An experimental study on sub-cooled flow boiling CHF of R134a at low pressure condition with atmospheric pressure (AP) plasma assisted surface modification

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Abstract
In this study, sub-cooled flow boiling critical heat flux tests at low pressure were conducted in a rectangular flow channel with one uniformly heated surface, using simulant fluid R-134a as coolant. The experiments were conducted under the following conditions: (1) inlet pressure (P) of 400–800 kPa, (2) mass flux (G) of 124–248 kg/m²s, (3) inlet sub-cooling enthalpy (∆H_i) of 12–26 kJ/kg. Parametric trends of macroscopic system parameters (G, P, ∆H_i) were examined by changing inlet conditions. Those trends were found to be generally consistent with previous understandings of CHF behavior at low pressure condition (i.e. reduced pressure less than 0.2). A fluid-to-fluid scaling model was utilized to convert the test data obtained with the simulant fluid (R-134a) into the prototypical fluid (water). The comparison between the converted CHF of equivalent water and CHF look-up table with same operation conditions were conducted, which showed good agreement. Furthermore, the effect of surface wettability on CHF was also investigated by applying atmospheric pressure plasma (AP-plasma) treatment to modify the surface characteristic. With AP-plasma treatment, the change of microscopic surface characteristic was measured in terms of static contact angle. The static contact angle was reduced from 80° on original non-treated surface to 15° on treated surface. An enhancement of 18% on CHF values under flow boiling conditions were observed on AP-plasma treated surfaces compared to those on non-treated heating surfaces.

1. Introduction
Sub-cooled nucleate boiling in forced convection have drawn significant attention in many thermal application fields due to its high heat transfer efficiency and heat removal capacity. However, the sub-cooled nucleate boiling is encountered with the limitation condition called critical heat flux (CHF), that causes vapor film formed by excess bubble aggregation envelops on the heated surface, consequently deteriorates heat transfer due to poor thermal conductivity of the vapor film, and possibly damaging the heating surface due to abrupt temperature rise. Therefore, the designs of heat transfer systems that operate in the sub-cooled nucleate boiling regime is limited by CHF. In water-cooled nuclear power plants, cladding material surrounding the fuel pellets serves as the first barrier to enclose the radioactive materials. It is crucial that nuclear reactors operate below CHF to prevent temperature excursions and subsequent failures of the heat transfer surfaces. Thus, increases in CHF provide a larger safety margin for the fuel and/ or enable power uprates in commercial nuclear power plants. As a typical example, it has been demonstrated that a 32% increase in CHF would allow for 20% power density uprates in pressurized water reactors (PWR), thereby improve the economics of electricity generation [1].

Most of the existing correlations of CHF are highly empirical and semi-analytical due to complexity of CHF mechanisms in both pool boiling and flow boiling conditions. Critical heat flux is an essential phenomenon for nuclear reactor operations, including both normal and accidental operation conditions. For example, under normal operation conditions, the local surface heat flux on fuel pins has to maintain within certain range to enforce the MDNBR safety limit (minimum departure from nucleate boiling ratio). The departure from nucleate boiling ratio is defined as the ratio of local predicted critical heat flux to actual local operating...
heat flux. Thus, the aim of present experimental flow boiling tests was to establish better understanding of CHF, to advance CHF prediction model development and to enhance CHF with various operational conditions. This includes surface treatment using an atmospheric pressure plasma coating technique to modify boiling surfaces to increase their wettability (i.e. hydrophilic).

In the literature, numerous studies on CHF with varying flow conditions, such as inlet sub-cooling level, pressure, and mass flux have been performed for flow boiling of water in round tube geometry. The studies have generated thousands of data sets, which led to numerous empirical correlations with limited success. These correlations mainly use system pressure, mass flux, inlet sub-cooling enthalpy (fixed inlet condition) or exit quality (fixed outlet condition) to predict the CHF over a wide range of operating conditions with various working fluids (e.g. water, R-12, R134a, and FC-72) [2–4]. Several system variables affect the critical heat flux: liquid sub-cooling level, flow velocity, system pressure, and surface wettability [5]. Generally CHF increases as sub-cooling level (enthalpy) increases. At low sub-cooling levels, CHF increases linearly when the sub-cooling level increases; this is identical with Zuber hydrodynamic model [6]. However, at medium and high sub-cooling levels, the CHF become nonlinear and independent of sub-cooling level. The flow velocity delays the onset of CHF occurrence because of the more effective coolant flow onto the heating surface, which leads to increased boiling heat transfer capabilities. For the system pressure effect, the CHF is increased as the pressure is increased in low-pressure condition (less than 0.2 reduced pressure, dimensionless parameter) to predict the CHF over a wide range of operating conditions with various working fluids (e.g. water, R-12, R134a, and FC-72) [2–4]. Several system variables affect the critical heat flux: liquid sub-cooling level, flow velocity, system pressure, and surface wettability [5]. Generally CHF increases as sub-cooling level (enthalpy) increases. At low sub-cooling levels, CHF increases linearly when the sub-cooling level increases; this is identical with Zuber hydrodynamic model [6]. However, at medium and high sub-cooling levels, the CHF become nonlinear and independent of sub-cooling level. The flow velocity delays the onset of CHF occurrence because of the more effective coolant flow onto the heating surface, which leads to increased boiling heat transfer capabilities. For the system pressure effect, the CHF is increased as the pressure is increased in low-pressure condition (less than 0.2 reduced pressure, 8 bar for R-134a and 45 bar for water). The increased system pressure usually hinders nucleate bubble boiling leading to the film boiling stage in low-pressure condition and leads to a slightly higher upper limit of CHF [7]. However, it is noted that more research is necessary to establish the quantitative correlation of CHF prediction with several system parameters including surface characteristics.

Recently researchers have documented the effect of the surface wetting characteristics on CHF performance. Liaw and Dhir [8] studied pool boiling of saturated water at atmospheric pressure (1 bar) on a vertical surface. They applied a surface treatment to the heating surface using oxidation, and the static contact angle was measured indicating the degree of wettability. Their findings indicated that the CHF increased with decreasing static contact angle. In their pool boiling heat transfer test, the normalized critical heat flux was measured as a function of static contact angle for both water and R-113 as working fluids. The data obtained with both fluids at a low static contact angle (≈18°) indicate good agreement with Zuber’s hydrodynamic theory. However, for contact angles ranging from 27° to 107°, the deviation error between the measured critical heat fluxes and those predictions by Zuber’s model becomes large and unpredictable. Therefore, Kolev [9] concluded that the surface wettability, i.e. static contact angle, is an important parameter for CHF prediction even though it cannot be easily implemented into existing classical models. Recently, Kim [10] showed that the estimated heat-flux gain due to capillary liquid supply along the porous layer was of the same order of magnitude as that due to wettability enhancement. Significant CHF enhancement of nano-fluid during pool boiling is a consequence of not only increased surface wettability, but also improved capillary resulting from the surface deposition of nanoparticles. A consensus explanation of the cause of CHF enhancement in nano-fluids seems to be obtainable via an intense study on the surface characteristics. In order words, the CHF of a nano-fluid is enhanced by its improved ability to actively wet the heating surface.

Despite these numerous efforts on understanding CHF mechanism, a complete understanding of the nature of the flow boiling CHF under low pressure condition has not been achieved. Furthermore, the surface wettability effect on CHF in flow boiling conditions has not yet been significantly investigated in the CHF technical community. This study aimed to expand the understanding of CHF phenomenon with macroscopic system parameter’s effect as well as microscopic surface characteristic.

2. Experimental setup

2.1. R-134a forced convection boiling test loop

In this current research, critical heat flux measurement and visualization have been carried out with R-134a as the working fluid under forced convection boiling condition. The experimental apparatus used in this study consists of: (1) a liquid reservoir of R-134a, (2) a cooler and a gear pump, (3) a test section including copper based heating block and visualization channel, (4) high-speed camera, and (5) a data acquisition system as shown in Fig. 1. The set-up of this experimental apparatus is able to provide...
the capability of observation on sub-cooled flow boiling heat transfer phenomena and to collect critical heat flux data with wide ranges of inlet temperatures, mass flow rates, system pressures, and different surface conditions of heating surface.

A typical and widely used refrigerant, R134a, is chosen as the working fluid for its relatively low critical pressure, saturation temperature, and latent heat. A liquid reservoir of R-134a is used to store refrigerant and stabilize the system pressure. A gear Pump, manufactured by Micro-Pump®, provides a variable range of volumetric flow rates, up to 4 LPM (liter per minute) which are measured by a Coriolis-type mass flow meter, manufactured by Micro-Motion®. An electric pre-heater controls inlet sub-cooling temperature of R-134a at the entrance to the test section, and is installed at upstream of the test section. A throttling valve located at the upstream of the test section is used to avoid flow fluctuations, which usually occur at low flow conditions. The rectangular test section is heated from the bottom by electric copper heater, and three quartz windows are installed on the other three sides of the test section. This enables direct observation of the flow boiling heat transfer phenomena through a high-speed visualization camera. A cooling component is installed downstream of the test section. It cools the refrigerant exiting from the test section, which is especially important for a flow boiling experiment to maintain a constant system pressure. Another cooling sub-loop is installed immediately upstream of the gear pump and downstream of the liquid reservoir, which ensures there is no refrigerant vapor entering the pump. The working fluid for these two cooling sub-loops is R-12, which is then cooled in two commercial water chillers. Numbers of type K thermocouples and BEC strain-gage type pressure transducers are installed in the loop to measure temperature, applied heat flux at the copper surface, and fluid pressure information at several locations as shown in Fig. 1.

2.2. Test section and visualization

A detailed drawing of the test section with exploded view is shown in Fig. 2. The test section consists of a 1 m long rectangular channel made with stainless steel, a copper block heating element with cartridge heaters, and three quartz windows for visual observations. The rectangular copper heating block, 12.7 mm by 107.95 mm width and length, respectively, is installed in the middle of a straight horizontal rectangular stainless steel flow channel. The dimensions of the flow channel are 1 m by 12.7 mm by 12.7 mm (length, with, and height, respectively). Thus, the hydraulic diameter of flow channel is calculated as 12.7 mm and the ratio of heated length to the hydraulic diameter of flow channel is 8.5. The entrance length, which is measured from the entrance of the straight flow channel to the leading edge of the heating surface on the test section, is 490 mm. The ratio of entrance length to the flow channel hydraulic diameter is calculated as 38.58. Thus, the flow profile at the entrance of test section is assumed to be as a fully developed flow. The test section is heated by seven cartridge heaters, which provide a maximum total power of 5050 W (750 W/C2).

Fig. 2. Exploded view of the test section assembly (A: Cartridge heaters, B: Copper base block, C: Heating block, D: Stainless steel flow channel, E: Rear quartz window, F: Front quartz window, G: Top quartz window, H: Rear stainless steel window mounting, I: Front stainless steel window mounting, J: stainless steel window mounting).

2.3. Surface modification with atmospheric pressure plasma

The atmospheric pressure plasma (AP-plasma) is well known for its great advantages in various kinds of industrial coating applications and has been widely used in manufacturing process including flat panel displays, thin films and semiconductor packaging. Surface modifications of copper surface using atmospheric pressure plasma coating are carried out to enhance the surface wettability and reduce static contact angle. Especially metallic surface treatment with AP-plasma technique is a promising way to get hydrophilic surface (heat pipe, advanced condensation or boiling) for various surface treatment applications [11]. In this study, atmospheric pressure plasmas are utilized to modify the heating surface of test section. 300 liter per minute of N2 gas and 0.2 liter per minute of air (N2 gas: Air = 99.4%: 0.06%) was utilized to produce plasma spraying on the current test copper block, the copper surface is placed facing toward to AP-plasma spray with 2.5 mm gap as shown in Fig. 5, the operating time of AP-plasma treatment for test-section copper surface is set to 800 s. Optimal AP-plasma treatment time was determined by the contact angle measurement with identical properties of coupon test over the range of AP-plasma treatment condition.
2.4. Experimental operating condition, testing procedure, and uncertainty analysis

In this study, the experiments on CHF with R-134a were performed with mass fluxes varying from 125 to 225 kg/m²s, pressures from 400 kPa to 800 kPa, and inlet sub-cooling enthalpy from 12 kJ/kg to 26 kJ/kg. Table 1 summarized the experimental test conditions as below. To achieve accurate critical heat flux data in this study, the following procedures were utilized to prepare for data acquisition as follows.
To obtain single boiling curve with CHF point at certain operating condition, many experimental testing procedure for R-134a boiling heat transfer need to follow. First turn on the cooling system to have a high quality of liquid phase of R-134a in whole test loop, and a cooling water loop was used to control the loop temperature. And then, a stable flow rate was obtained using the gear pump, whose flow rate is adjustable and is controlled by an auto-transformer. After the system pressure was stabilized, the inlet temperature was controlled to a desired level using the pre-heater, and mass flux was set as a selected value by adjusting the pump. Once the mass flux, system pressure, and inlet sub-cooling temperature are maintained as desired, the power to the test section was increased gradually in small steps. At each power level, the test parameters are allowed to stabilize for several minutes to achieve a quasi-steady state condition before raising the power level again. Prior to CHF occurrence, all test conditions are stabilized and the power to the test section is raised in incremental steps of 5–10 W. The onset of CHF is defined as the condition where the surface temperature of the test section rises dramatically. Right after the CHF occurrence, the power supply for the heater was shut down to avoid damage to the heating block and test section (pre-determined set point for the heater was approximately 80 °C). With continuous coolant flow, the wall temperature starts to decrease till nucleate boiling resumes. After investigating on raw data from data collection system, the heat flux and superheated surface temperature are selected at each steady state equilibrium condition. Then, a single boiling curve of R-134a with fixed pressure, mass flux, and inlet sub-cooled enthalpy condition is generated.

The heat flux functions as the experimentally determined parameters; it can be calculated in two manners such as thermal heat flux, electrical heat flux. Thermal heat flux \( q \) is calculated from the gradient of the temperature profiles in the copper block

\[
q^* = -k \frac{\Delta T}{\Delta x}
\]

where, \( k \) is the thermal conductivity of the copper block \([W/(mK)]\), \( \Delta T \) is the temperature difference between two thermocouples lying in the same vertical plane \([\degree C]\), and \( \Delta x \) is the distance \([m]\) between the thermocouples. The uncertainty of thermal heat flux is calculated using the Holman uncertainty calculation method as follows \([12]\):

\[
\frac{\omega_{\Delta T}}{q^*} = \sqrt{\left(\frac{\omega_i}{k}\right)^2 + \left(\frac{\omega_{\Delta T}}{\Delta T}\right)^2 + \left(\frac{\omega_{\Delta x}}{\Delta x}\right)^2}
\]

where, \( \omega \) is the statistical uncertainty value for each variable.

\[
\frac{\omega_{\Delta T}}{q^*} = \sqrt{(0.03^2) + (0.015)^2 + (0.045)^2} = 0.0561
\]

The uncertainty in the vertical distance between two thermocouples embedded in the copper block was estimated to be ±3%, which was determined from the positioning accuracy. The uncertainty of the thermal conductivity of the copper block was assumed to be ±1.5% based on thermo physical property table. The uncertainty of the temperature differential was estimated to be ±4.5% at the critical heat flux. Therefore, the total experimental uncertainty for the thermal heat flux was estimated to be ±5.61% at the critical heat flux points.

### 3. Results and discussion

Individual boiling curve and CHF point under various operating conditions were obtained in this study. In addition, bubble dynamics under flow boiling conditions are well captured with reasonable resolution using the high-speed video camera. Fig. 6 shows the visualization of the nucleate boiling near by the heating surface from the side view with increasing wall heat flux. At the low heat flux the bubble nucleating occurs at the heating surface independently, and as heat flux increase, the bubble departure diameter and frequency of bubble detachment start increasing. As the heat flux reaches to the critical heat flux level. The bubble interactions (i.e. bubble coalescence or break-up) become rigorous dominant and finally at the critical heat flux the film of vapor cover the heating surface and heat transfer mechanism rapidly degraded. An exact understanding of parametric trends of CHF is very important to develop a reliable CHF prediction model. Although there has been significant research on parametric trends of CHF \([13–15]\), some aspects are still not answered completely and surface characteristic effects on CHF need further investigation. Previous researchers have not adequately addressed, especially, parametric trends of CHF under the low pressure low flow (LPLF) condition. In this study, operating system pressure applying to CHF test is mainly low pressure condition where reduced pressure \((P/P_c)\) is below 0.2, the range of mass flux for CHF test is also arranged below 300 kg/m\(^2\)s. Therefore, the effect of system pressure, mass flux, and sub-cooled inlet enthalpy on R-134a CHF under low-pressure (less than 0.2 of reduced pressure), low-flow condition (below than 300 kg/m\(^2\)s) was investigated in following sections.

In flow boiling experiment, sudden temperature rising at the heating surface or significant heat flux drop is a good indicator for the onset of CHF. Fig. 7 shows the present test’s surface temperature profile as time progress with applying incremental heat flux on the heating surface, also demonstrates sudden temperature rising at the near CHF point. Usually about 4–5 h to produce a single boiling curve of each CHF testing condition was required in this study. A boiling curve in the present R-134a flow boiling CHF measurement at pressure 500 kPa, inlet temperature of 4 °C, and mass flux of 186 kg/m\(^2\)s is presented in Fig. 8. The temperatures measured from the heated wall represent the typical relation of heat flux vs. wall superheated temperature between a single-phase region (conductive heat transfer, no bubble generation) and two-phase region (nucleate boiling dominant, effective heat transfer mechanism). Visualization from side view was performed mainly in the two-phase region, from a low heat flux (10–15% of CHF) of the ONB (Onset of Nucleating Boiling) with discrete bubbles, to a near CHF with large vapor clots, by a violent coalescing behavior of those bubbles.

#### 3.1. Effect of inlet sub-cooling enthalpy on CHF

For CHF of forced convection boiling in vertical and horizontal uniformly heated tubes, it is reported that plots of CHF against sub-cooled inlet temperature of fixed mass flux and pressure often indicated the linear relationship \([16]\), and it can be written as follows:

\[
q_{\text{CHF,sub-cooled}} = q_{\text{CHF, saturation}} \left(1 + \frac{Ah}{T_{\text{fg}}}ight)
\]

The quantitative CHF increase with increase in inlet sub-cooling level is shown in Fig. 9. With higher sub-cooled fluid entering the

### Table 1

<table>
<thead>
<tr>
<th>Experimental parameter</th>
<th>Experimental condition (water equivalent condition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (kPa)</td>
<td>400–800 kPa (2600–5000 kPa)</td>
</tr>
<tr>
<td>Mass flux of R-134a (kg/m(^2)s)</td>
<td>124–248 kg/m(^2)s (176–355 kg/m(^2)s)</td>
</tr>
<tr>
<td>Inlet sub-cooling enthalpy (kJ/kg)</td>
<td>12–26 kJ/kg</td>
</tr>
</tbody>
</table>
heating zone, more effective boiling heat transfer takes place at the heating surface. Although the effect of inlet sub-cooled temperature on CHF in present study was not large, it was clear that the CHF increased with the increase in inlet sub-cooled temperature. Most of the previous investigators have reported that the inlet sub-cooling effect on CHF is negligible for low pressure \[17–19\], present experiments result show that the inlet sub-cooling effect certainly exists in low pressure low flow condition. Therefore, it can be concluded that the sub-cooling inlet temperature is a key parameter for the determination of CHF in sub-cooled flow boiling cases.

3.2. Effect of mass flux on CHF

Generally, it is reported that the CHF increases with the increase of mass flux for fixed system pressure, and sub-cooled temperature, however, the rate of increase decreases with increasing mass flux. The mass flux effect on CHF under the low flow condition follows a positive trend with sharp gradient. Beyond 1500 kg/m\(^2\)s of mass flux condition, the mass flux effect on CHF is negligible, whereas the CHF are more likely predominantly dependent of the equilibrium quality which is related to inlet sub-cooled temperature in fixed inlet condition \[20\]. In this study, CHF was measured for different mass flux conditions with fixed inlet sub-cooling level and pressures. Three mass fluxes were selected: 126.6 kg/m\(^2\)s, 190.4 kg/m\(^2\)s, and 253.3 kg/m\(^2\)s, respectively with a fixed sub-cooling enthalpy of 18 kJ/kg and a pressure range of 400–700 kPa. The quantitative CHF increase with mass flux found in current experimental data is shown in Fig. 10. At the boiling surface, i.e. interface between liquid phase and vapor phase, a high mass flux is important to detach bubbles from the heating surface, and to avoid the coalescence of bubbles, which can trigger film boiling, or onset of critical heat flux. Therefore, it is also reasonably accepted that the mass flux is one of key parameter that determines CHF.
3.3. Effect of system pressure on CHF

It is generally known that CHF increases with the increase of pressure, goes through a maximum where the reduced pressure is around 0.2, then decreases with pressure [19]. As pressure increases, surface tension, latent heat of vaporization and steam-to-water specific volume ratio decrease. In particular, the specific volume ratio decreases sharply from about 1600 at 1 bar to about 55 at 50 bar, then it decreases slowly with increasing pressure. Fig. 11 indicated the CHF variation according to reduced pressure, \( \frac{P}{P_{cr}} \) [a dimensionless parameter defined as its actual pressure (\( P \))] divided by its critical pressure (\( P_{cr} \)), extracted from the CHF look-up table for different mass flux (300 kg/m\(^2\)s, 500 kg/m\(^2\)s, 750 kg/m\(^2\)s) and fixed exit quality (\( X_{exit} = -0.05 \)) conditions. As seen from Fig. 11, CHF increases with increase of reduced pressure till 0.2, and then CHF decrease with increase of reduced pressure.

The effect of system pressure on CHF observed in this study is presented in Fig. 12. In the figure, the CHF increases with the increase in the pressure range of 4–8 bar (below than 0.2 reduced pressure for R-134a). Kim [21] also reported that at low-pressure conditions CHF is proportional to the system pressure in linear fashion. A trend of CHF with system pressure in this present study also show good agreement with CHF look-table result and other literature for system pressures of less than 0.2 reduced pressure; 400 kPa, 500 kPa, 600 kPa, 700 kPa, and 800 kPa, respectively.

3.4. R-134a to water scaling method and comparison work

Flow boiling CHF experiments using water as working fluid suffer from high temperatures and high pressures and encounter certain difficulties, for example, high expenditure for materials and more complex experimental platform construction. To avoid these difficulties, Barnett was the first investigator to propose fluid-to-fluid CHF modeling using low latent heat of working fluid such as Freon R-12, R-35 and developed scaling laws for application [22]. The scaling factors is be determined by the classical dimensional analysis or similarity theories. The results derived from modeling experiments of CHF in R134a can be extended to apply to prototype fluid (i.e. water) according to fluid-to-fluid scaling factors. The purpose of this conversion to water and R134a is to reduce the expenditure and difficulties of prototype experiments under high temperature and pressure. Actually, the CHF phenomenon is too complicated to be described in a mathematical equation accurately, so the most effective way to study the essence of CHF is to use dimensional analysis method to find out the relationships among all the main variables. Ahmad’s compensated distortion model and the Katto model are widely used and are accurate enough in engineering applications [23,24]. Katto model (Fluid-to-Fluid Scaling Method) is chosen as scaling models in this study. Katto introduced five dimensionless groups to fluid-to-fluid CHF modeling method based on dimensional analysis and the similarity criteria formula as follows:

\[
\frac{q_{CHF}}{G^2D} = f\left(\frac{\sqrt{\eta D}}{\sqrt{\sigma \rho_l}}, \frac{\Delta H}{\lambda}, \rho_l, \frac{L}{D}\right)
\]

To develop fluid-to-fluid CHF model in prototype fluid (water) using modeling fluid (R-134a) with Katto method, the following equations should be satisfied at the same time:

\[
\left(\frac{L}{D}\right)_p = \left(\frac{L}{D}\right)_M : \text{Size modeling factor (F}_L\)
\]

\[
\left(\frac{\Delta H}{\lambda}\right)_p = \left(\frac{\Delta H}{\lambda}\right)_M : \text{Latent modeling factor (F}_H\)
\]

\[
\left(\frac{\rho_l}{\rho_k}\right)_p = \left(\frac{\rho_l}{\rho_k}\right)_M : \text{Pressure modeling factor (F}_P\)
\]

\[
\left(\frac{G\sqrt{D}}{\sqrt{\sigma \rho_l}}\right)_p = \left(\frac{G\sqrt{D}}{\sqrt{\sigma \rho_l}}\right)_M : \text{Mass flux modeling factor (F}_C\)
\]

Three equations (4–6), (4–7) and (4–8) of the four criteria equations are identical except the fourth one (4–9). That is to say, there is only one condition different for the two modeling models. The following items can be used to calculate the four modeling scaling factors: \( F_L, F_P, F_H, \) and \( F_C. \)

(a) Because of the uncertain influence of flow channel on fluid modeling of CHF, geometry size of model is usually the same as prototype. Herein, geometric similarity is assumed as factor of \( F_L = 1. \)

(b) Find out the pressure of prototype fluid and the pressure of modeling fluid at the same density ratio point. Then pressure modeling scaling factor \( F_P \) can be obtained by \( \frac{P_{lp}}{P_{mp}}. \)

(c) Latent modeling scaling factor \( F_H \) can be determined by \( \Delta H_{lp}/\Delta H_{mp}. \)
A summary of R-134a–water scaling factor. 

**Table 2**

Selected conditions in R-134a and the corresponding conditions in water.

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>R-134a Saturation temp. °C</th>
<th>Water Mass Flux (R-134a), kg/m² s</th>
</tr>
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<tbody>
<tr>
<td>4</td>
<td>26</td>
<td>124</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>186</td>
</tr>
<tr>
<td>6</td>
<td>38</td>
<td>248</td>
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<tr>
<td>7</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>50</td>
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</tr>
</tbody>
</table>

**Table 3**

A summary of R-134a–water scaling factor.

<table>
<thead>
<tr>
<th>No.</th>
<th>R-134a, pressure (bar)</th>
<th>F_L</th>
<th>F_P</th>
<th>F_H</th>
<th>F_C</th>
<th>F_CHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.0</td>
<td>1</td>
<td>6.50</td>
<td>9.55</td>
<td>1.44</td>
<td>13.75</td>
</tr>
<tr>
<td>5</td>
<td>5.0</td>
<td>1</td>
<td>6.40</td>
<td>9.56</td>
<td>1.44</td>
<td>13.77</td>
</tr>
<tr>
<td>6</td>
<td>6.0</td>
<td>1</td>
<td>6.33</td>
<td>9.55</td>
<td>1.43</td>
<td>13.66</td>
</tr>
<tr>
<td>7</td>
<td>7.0</td>
<td>1</td>
<td>6.43</td>
<td>9.53</td>
<td>1.43</td>
<td>13.36</td>
</tr>
<tr>
<td>8</td>
<td>8.0</td>
<td>1</td>
<td>6.25</td>
<td>9.52</td>
<td>1.42</td>
<td>13.52</td>
</tr>
</tbody>
</table>

**Fig. 12.** Effect of system pressure on CHF with a range of mass flux of 124–248 kg/m² s and a range of sub-cooled enthalpy of 14–26 kJ/kg.

(d) Mass flux modeling scaling factor $F_C$ can be calculated as follows:

$\left( \frac{\sqrt{P}}{\sqrt{h}} \right)_P / \left( \sqrt{P} \right)_M$

The selected operating condition in R-134a CHF test and water equivalent condition are tabulated in Table 2. All the four modeling scaling factors of R-134a to water ($F_L$, $F_P$, $F_H$, and $F_C$) were calculated based on the thermo physical properties data published in ASHRAE for R134a and reference for water [25] as shown in Table 3. The validity of the fluid-to-fluid modeling method was confirmed by comparing the water equivalent CHF data converted from R-134a flow boiling experimental data with existing CHF data in water provided from CHF look-up table [26].

The validity of the fluid-to-fluid modeling method was performed. Comparison between water equivalent CHF and 2006 CHF look-up table was also conducted along pressures range of 4, 5, 6, 7, and 8 bars. A good agreement is achieved between the water equivalent CHF data converted from R-134a CHF data and the existing water CHF data from 2006 CHF look-up table under identical operating conditions, with an error of 25% as indicated in Fig. 13.

### 3.5. Effect of surface modification by AP-plasma

In this study, atmospheric pressure (AP) plasma coating has been applied for surface modification of the copper heating block. Nitrogen gas is fed into the upper-grounded electrode, the lower electrode is connected to the high-voltage power supply and covered with a layer of dielectric, and then a stable plasma spray is formed and blown out into air. Many plasma applications in the surface modification are made at reduced pressure in the order of 1–10 Pa, and many kinds of low-pressure plasma systems have been developed up to now [27]. Generally, these plasma systems require vacuum equipment, which make complexity and cost for materials processing. AP-plasma, however, can provide an advantage over the low pressure plasma system because they do not need vacuum equipment and they have been shown to be of prospect for a number of industrial applications. The AP-plasma gas temperature is only 25–30 °C, thus thermal damage to treated materials can be easily avoided. For these reasons, AP-plasma can be easily employed in this experimental setting for modifying surface at atmospheric pressure. AP-plasma has shown great promise when applied to change the surface properties of metals, and better hydrophilicity of metal surface is achieved [28].

In this research, we introduce a state of the art technique of atmospheric pressure plasma coating which is excited by a low frequency (30 kHz) of 12 kV and 2.8 kW DC power supply. The gas temperature of AP-plasma is at about room temperature 25–30 °C, so the plasma jet spray is more suitable for treating vulnerable object. The gap between plasma spray and copper block is fixed as 2.5 mm. The AP-plasma treatment time for the copper block is manually set at 80 s for each surface treatment. The surface was initially cleaned with air blower and acetone leaching to eliminate any impurity on it. After AP-plasma treatment is completed, the treated surface was sealed by contamination free paper till the test section is remounted into the flow loop. With the AP-plasma, hydrophilic surface fabrication process was conducted by using nitrogen gas with small amount of air or hydrogen insertion.
In order to understand the surface morphologies of untreated (plain) and treated samples, optical CCD image and scanning electron microscopy (SEM) image were taken, as shown in Fig. 14.

To identify the surface feature change after AP-plasma treatment, static contact angle measurement with sessile drop method and visualization of contact angle change were performed. Copper coupons (diameter of 25.4 mm with 3 mm thickness, like the size of a quarter coin), with identical properties to that of the copper block in test was prepared to conduct contact angle measurement, thickness measurement at different AP-plasma operating time. Figs. 15 and 16 demonstrate the contact angle reduction in measurement and visualizations of contact angle change with increasing AP-plasma treatment time. The thickness of oxidation layer on top of copper surface is saturated to about 3 µm with 400 s of AP-plasma operating time. The decrease of the water contact angle indicates that the chemical changes have taken place at the copper surface due to atmospheric pressure plasma treatment [29]. Thus, these changes make the treated copper surfaces more hydrophilic compared to the original surfaces. As shown in Fig. 16, after 400 s of AP-plasma treatment, the water contact angle on treated surface reduced to 15–21°, from the original contact angle (~80°) on pure copper surface. It is noted that overlong time of AP-plasma treatment may not always be good for retaining the most hydrophilic modification in term of contact angle reduction as shown in Fig. 15.

The static contact angle is the contact angle that a droplet would form with a given material if the surface of that material were perfectly flat. It is a good indication of the fluid wettability on the heating surface. Since the actual bubble dynamic contact angle on the heating surface under flow conditions are very hard to observe, especially at high flow rate and high heat flux condition, the bubble dynamic contact angle measurements are difficult to achieve. Fortunately, with static contact angle available from the sessile drop method, the bubble dynamic contact angle can be replaced with static contact angle in terms of evaluating the effect of fluid wettability [30] (see Fig. 17).

AP-plasma treated surface modification adopted in this study was prepared before flow boiling tests. Modified surface is

![Image](https://via.placeholder.com/150)

**Fig. 13.** Ratios of the water-equivalent CHF data converted from the CHF data in R-134a to the CHF data from 2006 look-up table with identical operating condition along with pressure.

![Image](https://via.placeholder.com/150)

**Fig. 14.** Observation of copper surface with and without treatment (a) ×500 optical CCD image on untreated pure Cu surface, (b) SEM image for Cu surface before plasma treatment, (c) ×500 optical CCD image on plasma treated Cu surface, (d) SEM image for Cu surface.
remounted into the flow boiling test loop and CHF measurement tests were conducted under different operating conditions. The static contact angle of modified surface is measured as 18°, which is around 60° of contact angle reduction compared to that of untreated original copper surface (80°). Taking the baseline case (pressure of 4 bar, mass flux of 124 kg/m² s and 14 kJ/kg of inlet sub-cooled enthalpy) as an example, the CHF value with untreated copper surface was measured at 495 kw/m², and the measured CHF value with AP-plasma treated copper surface was at 584 kw/m². It was observed that an 18% of CHF enhancement was achieved in this case. In order to achieve repeatability, several CHF measurement tests were conducted in different operating condition with modified surface by AP-plasma. From the analysis of parametric trends study and assessments of surface modification effect on the CHF, the following conclusions can be made; (1) The observed parametric trends of CHF data based on fixed inlet condition agree with those in previous studies. For low pressure (less than 0.2 reduced pressure, in case of R-134a, it ranges from 1 bar to 8 bar) the CHF increases with increase in pressure. A same trend is also found in water CHF data in 2006 look-up table; (2) Fluid-to-fluid scaling method of Katto [24] was used to convert the CHF data of R-134a into the equivalent CHF data of water. Then the equivalent CHF data is compared with water CHF look-up table data. The comparison study showed good agreement with less than 25% of deviation; (3) AP-plasma technique was applied to modify the heating surface of copper. The surface feature of treated heater was identified by reduction of static contact angle (80° to 15°); (4) the enhancement of CHF with reduction of static contact angle is observed in experimental results. It is found that the CHF value is improved 18% from AP-plasma treatment on the heating surface. A most plausible reason for CHF enhancement is that wettability changing with AP-plasma treated heating surface compared to collected in this study. However, the current experimental result of CHF enhancement with AP-plasma treatment is consistent with previous finding and expands the prospect of CHF enhancement in flow boiling condition. This fact suggests that the change of surface wettability is the most plausible reason for CHF enhancement. However, the sustainability of AP-plasma coating on the flow boiling condition with various pressure conditions needs to be further investigated for practical operating perspective. Also the water based CHF flow boiling with AP-plasma assisted surface modification in low pressure (reduced pressure less than 0.2) and high pressure (reduced pressure larger than 0.2) is strongly suggested for further research to evaluate the clear link between wettability and CHF enhancement.

4. Summary and conclusions

In this study, sub-cooled flow boiling CHF with R-134a on copper heating surfaces was experimentally investigated to understand the effects of both macroscopic and microscopic operating parameters. A total of 36 CHF data were obtained for low pressure (less than 0.2 reduced pressure) and following conditions (P = 400–800 kPa, G = 124–248 kg/m² s, Δh = 9–45 kJ/kg) to investigate CHF behavior. In addition, surface modification using AP-plasma was conducted for copper heating surface. From the analysis of parametric trends study and assessments of surface modification effect on the CHF, the following conclusions can be made; (1) The observed parametric trends of CHF data based on fixed inlet condition agree with those in previous studies. For low pressure (less than 0.2 reduced pressure, in case of R-134a, it ranges from 1 bar to 8 bar) the CHF increases with increase in pressure. A same trend is also found in water CHF data in 2006 look-up table; (2) Fluid-to-fluid scaling method of Katto [24] was used to convert the CHF data of R-134a into the equivalent CHF data of water. Then the equivalent CHF data is compared with water CHF look-up table data. The comparison study showed good agreement with less than 25% of deviation; (3) AP-plasma technique was applied to modify the heating surface of copper. The surface feature of treated heater was identified by reduction of static contact angle (80° to 15°); (4) the enhancement of CHF with reduction of static contact angle is observed in experimental results. It is found that the CHF value is improved 18% from AP-plasma treatment on the heating surface. A most plausible reason for CHF enhancement is that wettability changing with AP-plasma treated heating surface compared to

![Fig. 15. The contact angle measurements along with AP-plasma treatment time (80–800 s).](image1)

![Fig. 16. A series of picture of reduced contact angle along with increasing AP-plasma time.](image2)

![Fig. 17. Comparison between CHF measurement with AP-plasma treatment and without treatment.](image3)
the reference untreated heating surface. The sustainability of AP-plasma coating under flow boiling condition needs to be further evaluated for economic of boiling heat transfer system.

Conflict of interest

None declared.

References


