC increased with flow velocity and decreasing gap.

Three types of boiling curves, specified based on their shapes, were observed in the present experiments, i.e. typical, unclear typical and non-typical boiling curves. The typical boiling curve, which is a bend line where there is a crisis between forced convective heat transfer region and subcooled nucleate boiling heat transfer region, was observed under larger gap and lower flow velocity. On the other hand, non-typical boiling curve, where boiling curve tends to a straight line, was observed under smaller gap and/or larger flow velocity, demonstrating that the convective heat transfer effect becomes more significant. Unclear typical boiling curve is a slight bend line where subcooled nucleate boiling heat transfer effect seems insignificant.

Based on the experimental results, an empirical correlation was developed, indicating the dependency of CHF on gap and flow velocity, covering flow velocities from $5$ to $15$ ms$^{-1}$, the gaps from $0.2$ to $3.0$ mm, flow length of $50.0$ mm, pressure at $0.1$ MPa, inlet coolant subcooling at $50^\circ$C. Resulting CHF values varied from $3.56$ to $9.58$ MWm$^{-2}$. For the present experimental data, all of data points were predicted within $\pm 18\%$ error band.

Meanwhile, another similitude–based correlation was also developed, indicating the dependency of Boiling number (Bo) on Reynolds number (Re) and the variable of $\text{Gap/La}$. For the present experimental data, all of data points were predicted within $\pm 16\%$ error band.

In addition, the comparisons of predictions obtained by using Westinghouse and modified–Tong correlations with present experimental data were also presented. From these results, it can be noticed that Westinghouse correlation provides a systematic underprediction, and modified–Tong correlation gives a systematic overprediction of the present experimental CHF data except for larger gap in $D_{\text{heated}}$ case. Over all, these correlations need to be modified to predict CHF for the present experiments. Modifications must be made for both terms of indicating flow velocity and geometry effects for a narrow one–side heated flow channel.
ACKNOWLEDGEMENT

The authors wish to thank Mr. Hironori WATANABE for his experimental support to the present research.

REFERENCES


APPENDIX

A-1 Description of Data Processing Flow

As mentioned, eight parameters are recorded into the floppy disc during the CHF experiment. These are as follows.

- Volumetric flow rate;
- Electric voltage across the test section;
- Electric current of the test section;
- Electric power of the test section;
- Inlet coolant temperature of the test section;
- Outlet coolant temperature of the test section;
- Electric voltage across the test section node No.1;
- Electric voltage across the test section node No.2.

But, all of above parameters except for the inlet and outlet coolant temperature are recorded into some electric parameters in the units of electric voltage. Therefore, it's necessary to do some unit conversion calculation in order to restore the physical values of these parameters.

Table A-1.1 Ranges of Measured and Actual Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of Measured Parameter</th>
<th>Range of Actual Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric flow rate:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Large flow rate</td>
<td>1 to 5 (V)</td>
<td>0 to 38 (l/min)</td>
</tr>
<tr>
<td>b. Intermediate flow rate</td>
<td>1 to 5 (V)</td>
<td>0 to 12.6 (l/min)</td>
</tr>
<tr>
<td>c. Small flow rate</td>
<td>1 to 5 (V)</td>
<td>0 to 4.24 (l/min)</td>
</tr>
<tr>
<td>d. Very small flow rate</td>
<td>1 to 5 (V)</td>
<td>0 to 1.0 (l/min)</td>
</tr>
<tr>
<td>Electric voltage across the test section</td>
<td>1 to 5 (V)</td>
<td>0 to 50 (V)</td>
</tr>
<tr>
<td>Electric current of the test section</td>
<td>1 to 5 (V)</td>
<td>0 to 2000 (A)</td>
</tr>
<tr>
<td>Electric power of the test section heater</td>
<td>1 to 5 (V)</td>
<td>0 to 99.99 (kW)</td>
</tr>
<tr>
<td>Inlet coolant temp.</td>
<td>0 to 100 (°C)</td>
<td>0 to 100 (°C)</td>
</tr>
<tr>
<td>Outlet coolant temp.</td>
<td>same as above</td>
<td>same as above</td>
</tr>
<tr>
<td>Electric voltage of Node 1</td>
<td>0 to 5 (V)</td>
<td>0 to 5 (V)</td>
</tr>
<tr>
<td>Electric voltage of Node 2</td>
<td>same as above</td>
<td>same as above</td>
</tr>
</tbody>
</table>
The flow chart of experimental data processing is given below.

![Flow chart of experimental data processing](Figure A-1.1)

Fig. A-1.1 Flow chart of experimental data processing
A–2 Description of Data Processing Program

As mentioned above, AR2OA, READO and WRITEO programs are developed and used to convert the experimental data recorded on the floppy disc into the physical values of the experimental parameters. READO program is used to read the input data in the M780 computer which named as @3.ASC and transmitted from the floppy disc. And then AR2OA program restores all of the experimental parameters into their physical values and produces some additional necessary parameters. After that, WRITEO program establishes an output data file which named as @@@.DATA and recorded all of the necessary experimental parameters. There are total 12 parameters recorded in that output data file which listed as follows.

- Time (s);
- Volumetric flow rate (l/min);
- Electric voltage across the test section (V);
- Electric current of the test section (A);
- Electric power of the test section (kW);
- Inlet coolant temperature of the test section (° C);
- Outlet coolant temperature of the test section (° C);
- Electric voltage across the test section node No.1 (V);
- Electric voltage across the test section node No.2 (V);
- Average film temperature of the test section (° C);
- Film temperature for the test section node No.1 (° C);
- Film temperature for the test section node No.2 (° C).

The detailed procedure of converting data format compatible to IPLOT program with M780 computer is as follows:

Step 1 : To compile the program mentioned above and to make a load module, i.e.

```
FORT TEST.FORT ELM(AR2OA, READO, WRITEO) OBJ(A)
LINK A LIB('SYS2.IPFLIB') F
```

Step 2 : To execute the load module, i.e.

```
CALL A.LOAD(TEMPNAME)
```
After these necessary parameters are given, the following plots which needed for analyzing experimental data can be made with IPLOT program which named as CHFPLONTN.

- Inlet & outlet coolant temperature of the test section (°C);
- Pressure (MPa);
- Exit subcooling (°C);
- Exit quality (–);
- Electric current of the test section (A);
- Electric voltage across the test section (V);
- Electric voltage across the test section node No.1 & No.2 (V);
- Film temperature of the test section (°C);
- Mass flow rate (kg/sec);
- Mass flux (kg/m².sec);
- Heat flux of the test section (W/m²);
- Heat transfer coefficient (HTC) (W/m².°C)
- Heat flux varied with the exit subcooling;
- Heat flux varied with the film superheating;
- Heat flux varied with the film superheating for the test section node No.1;
- Heat flux varied with the film temperature for the test section node No.1;
- Heat flux varied with the quality for the test section node No.1;
A-3 Description of Design of Orifice for Test Facility

A-3.1 Experimental Parameters

(1) Pressure (MPa): 0.1
(2) Inlet temperature (°C): 50.0
(3) Flow velocity at test section inlet (m/s): 5.0, 7.5, and 10.0
(4) Test section geometric parameters:
   - Rectangular channel
     • Length (mm): 50.0
     • Width (mm): 12.0
     • Effective heated width (mm): 10.0
     • Gap (mm): 0.1, 0.2, 0.5, 1.0, and 3.0
     • Designed film thickness (μm): 9.0

(5) Experimental volumetric flow rate (l/min):

<table>
<thead>
<tr>
<th>Q (l/min)</th>
<th>Flow velocity (m/s)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.5</th>
<th>1.0</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.0</td>
<td>0.36</td>
<td>0.72</td>
<td>1.80</td>
<td>3.60</td>
<td>10.80</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>0.54</td>
<td>1.08</td>
<td>2.70</td>
<td>5.4</td>
<td>16.20</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0.72</td>
<td>1.44</td>
<td>3.60</td>
<td>7.20</td>
<td>21.60</td>
</tr>
</tbody>
</table>

A-3.2 The Design of the Orifices used in the CHF Test Facility

As mentioned, three orifices are used to measure the volumetric flow rate in the test section for three flow rate conditions. But one additional orifice is also needed for a very small flow rate condition according to the experimental requirement. These are as follows:

(1) Large flow rate condition which ranges from 0 to about 38 (l/min);
(2) Intermediate flow rate condition which ranges from 0 to 12.6 (l/min);
(3) Small flow rate condition which ranges from 0 to 4.24 (l/min);
(4) Very small flow rate condition which ranges from 0 to 1.0 (l/min).

In order to design the proper orifices for each flow rate condition, the following correlations are used to calculate the measured local and total pressure drop across the test section orifices.
\[ Q = \alpha \cdot A \sqrt{\frac{2 \cdot \Delta P_{Local}}{\rho}} \]  

(A-3.1)

where:

\[ Q \] : Volumetric flow rate (m³/s);
\[ \alpha \] : Flow discharge coefficient (-);
\[ \Delta P_{Local} \] : The measured local pressure drop (Pa);
\[ \rho \] : Fluid density (kg/m³).

\[ \alpha = 0.597 - 0.011 \cdot \beta + 0.432 \cdot \beta^2 \]  

(A-3.2)

where:

\[ \alpha \] : Flow discharge coefficient (-);
\[ \beta \] : Orifice diameter ratio, it's defined by using the correlation (A-3.3);

\[ \beta = \left( \frac{d}{D} \right)^2 \]  

(A-3.3)

where:

\[ \beta \] : Orifice diameter ratio;
\[ d \] : Hole diameter of a certain orifice (m);
\[ D \] : Pipe diameter of a certain orifice pipe (m).

\[ \Delta P_{Total} = (1 - \beta) \cdot \Delta P_{Local} \]  

(A-3.4)

where:

\[ \Delta P_{Total} \] : The measured total pressure drop (Pa);
\[ \Delta P_{Local} \] : The measured local pressure drop (Pa).
According to the requirements of the CHF test facility, the upper limit of the measured local pressure drop is 500 mmH₂O and the flow range for each flow rate condition is also given. And then the proper hole diameter of the orifices can be calculated by using the correlations listed above [(A-3.1), (A-3.2), (A-3.3) and (A-3.4)].

In this way, the designed hole diameter for each orifice has been determined which listed in Table A-3.2.

Table A-3.2 The Geometric Parameters of the Orifice for Each Flow rate Condition

<table>
<thead>
<tr>
<th>Flowrate Condition</th>
<th>Very small</th>
<th>Small</th>
<th>Intermediate</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Diameter (m)</td>
<td>0.0230</td>
<td>0.0230</td>
<td>0.0284</td>
<td>0.0430</td>
</tr>
<tr>
<td>Hole Diameter (m)</td>
<td>0.0030</td>
<td>0.0065</td>
<td>0.0115</td>
<td>0.0200</td>
</tr>
<tr>
<td>(No.1)</td>
<td>(No.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As mentioned, there are four flow rate cases. Thus, different orifice should be used for the different flow rate case. So the applicable distribution of the orifices is provided in Table A-3.3.

Table A-3.3 Experimental Applicable Distribution of the Orifices

<table>
<thead>
<tr>
<th>[A, B, C, D]</th>
<th>Gap(mm)</th>
<th>Flow velocity(m/s)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.5</th>
<th>1.0</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td></td>
<td></td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>7.5</td>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>10.0</td>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

Note:
A : Small orifice No.1 should be used for a very small flow rate case;  
B : Small orifice No.2 should be used for small flow rate case;  
C : Middle orifice should be used for intermediate flow rate case;  
D : Large orifice should be used for large flow rate case.

A-3.3 Calibration Test

According to the previous experimental experience, the orifices must be calibrated before the CHF experiment in order to obtain the accurate experimental data.
A-4 Summary of Experimental Results

Summary of experimental results is listed in Table A-4.1. And summary of plotted experimental results is attached as follows.

Table A-4.1 CHF Experimental Data

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Gap (mm)</th>
<th>Velocity (m/s)</th>
<th>Re ($\times 10^3$)</th>
<th>Inlet Temp.(C)</th>
<th>CHF (MW/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>231</td>
<td>0.2</td>
<td>4.58</td>
<td>0.3152</td>
<td>48.1</td>
<td>4.0345</td>
</tr>
<tr>
<td>232</td>
<td>0.2</td>
<td>7.50</td>
<td>0.5329</td>
<td>50.0</td>
<td>3.8180</td>
</tr>
<tr>
<td>256</td>
<td>0.2</td>
<td>7.50</td>
<td>0.5329</td>
<td>50.0</td>
<td>3.9860</td>
</tr>
<tr>
<td>249</td>
<td>0.2</td>
<td>8.97</td>
<td>0.6363</td>
<td>49.9</td>
<td>5.8307</td>
</tr>
<tr>
<td>233</td>
<td>0.2</td>
<td>10.0</td>
<td>0.7106</td>
<td>50.0</td>
<td>5.1220</td>
</tr>
<tr>
<td>260</td>
<td>0.2</td>
<td>15.0</td>
<td>1.0660</td>
<td>50.0</td>
<td>5.1260</td>
</tr>
<tr>
<td>245</td>
<td>0.5</td>
<td>4.84</td>
<td>0.8363</td>
<td>49.8</td>
<td>5.6930</td>
</tr>
<tr>
<td>225</td>
<td>0.5</td>
<td>4.86</td>
<td>0.8356</td>
<td>49.5</td>
<td>4.1003</td>
</tr>
<tr>
<td>226</td>
<td>0.5</td>
<td>7.14</td>
<td>1.2300</td>
<td>49.6</td>
<td>4.3133</td>
</tr>
<tr>
<td>240</td>
<td>0.5</td>
<td>7.22</td>
<td>1.1850</td>
<td>46.8</td>
<td>7.4185</td>
</tr>
<tr>
<td>246</td>
<td>0.5</td>
<td>7.37</td>
<td>1.2400</td>
<td>48.2</td>
<td>5.7986</td>
</tr>
<tr>
<td>257</td>
<td>0.5</td>
<td>10.0</td>
<td>1.7340</td>
<td>50.0</td>
<td>5.3750</td>
</tr>
<tr>
<td>227</td>
<td>0.5</td>
<td>10.06</td>
<td>1.7030</td>
<td>48.6</td>
<td>4.9959</td>
</tr>
<tr>
<td>259</td>
<td>0.5</td>
<td>15.0</td>
<td>2.6010</td>
<td>50.0</td>
<td>7.6220</td>
</tr>
<tr>
<td>229</td>
<td>1.0</td>
<td>4.81</td>
<td>1.6010</td>
<td>49.9</td>
<td>5.4842</td>
</tr>
<tr>
<td>236</td>
<td>1.0</td>
<td>4.89</td>
<td>1.6330</td>
<td>50.1</td>
<td>4.4308</td>
</tr>
<tr>
<td>228</td>
<td>1.0</td>
<td>4.92</td>
<td>1.6570</td>
<td>50.6</td>
<td>5.5678</td>
</tr>
<tr>
<td>237</td>
<td>1.0</td>
<td>7.25</td>
<td>2.3810</td>
<td>49.1</td>
<td>6.0930</td>
</tr>
<tr>
<td>224</td>
<td>1.0</td>
<td>9.61</td>
<td>3.1450</td>
<td>48.9</td>
<td>7.1997</td>
</tr>
<tr>
<td>238</td>
<td>1.0</td>
<td>9.89</td>
<td>3.2480</td>
<td>49.1</td>
<td>6.4941</td>
</tr>
<tr>
<td>258</td>
<td>1.0</td>
<td>15.0</td>
<td>5.0010</td>
<td>50.0</td>
<td>5.9560</td>
</tr>
<tr>
<td>36001</td>
<td>0.2</td>
<td>5.0</td>
<td>50.0</td>
<td>3.3000</td>
<td></td>
</tr>
</tbody>
</table>
Table A-4.1 CHF Experimental Data (continued)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Gap (mm)</th>
<th>Velocity (m/s)</th>
<th>Re ($\times 10^4$)</th>
<th>Inlet Temp.(C)</th>
<th>CHF (MW/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>116</td>
<td>3.0</td>
<td>4.98</td>
<td>4.3170</td>
<td>50.0</td>
<td>5.64</td>
</tr>
<tr>
<td>75</td>
<td>3.0</td>
<td>5.03</td>
<td>4.1580</td>
<td>47.2</td>
<td>6.11</td>
</tr>
<tr>
<td>150</td>
<td>3.0</td>
<td>5.09</td>
<td>4.5910</td>
<td>52.4</td>
<td>5.91</td>
</tr>
<tr>
<td>151</td>
<td>3.0</td>
<td>7.44</td>
<td>6.6560</td>
<td>51.9</td>
<td>6.48</td>
</tr>
<tr>
<td>76</td>
<td>3.0</td>
<td>7.61</td>
<td>6.4430</td>
<td>48.6</td>
<td>6.80</td>
</tr>
<tr>
<td>152</td>
<td>3.0</td>
<td>9.76</td>
<td>8.6740</td>
<td>51.5</td>
<td>8.43</td>
</tr>
<tr>
<td>121</td>
<td>3.0</td>
<td>9.93</td>
<td>8.4500</td>
<td>48.9</td>
<td>8.03</td>
</tr>
<tr>
<td>117</td>
<td>3.0</td>
<td>9.93</td>
<td>8.6080</td>
<td>50.0</td>
<td>7.14</td>
</tr>
<tr>
<td>77</td>
<td>3.0</td>
<td>9.93</td>
<td>8.6660</td>
<td>50.4</td>
<td>7.49</td>
</tr>
<tr>
<td>175</td>
<td>3.0</td>
<td>14.83</td>
<td>12.960</td>
<td>50.5</td>
<td>10.89</td>
</tr>
<tr>
<td>201</td>
<td>3.0</td>
<td>15.23</td>
<td>13.340</td>
<td>50.6</td>
<td>10.37</td>
</tr>
<tr>
<td>154</td>
<td>3.0</td>
<td>15.27</td>
<td>13.640</td>
<td>51.8</td>
<td>12.90</td>
</tr>
</tbody>
</table>
RUN NO. 237: GAP = 1.0 MM, LENGTH = 50 MM, Q = 5.40 L/MIN

- - - AVG. FILM TEMP. (C) (O)
- - - FILM TEMP. (V-1) (C) (△)
- - - FILM TEMP. (V-2) (C) (□)

RUN NO. 237: GAP = 1.0 MM, LENGTH = 50 MM, Q = 5.40 L/MIN

- - - HEAT FLUX (W/M²) (O)

RUN NO. 237: GAP = 1.0 MM, LENGTH = 50 MM, Q = 5.40 L/MIN

- - - MASS FLUX (KG/M².S) (O)

RUN NO. 237: GAP = 1.0 MM, LENGTH = 50 MM, Q = 5.40 L/MIN

- - - HEAT TRANSFER COEF. (W/M².K) (O)
RUN NO. 228: GAP = 1.0 MM, LENGTH = 50 MM, Q = 3.60 L/MIN

Film Temp. (C)

Time (SEC.)

Heat Flux (W/M2)

Film Temp. (C)

Mass Flux (kg/m2.s)

Time (SEC.)

Heat Transfer Coef. (W/m2.K)

Film Temp. (C)
RUN NO. 229 : GAP = 1.0 mm, LENGTH = 50 mm, Q = 3.60 L/min

(a)
RUN NO. 259 : GAP = 0.5 mm, LENGTH = 50 mm, Q = 5.40 L/min

- AVG. FILM TEMP. (°C)
- FILM TEMP. (V-1) (°C)
- FILM TEMP. (V-2) (°C)

HEAT FLUX (W/m²)(NO. 1)

FILM TEMP. (°C)

MASS FLUX (kg/m².s)

TIME (SEC.)

HEAT TRANSFER COEF. (W/m²°C)

FILM TEMP. (°C)
CRITICAL HEAT FLUX OF FORCED FLOW BOILING IN A NARROW ONE-SIDE HEATED RECTANGULAR FLOW CHANNEL