CHAPTER 4

SATURATED FLOW BOILING OF R-407C IN A HORIZONTAL NARROW ANNULAR DUCT

Results from the present measured heat transfer data and observed bubble characteristics for the saturated flow boiling of R-407C in the narrow annular duct affected by the refrigerant mass flux, system pressure and duct size are examined here. In the tests we have saturated liquid R-407C at the inlet of the duct ($x_{in} = 0$). The experiments are performed for the refrigerant mass flux varying from 300 to 600 kg/m$^2$s, imposed heat flux $q$ from 0 to 45 kW/m$^2$ with the system pressure set at 776 kPa and 899 kPa (corresponding to the R-407C saturation temperature $T_{sat}=10^\circ$C and $15^\circ$C) for the annular gap of the duct $\delta=1.0$ mm and 2.0 mm. The measured boiling heat transfer data are expressed in terms of the boiling curves and boiling heat transfer coefficient. Besides, the close view flow photos taken at a small region around the middle axial station $z =80$ mm are presented to illustrate the bubble characteristics in the boiling flow. Then, comparison between the R-134a and R-407C saturated flow boiling data is conducted. Furthermore, the present data of R-407C heat transfer coefficient in the saturated flow boiling are compared with some existing correlations in the literature. Finally, empirical correlations will be proposed to correlate the present data for the saturated flow boiling heat transfer coefficient, mean bubble departure diameter, mean bubble departure frequency and average active nucleation site density.

4.1 Single-phase Heat Transfer

Before beginning the two-phase flow boiling experiments, the single-phase convective heat transfer experiments are conducted for liquid R-407C. The measured single-phase convection heat transfer coefficients are compared with the correlations proposed by Dittus-Boelter [33] and Gnielinski [42]. In the single-phase heat transfer tests the refrigerant mass flux is varied from 200 to 1,050 kg/m$^2$s for the annular gap of the duct $\delta=1.0$ mm and 2.0 mm (corresponding to the Reynolds number of the refrigerant flow...
from 3,459 to 14,640) for the refrigerant saturate temperature $T_{\text{sat}}=15\, ^\circ \text{C}$ and inlet liquid subcooling $\Delta T_{\text{sub}}=3\, ^\circ \text{C}$. Selected results from these tests are plotted in Figure 4.1.

The Dittus-Boelter correlation is

$$Nu_f = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \quad \text{for } Re > 10^4$$

(4.1)

and the Gnielinski correlation is

$$Nu_f = \frac{\left(\frac{f_f}{8}\right)(Re-1000) Pr}{1+12.7\sqrt{\frac{f_f}{8}}(Pr^{\frac{2}{3}}-1)} \quad \text{for } 2,300 < Re < 10^6$$

(4.2)

where $f_f = (1.82 \times \log_{10} Re - 1.64)^{-2}$

(4.3)

The results in Figure 4.1 manifest that the present data for $h_1$ can be well correlated by the Gnielinski correlations with a mean absolute error of 3.9%.

### 4.2 Saturated Flow Boiling Curves

The effects of the refrigerant mass flux, refrigerant saturated temperature and gap size of the duct on the R-407C saturated flow boiling characteristics at the middle axial location ($z = 80$ mm) of the narrow annular duct are shown in Figures 4.2-4.4 by presenting the boiling curves for various $G$, $T_{\text{sat}}$ and $\delta$.

First, the effects of the refrigerant mass flux on the saturated flow boiling curves are shown in Figure 4.2. The results indicate that at a low imposed heat flux the wall superheat is lower than that for the onset of nucleate boiling (ONB) and no bubble nucleates from the heating surface. Hence heat transfer in the flow results completely from the single-phase forced convection. As the imposed wall heat flux is raised gradually, the wall superheat increases correspondingly. At a certain wall superheat bubbles start to nucleate from the heating surface and we have onset of nucleate boiling in the flow. Beyond the ONB there is a significant increase in the slope of the boiling curves, implying that a small rise in the wall superheat causes a large increase in the heat transfer rate from the wall to refrigerant. Note that beyond ONB the boiling curves are only slightly affected by the refrigerant mass flux, suggesting that the heat transfer is dominated by the bubble nucleation on the heating
surface. But the required imposed heat flux and wall superheat to achieve ONB are influenced noticeably by the change in the mass flux. Specifically, the required imposed heat flux and wall superheat to achieve ONB are slightly higher for a higher mass flux due to the thinner thermal boundary layer. When compared with the results for the subcooled flow boiling to be presented in chapter 5, no apparent temperature overshoot occurs during the onset of boiling when the flow is saturated.

Then, the data shown in Figure 4.3 suggest that the boiling curves slightly shift to the right for a reduction in the refrigerant saturated temperatures. Besides, the wall superheat at ONB is slightly higher at the lower $T_{sat}$. It is due to the higher surface tension force for a lower $T_{sat}$ for R-407C and the bubble nucleation is more difficult. Then, the effects of the duct size on the saturated flow boiling curves are shown in Figure 4.4. It is noted that the boiling curve shifts significantly to the left as the gap in the duct is reduced, indicating that the boiling heat transfer in the smaller duct is substantially better. It is also evident from the data that lower imposed heat flux and wall superheat are needed to initiate boiling on the heated surface for the smaller duct. This mainly results from the fact that for given $G$, $q$ and $T_{sat}$ the mass flow rate through the duct is lower for a smaller gap. For the lower refrigerant mass flow rate the axial temperature rise of the refrigerant flow is faster, which, in turn, causes earlier bubble nucleation for a smaller gap.

### 4.3 Saturated Flow Boiling Heat Transfer Coefficient

The effects of the refrigerant mass flux, duct size and refrigerant saturated temperature on the saturated flow boiling heat transfer of R-407C at the middle axial location ($z = 80$ mm) in the narrow annular duct are shown in Figures 4.5-4.7 by presenting the saturated flow boiling heat transfer coefficient against the imposed heat flux for various $G$, $T_{sat}$ and $\delta$. The results indicate that at given $G$, $T_{sat}$ and $\delta$ the saturated boiling heat transfer coefficient increases substantially with the imposed heat flux. For example, at $T_{sat} = 15^\circ C$, $\delta = 1.0$ mm and $G = 500$ kg/m$^2$s, the saturated boiling heat transfer coefficient for $q = 45$ kW/m$^2$ is about 148% higher than that for $q = 9$ kW/m$^2$ (Figure 4.5(b)). This large increase in the saturated boiling heat transfer coefficient is ascribed to the higher active nucleation site density on the heating surface and higher bubble departure frequency for a higher imposed heat flux. The data shown in Figures 4.5 and 4.6 suggest that the saturation temperature and mass flux of the refrigerant exhibits relatively weak effects on the boiling
heat transfer coefficient. The heat transfer coefficient for a higher saturated temperature is only slightly higher. Then, the data shown in Figure 4.7 indicate that the saturated boiling heat transfer increases noticeably with a decrease in the channel gap. For example, at \( q = 45 \text{ kW/m}^2 \), \( T_{\text{sat}} = 15^\circ \text{C} \) and \( G = 500 \text{ kg/m}^2\text{s} \) the saturated boiling heat transfer coefficient for \( \delta = 1.0 \text{ mm} \) is about 38\% higher than that for \( \delta = 2.0 \text{ mm} \) (Figure 4.7(a)). Since the shear stress of the flow acting on the heated surface in a smaller channel is higher, the bubbles on the heating surface can be more easily swept away from the heated surface. Moreover, the flow pattern change from the bubbly flow to the slug flow for \( \delta = 1.0 \text{ mm} \) occurs at a lower imposed heat flux than that for \( \delta = 2.0 \text{ mm} \). These effects are thought to be the main reasons for the enhancement of flow boiling heat transfer when the channel size is reduced.

### 4.4 Bubble Characteristics in Saturated Flow Boiling

The bubble characteristics in the narrow duct around the middle axial location for \( \delta = 1.0 \text{ mm} \) affected by the R-407C refrigerant mass flux and saturated temperature and the imposed heat flux are illustrated by the photos in Figure 4.8. First of all, it is noted from the photo taken from the duct for \( \delta = 1.0 \text{ mm} \) shown in Figure 4.8(a) for the case at \( T_{\text{sat}} = 15^\circ \text{C} \) and \( G = 500 \text{ kg/m}^2\text{s} \) at the imposed heat flux \( q = 15 \text{ kW/m}^2 \) that a number of discrete bubbles nucleate from the cavities and slide along the heating surface. As the imposed heat flux is increased to \( q = 25 \text{ kW/m}^2 \), the active bubble nucleation density increases and a lot of coalescence bubbles appear (Figure 4.8(b)). More coalescence bubbles are seen and they are confined by the duct walls to become slightly deformed as the heat flux is raised to \( q = 35 \text{ kW/m}^2 \) (Figure 4.8(c)). At even higher heat fluxes the duct is filled with the coalescence bubbles and the bubble characteristics can not be measured. The results in Figures 4.8(a)-(f) indicate that at a higher mass flux the liquid refrigerant flow moves at a higher speed, which in turn tends to sweep the bubbles more quickly away from the heating surface. Besides, the bubble departure frequency is higher and the bubbles are smaller and in violent agitating motion. However, the higher liquid speed causes the shorter residence time of the refrigerant on the heating surface and the liquid is heated to a lower temperature, resulting in a smaller active nucleation site density at a higher mass flux. Note that at the lower mass flux the bubble coalescence is more important and a number of bigger bubbles form in the duct. Then, the effects of the refrigerant saturation
temperature on the bubble characteristics are illustrated by comparing the photos in Figures 4.8(d)~(f) with Figures 4.8(g)~(i). The results indicate that at a lower saturation temperature the bubbles grow bigger and depart at a lower rate, and the active nucleation site density is lower due to the higher surface tension and enthalpy of vaporization. The photos of the boiling flow taken for the cases at different duct sizes and imposed heat fluxes in the small region around the middle axial location are shown in Figure 4.9. It is noted that more bubbles appear in the narrower duct at the imposed heat flux \(q=15\ \text{kW/m}^2\) (Figures 4.9(a) and (d)). As the imposed heat flux is increased to \(q=25\ \text{kW/m}^2\) (Figures 4.9(b) and (e)), in the smaller duct the bubble departure frequency is higher and the bubbles collide and coalesce more frequently due to the less space available for the boiling flow (the confinement effect). As the heat flux is raised to \(q=35\ \text{kW/m}^2\) (Figures 4.9(c) and (f)), in the smaller duct large coalesced bubbles dominate. For a further increase in the imposed heat flux, the flow pattern in the middle portion of the small duct \(\delta = 1.0\ \text{mm}\) changes from a bubbly flow regime to a slug flow regime.

To be more quantitative on the bubble characteristics, we move further to estimate the average bubble departure diameter and frequency and the average active bubble nucleation site density on the heating surface for the cases with the bubbly flow dominated in the duct from the images of the boiling flow stored in the video tapes. The results from this estimation are examined in the following. The effects of the three parameters, namely, the refrigerant mass flux, refrigerant saturated temperature and duct size on the mean bubble departure diameter for the saturated flow boiling of R-407C at the middle axial location \(z=80\ \text{mm}\) in the annular duct are shown in Figures 4.10-4.12 by presenting the average bubble departure diameter against the imposed heat flux for various \(G, T_{\text{sat}}\) and \(\delta\). First, the effects of the refrigerant mass flux on the average bubble departure diameter shown in Figure 4.10 indicate that the average departing bubble is only slightly larger for a lower refrigerant mass flux. For example, at \(q =25\ \text{kw/m}^2, T_{\text{sat}} =15\ \text{C}\) and \(\delta = 1.0\ \text{mm}\), the average bubble departure diameter for \(G =500\ \text{kg/m}^2\text{s}\) is only about 8% larger than that for \(G =600\ \text{kg/m}^2\text{s}\) (Figure 4.10(b)). Then, the results in Figure 4.11 indicate that the average bubble departure diameter is smaller for a higher refrigerant saturated temperature. For instance, at \(q =25\ \text{kw/m}^2, G =500\ \text{kg/m}^2\text{s}\) and \(\delta = 2.0\ \text{mm}\), the average departing bubble for \(T_{\text{sat}} =10\ \text{C}\) is about 20% larger than that for \(T_{\text{sat}} =15\ \text{C}\) (Figure 4.11(a)). Finally, it is of interest to note from the data given in Figure 4.12 that the effects of the duct gap on the
bubble departure diameter are relatively small.

How the bubble departure frequency is affected by the three parameters for the saturated flow boiling of R-407C at the middle axial location (z =80 mm) in the annular duct are shown in Figures 4.13-4.15 by presenting the average bubble departure frequency against the heat flux for various G, T_{sat} and δ. Note that the increase of the bubble departure frequency with the imposed heat flux is rather significant for all cases presented here. First, the effects of the refrigerant mass flux on the saturated flow boiling average bubble departure frequency are shown in Figure 4.13. The results indicate that the average bubble departure frequency is somewhat higher for a higher refrigerant mass flux. For example, at q =25 kw/m^2, T_{sat} =15 ℃ and δ = 1.0 mm, the average bubble departure frequency for G =600 kg/m^2s is about 22% higher than that for G =500 kg/m^2s (Figure 4.13(b)). Then, the data given Figure 4.14 indicate that the average bubble departure frequency is slightly higher for a higher saturated temperature. As an example, at q =25 kw/m^2, G =600 kg/m^2s and δ = 1.0 mm the average bubble departure frequency for T_{sat} =15 ℃ is about 10% higher than that for T_{sat} =10 ℃ (Figure 4.14(b)). Finally, the effects of the duct size on the saturated flow boiling average bubble departure frequency shown in Figure 4.15 manifest that the average bubble departure frequency is also slightly higher in the smaller duct. For instance, at q =25 kw/m^2, T_{sat} =15 ℃ and G =500 kg/m^2s the average bubble departure frequency for δ = 1.0 mm is about 11% higher than that for δ = 2.0 mm (Figure 4.15(a)).

The number density of the active nucleation sites for ONB affected by the three parameters for the saturated flow boiling of R-407C at the middle axial location (z =80 mm) in the annular duct are shown in Figures 4.16-4.18 by presenting the average active nucleation site density against the imposed heat flux for various G, T_{sat} and δ. The data clearly show the substantial increase of the active nucleation site density with the imposed heat flux for all cases examined here. First, the effects of the refrigerant mass flux on the saturated flow boiling average active nucleation site density are shown in Figure 4.16. The results indicate that the average active nucleation site density is significantly higher for a smaller refrigerant mass flux except at low imposed heat flux. For example, at q =25 kw/m^2, T_{sat} =15 ℃ and δ = 1.0 mm, the average active nucleation site density for G =500 kg/m^2s is about 33% higher than that for G =600 kg/m^2s (Figure 4.16(b)). Then, the data
shown in Figure 4.17 suggest that the average active nucleation site density increases significantly with $T_{\text{sat}}$. As an example, at $q = 25$ kw/m$^2$, $G = 500$ kg/m$^2$s and $\delta = 2.0$ mm the average active nucleation site density for $T_{\text{sat}} = 15^\circ$C is about 19% higher than that for $T_{\text{sat}} = 10^\circ$C (Figure 4.17(a)). Finally, the effects of the duct size on the saturated flow boiling average active nucleation site density shown in Figure 4.18 manifest that the effect of the gap size for average active nucleation site density is insignificant.

4.5 Comparison between R-407C and R-134a Flow Boiling

We move further to compare the present data for the R-407C saturated flow boiling characteristics with measured data for R-134a from Lie [43] in the same narrow annular duct. The results from this comparison are shown in Figures 4.19-4.24. The results in Figure 4.19 indicate that a higher imposed heat flux is needed to initiate boiling for R-134a especially when the duct gap is smaller (Figure 4.19(b)). This can be attributed to the lower surface tension for R-407C. Besides, the slopes of the boiling curves for R-407C are much steeper particularly for the narrower duct with $\delta = 1.0$ mm, suggesting the saturated flow boiling heat transfer for R-407C is much better. Indeed, the data in Figure 4.20 manifest that R-407C has a much higher boiling heat transfer coefficient except at the low heat flux near ONB. For example, at $T_{\text{sat}} = 15^\circ$C, $G = 500$ kg/m$^2$s, $\delta = 1.0$ mm and $q = 45$ kW/m$^2$, the saturated boiling heat transfer coefficient for R-407C is about 45% higher than that for R-134a (Figure 4.20(b)).

The bubble characteristics in the narrow duct around the middle axial location at $T_{\text{sat}} = 15^\circ$C, $G = 600$ kg/m$^2$s and $\delta = 1.0$ mm for refrigerants R-407C and R-134a are illustrated by the photos in Figure 4.21. Because of the lower surface tension force, the departing bubbles are smaller for R-407C. However, the bubble departure frequency of R-407C is higher than R-134a. It is also noted that the active nucleation site density for R-407C is higher than R-134a, and there are more coalescence bubbles seen in the R-407C flow boiling. Then, the mean bubble departure diameters for the two refrigerants for selected cases are shown in Figure 4.22. It is noted that the mean bubble departure diameter for R-407C is significantly smaller than R-134a. For example, at $T_{\text{sat}} = 15^\circ$C, $G = 500$ kg/m$^2$s, $\delta = 1.0$ mm and $q = 30$ kw/m$^2$, the average bubble departure diameter for R-134a is about 70% larger than that for R-407C (Figure 4.22(b)). Then, the mean bubble
departure frequencies for R-134a and R-407C are shown in Figure 4.23. It is noted that the mean bubble departure frequency for R-407C is substantially higher than R-134a, especially at high imposed heat flux. For example, at $T_{\text{sat}} = 15^\circ \text{C}$, $G = 500 \text{ kg/m}^2\text{s}$, $\delta = 1.0 \text{ mm}$ and $q = 30 \text{ kw/m}^2$, the average bubble departure frequency for R-407C is about 27% larger than that for R-134a (Figure 4.23(b)). Finally, the mean active nucleation site densities for the two refrigerants are shown in Figure 4.24. The results indicate that the mean active nucleation site density for R-407C is higher than R-134a only at high imposed heat flux for the smaller duct (Figure 4.24(b)).

### 4.6 Comparison with Existing Correlations

Moreover, the present data for the R-407C saturated flow boiling heat transfer coefficient are compared with some existing empirical correlations proposed in the literature. These correlations are listed in Table 1.2. The results from this comparison are shown in Figure 4.25. Note that the correlation from Lazarek and Black [4] substantially overpredicts our data. Besides, the correlations from Bao et al. [6], Tran et al. [17], Lin and Winterton [35] and Kandlikar [38] overpredict our data to some degree. However, our data are well correlated by the correlation of Fujita et al. [5] (Figure 4.25(b)). To be more quantitative the mean deviations between our data and these correlations $\varepsilon$ and the fraction of our data predicted within $\pm 30\%$ by these correlations $\lambda$ are given in Table 4.1.

### 4.7 Correlation Equations

According to flow boiling mechanisms, the heat transfer in the flow boiling in the bubbly flow regime can be roughly considered as a combination of single-phase convection heat transfer $q_c$ and pool boiling heat transfer $q_b$. Thus the total heat flux input to the boiling flow $q_t$ can be expressed as

$$q_t = q_b + q_c \quad (4.4)$$

Here $q_b$ and $q_c$ can be calculated from the relations

$$q_b = \rho \dot{V}_b f N_{\text{nc}} l_g \quad (4.5)$$

and

$$q_c = h_l \Delta T_{\text{sat}} \quad (4.6)$$

Note that $q_b$ expressed in Equation (4.5) in fact represents the latent heat carried away from the heating surface during the departure of bubbles from the surface. The single-phase
forced convection heat transfer coefficient is estimated from the correlation for the Nusselt number $\text{Nu}_l$ as

$$ h_l = \text{Nu}_l \frac{k_l}{D_h} \quad (4.7) $$

Note that $\text{Nu}_l$ is estimated from the Gnielinski correlation [42],

$$ \text{Nu}_l = \frac{f_l/8}{1 + 12.7 f_l / 8 (Pr_l/2.5 - 1)} , \text{ for } Re_l \geq 2,300 \quad (4.8) $$

Here the friction factor $f_f$ is evaluated from the relation

$$ f_f = (1.82 \times 10^3) \log_{10}(Re_l - 1.64) - 2 \quad (4.9) $$

Moreover, the Reynolds number of the liquid flow is defined as

$$ Re_l = \frac{GD_l (1 - x)}{\mu_l} \quad (4.10) $$

In the above equations $\rho_g$ is the vapor density, $V_g$ is the mean vapor volume of a departing bubble which is equal to $\frac{4\pi}{3} \left( \frac{d_p}{2} \right)^3$, $f$ is bubble departure frequency, $N_{ac}$ is the active nucleation site density, $i_{fg}$ is the enthalpy of vaporization. Because the range of experimental $Re_l$ is between 5600 to 11500, we use Gnielinski correlation for $Re_l > 2,300$ to represent single phase convection heat transfer term ($h_l$). It is difficult to distinguish the individual bubbles at a higher imposed heat flux. Hence the above correlations do not apply to the data for $q > 30 \text{ kW/m}^2$.

To enable the usage of the above correlation for the flow boiling heat transfer in the bubbly flow regime, the mean bubble size and departure frequency and the active nucleation density on the heating surface need to be correlated in advance. The average bubble departure diameter in the saturated flow boiling of R-407C in the narrow annular duct estimated from the present flow visualization can be correlated as

$$ \frac{d_p}{\sqrt{\frac{\sigma}{g\Delta\rho}}} = 0.9 \left( \frac{\rho_l}{\rho_g} \right)^{0.25} \text{Re}_l^{0.2} \cdot \text{Bo}^{0.2} \cdot N_{conf}^{-0.2} \quad (4.11) $$

Figure 4.26 shows that almost all the present experimental data for $d_p$ fall within $\pm 20\%$ of the above correlation and the mean absolute error is $5\%$. Besides, an empirical equation is proposed for the product of the mean bubble departure diameter and departure frequency
\[
\frac{f \cdot d_p}{\mu_l/(\rho_l D_h)} = 1.61 Re_l^{1.4} \cdot Pr_l^2 \cdot Bo^{0.7} \cdot N_{conf}
\] (4.12)

Note that almost all the experimental data for \( f \cdot d_p \) collected in this study can be correlated within ±30% by Equation (4.12) and the mean absolute error is 19% (Figure 4.27). Finally, we propose an empirical correlation for the average active nucleation site density in the saturated flow boiling of R-407C as

\[
N_{ac} \cdot d_p^2 = -0.009 + 1000 Bo^{1.25} Re_l^{0.05} N_{conf}^{0.06}
\] (4.13)

Figure 4.28 shows that nearly all the present experimental data fall within ±30% of the above correlation and the mean absolute error is 18%.

When the correlations for \( d_p, f, \) and \( N_{ac} \) given in Equations (4.12)-(4.14) are combined with Equations (4.4)-(4.11) for \( q_i \), most heat transfer data measured in the present study fall within ±30% of the correlation proposed here with the mean absolute error of 20.5% (Figure 4.29).

### 4.8 Concluding Remarks

The experimental heat transfer data for the saturated flow boiling of R-407C in the narrow annular duct have been presented here. Meanwhile, the bubble behavior in the boiling flow is examined. The effects of the imposed heat flux, refrigerant mass flux, saturated temperature, and duct size on the R-407C saturated flow boiling heat transfer coefficient and associated bubble characteristics have been investigated in detail. Besides, the present data are compared with those for R-134a in the same narrow duct. Moreover, comparison of the present data with some existing correlations is conducted. The major results obtained here can be summarized in the following.

1. The temperature overshoot at ONB are insignificant for the saturated flow boiling of R-407C in the horizontal narrow annular duct.

2. The saturated boiling heat transfer coefficients increase with a decrease in the gap size.
Besides, raising the imposed heat flux can cause a significant increase in the boiling heat transfer coefficient. However, the effects of the refrigerant mass flux and saturated temperature on the boiling heat transfer coefficient are small.

(3). The results from the flow visualization show that the mean diameter of the bubbles departing from the heating surface decreases slightly with increasing refrigerant mass flux and with increasing refrigerant saturated temperature. Besides, at a high imposed heat flux many bubbles generated from the cavities in the heating surface tend to merge together to form big bubbles. The bubble departure frequency increases with the increasing refrigerant mass flux and saturated temperature and with the decreasing duct size. The active nucleation site density is much lower at a higher refrigerant mass flux and lower saturation temperature.

(4). The comparison of the present data for the R-407C saturated flow boiling with R-134a shows that the flow boiling heat transfer in R-407C is better than R-134a at high imposed heat flux. The mean bubble departure diameter of R-407C is substantially smaller than R-134a. The mean bubble departure frequency of R-407C is higher than R-134a.
Table 4.1 Comparison between various heat transfer correlations and present experimental data sets

<table>
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<tr>
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<td>ε (%)</td>
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<tr>
<td>Lazarek and Black [4]</td>
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<td>Fujita et al. [5]</td>
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<td>Kandlikar [38]</td>
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Fig. 4.1 Comparison of the present single-phase liquid convection heat transfer data $h_l(a)$ and $N_u_l(b)$ with the correlations of Gnielinski and Dittus-Boelter.
Fig. 4.2  Saturated flow boiling curves for R-407C for various refrigerant mass fluxes at (a) \( T_{\text{sat}} = 15^\circ\text{C} \) & \( \delta = 2.0 \text{ mm} \) and (b) \( T_{\text{sat}} = 15^\circ\text{C} \) & \( \delta = 1.0 \text{ mm} \). (ONB(300) denotes the ONB for \( G = 300 \text{ kg/m}^2\text{s} \))
Fig. 4.3 Saturated flow boiling curves for R-407C for various refrigerant saturated temperatures at (a) $G=500\,\text{kg/m}^2\text{s}$ & $\delta = 2.0\,\text{mm}$ and (b) $G=600\,\text{kg/m}^2\text{s}$ & $\delta = 1.0\,\text{mm}$. 
Fig. 4.4 Saturated flow boiling curves for R-407C for various gap sizes at (a) $T_{\text{sat}}=15^\circ\text{C}$ & $G=500\text{kg/m}^2\text{s}$ and (b) $T_{\text{sat}}=15^\circ\text{C}$ & $G=400\text{kg/m}^2\text{s}$. 
Fig. 4.5  Saturated flow boiling heat transfer coefficient for R-407C for various refrigerant mass fluxes at (a) $T_{\text{sat}}=15^\circ\text{C}$ & $\delta = 2.0$ mm and (b) $T_{\text{sat}}=15^\circ\text{C}$ & $\delta = 1.0$ mm.
Fig. 4.6 Saturated flow boiling heat transfer coefficient for R-407C for various refrigerant saturated temperatures at (a) $G=500\,\text{kg/m}^2\text{s}$ & $\delta = 2.0\,\text{mm}$ and (b) $G=600\,\text{kg/m}^2\text{s}$ & $\delta = 1.0\,\text{mm}$. 
Fig. 4.7 Saturated flow boiling heat transfer coefficient for R-407C for various gap sizes at (a) $T_{\text{sat}}=15 \, ^\circ\text{C}$ & $G=500 \, \text{kg/m}^2\text{s}$ and (b) $T_{\text{sat}}=15 \, ^\circ\text{C}$ & $G=400 \, \text{kg/m}^2\text{s}$. 
Fig. 4.8 Photos of bubbles in the saturated flow boiling of R-407C in a small region around middle axial location at $\delta=1$ mm for various imposed heat fluxes, mass fluxes and saturated temperatures.
Fig. 4.9 Photos of bubbles in the saturated flow boiling of R-407C in a small region around middle axial location at T$_{sat}$=15°C & G=500kg/m²s for various imposed heat fluxes and gap sizes.
Fig. 4.10 Saturated flow boiling mean bubble departure diameter for various refrigerant mass fluxes at (a) $T_{sat} = 15^\circ C$ & $\delta = 2.0$ mm and (b) $T_{sat} = 15^\circ C$ & $\delta = 1.0$ mm.
Fig. 4.11 Saturated flow boiling mean bubble departure diameter for various refrigerant saturated temperatures at (a) $G = 500$ kg/m$^2$s & $\delta = 2.0$ mm and (b) $G = 600$ kg/m$^2$s & $\delta = 1.0$ mm.
Fig. 4.12 Saturated flow boiling mean bubble departure diameter for various gap sizes at (a) $T_{\text{sat}} = 15^\circ C$ & $G = 500 \text{ kg/m}^2\text{s}$ and (b) $T_{\text{sat}} = 15^\circ C$ & $G = 400 \text{ kg/m}^2\text{s}$. 
Fig. 4.13 Saturated flow boiling mean bubble departure frequency for various refrigerant mass fluxes at (a) $T_{\text{sat}} = 15^\circ \text{C}$ & $\delta = 2.0 \text{ mm}$ and (b) $T_{\text{sat}} = 15^\circ \text{C}$ & $\delta = 1.0 \text{ mm}$. 

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Fig. 4.14 Saturated flow boiling mean bubble departure frequency for various refrigerant saturated temperatures at (a) $G = 500 \text{ kg/m}^2\text{s}$ & $\delta = 2.0 \text{ mm}$ and (b) $G = 600 \text{ kg/m}^2\text{s}$ & $\delta = 1.0 \text{ mm}$. 
Fig. 4.15 Saturated flow boiling mean bubble departure frequency for various gap sizes at (a) $T_{\text{sat}} = 15^\circ \text{C}$ & $G = 500$ kg/m$^2$s and (b) $T_{\text{sat}} = 15^\circ \text{C}$ & $G = 400$ kg/m$^2$s.
Fig. 4.16 Saturated flow boiling mean active nucleation site density for various refrigerant mass fluxes at (a) $T_{\text{sat}} = 15^\circ\text{C}$ & $\delta = 2.0 \text{ mm}$ and (b) $T_{\text{sat}} = 15^\circ\text{C}$ & $\delta = 1.0 \text{ mm}$. 
Fig. 4.17 Saturated flow boiling mean active nucleation site density for various refrigerant saturated temperatures at (a) $G = 500 \text{ kg/m}^2\text{s}$ & $\delta = 2.0 \text{ mm}$ and (b) $G = 600 \text{ kg/m}^2\text{s}$ & $\delta = 1.0 \text{ mm}$. 
Fig. 4.18 Saturated flow boiling mean active nucleation site density for various gap sizes at (a) $T_{\text{sat}} = 15^\circ\text{C}$ & $G = 500$ kg/m$^2$s and (b) $T_{\text{sat}} = 15^\circ\text{C}$ & $G = 400$ kg/m$^2$s.
Fig. 4.19 Saturated flow boiling curves for various refrigerants at (a) $T_{\text{sat}}=15 \, ^\circ\text{C}$, $G=500 \, \text{kg/m}^2\text{s} \, \delta = 2.0 \, \text{mm}$ and (b) $T_{\text{sat}}=15 \, ^\circ\text{C}$, $G=500 \, \text{kg/m}^2\text{s} \, \delta = 1.0 \, \text{mm}$. 

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Fig. 4.20 Saturated flow boiling heat transfer coefficient for various refrigerants at (a) $T_{\text{sat}}=15^\circ\text{C}$, $G=500\text{kg/m}^2\text{s}$ & $\delta = 2.0 \text{ mm}$ and (b) $T_{\text{sat}}=15^\circ\text{C}$, $G=500\text{kg/m}^2\text{s}$ & $\delta = 1.0 \text{ mm}$. 

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Fig. 4.21 Photos of bubbles in the saturated flow boiling in a small region around middle axial location at $T_{\text{sat}}=15^\circ\text{C}$, $G=600\text{kg/m}^2\text{s}$ & $\delta = 1.0 \text{ mm}$ for various imposed heat fluxes and refrigerants.
Fig. 4.22 Saturated flow boiling mean bubble departure diameter for various refrigerants at (a) $T_{\text{sat}}=15^\circ\text{C}$, $G=500\,\text{kg/m}^2\text{s}$ & $\delta = 2.0\,\text{mm}$ and (b) $T_{\text{sat}}=15^\circ\text{C}$, $G=500\,\text{kg/m}^2\text{s}$ & $\delta = 1.0\,\text{mm}$.
Fig. 4.23 Saturated flow boiling mean bubble departure frequency for various refrigerants at (a) $T_{\text{sat}}=15^\circ\text{C}$, $G=500\text{ kg/m}^2\text{s}$ & $\delta = 2.0 \text{ mm}$ and (b) $T_{\text{sat}}=15^\circ\text{C}$, $G=500\text{ kg/m}^2\text{s}$ & $\delta = 1.0 \text{ mm}$.
Fig. 4.24 Saturated flow boiling mean active nucleation site density for various refrigerants at (a) $T_{\text{sat}}=15^\circ\text{C}$, $G=500\text{ kg/m}^2\text{s}$ & $\delta = 2.0$ mm and (b) $T_{\text{sat}}=15^\circ\text{C}$, $G=500\text{ kg/m}^2\text{s}$ & $\delta = 1.0$ mm.
Fig. 4.25 Comparison of the present data for heat transfer coefficient in the saturated flow boiling of R-407C with the proposed correlation of (a) Lazarek and Black (1982), (b) Fujita et al. (2000), (c) Bao et al. (2000), (d) Tran et al. (1996), (e) Lin and Winterton (1991), and (f) Kandlikar (1990).
Fig. 4.25 Continued
Fig. 4.25 Continued.
Fig. 4.26 Comparison of the measured data for mean bubble departure diameter in the saturated flow boiling of R-407C with the proposed correlation.
Fig. 4.27 Comparison of the measured data for mean bubble departure frequency in the saturated flow boiling of R-407C with the proposed correlation.
Fig. 4.28 Comparison of the measured data for mean active nucleation site density in the saturated flow boiling of R-407C with the proposed correlation.
Fig. 4.29 Comparison of the measured data for heat transfer coefficient in the saturated flow boiling of R-407C in the bubbly flow regime with the proposed correlation.