CHAPTER 5

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

The present data for the subcooled flow boiling heat transfer and associated bubble characteristics of refrigerant R-407C flowing in the horizontal narrow annular duct are inspected in this chapter. The experiments were conducted for the refrigerant mass flux $G$ varying from 300 to 600 kg/m$^2$s, imposed heat flux $q$ from 0 to 45 kW/m$^2$, inlet liquid subcooling $\Delta T_{\text{sub}}$ from 3 to 6 ℃, duct gap $\delta$ from 1.0 to 2.0 mm (corresponding to the hydraulic diameter $D_h$ from 2.0 to 4.0 mm) and the refrigerant saturated temperature $T_{\text{sat}}$ from 10 to 15 ℃ (corresponding to the R-407C saturated pressure from 776 to 899 kPa).

In what follows, the heat transfer characteristics in the R-407C subcooled flow boiling are expressed in terms of the boiling curves, which are the plots for the imposed heat flux $q$ versus the wall superheat ($T_w-T_{\text{sat}}$) for various flow and thermal conditions. Besides, selected experimental data and flow photos from the present study are presented to illustrate the subcooled flow boiling heat transfer coefficient and associated bubble characteristics in the boiling flow including the mean bubble departure diameter, departure frequency and active nucleation site density. Then, comparison between the R-134a and R-407C subcooled flow boiling data in the same annular duct is conducted. Furthermore, the present data of R-407C heat transfer coefficient in the subcooled flow boiling are compared with some existing correlations in the literature. Finally, empirical correlations will be proposed to correlate the present data for the subcooled flow boiling heat transfer coefficient, mean bubble departure diameter, mean bubble departure frequency and average active nucleation site density.

5.1 Subcooled Flow Boiling Curves

The effects of the experimental parameters, namely, the refrigerant mass flux, inlet subcooling, saturated temperature, and gap size of the duct, on the subcooled flow boiling characteristics at the middle axial location ($z = 80$ mm) of the annular duct are shown in
Figures 5.1-5.4 by presenting the boiling curves for various $G$, $\Delta T_{\text{sub}}$, $T_{\text{sat}}$ and $\delta$.

First, the effects of the refrigerant mass flux on the R-407C subcooled flow boiling curves are illustrated in Figure 5.1. The results indicate that for a given boiling curve, at low imposed heat flux the temperature of the heated wall is also below the saturated temperature of R-407C and heat transfer in the duct is completely due to the single-phase forced convection. As the imposed heat flux is raised gradually, the heated wall temperature increases slowly to become above $T_{\text{sat}}$ at a certain $q$ and we have a positive wall superheat $\Delta T_{\text{sat}} (= T_{\text{w}} - T_{\text{sat}})$. When the positive wall superheat reaches certain critical level, a smaller increase in $q$ causes boiling to suddenly appear on the heated wall and the heated wall temperature drops immediately to a noticeable degree. Thus there is a significant temperature overshoot during the onset of nucleate boiling (ONB) in the subcooled flow boiling. Note that the temperature overshoot can be as high as $5.2^\circ C$ for $G = 500 \text{ kg/m}^2\text{s}$, $\delta = 2.0 \text{ mm}$, $T_{\text{sat}} = 15 \text{ }^\circ \text{C}$ and $\Delta T_{\text{sub}} = 3 \text{ }^\circ \text{C}$ (Figure 5.1(a)). Note that the influence of the refrigerant mass flux on the magnitude of the temperature overshoot during ONB is slight. Besides, a slightly higher wall superheat is needed to initiate the nucleate boiling for a higher $G$ due to the thinner thermal boundary layer. Beyond the ONB a small rise in the wall superheat causes a large increase in the wall heat transfer rate and the slopes of the boiling curves are much steeper than those for the single-phase convection. Checking with the data in Figure 5.1 further reveals that beyond ONB the refrigerant mass flux exhibits rather slight effects on the boiling curves. But in the single-phase region the heated wall temperature is somewhat affected by the refrigerant mass flux. The higher $G$ causes the higher liquid velocity in the channel resulting in the shorter time for the refrigerant to be heated. Thus at a higher mass flux the imposed heat flux needed to initiate ONB is larger.

Next, the effects of the inlet liquid subcooling on the subcooled boiling curves are shown in Figure 5.2. A higher wall superheat is needed to initiate the boiling on the heated surface for a higher $\Delta T_{\text{sub}}$. It is also noted that the boiling curves are not affected to a noticeable degree by the subcooling in the two-phase region. It is evident that a higher imposed heat flux is needed to initiate boiling on the heated surface for a higher inlet liquid subcooling for a given $G$. However, in the single-phase region a higher liquid subcooling results in a higher heat transfer from the wall so that at a given wall superheat the imposed heat flux is significantly higher for a higher liquid inlet subcooling.
Then, the effects of the refrigerant saturated temperature on the subcooled boiling curves are shown in Figure 5.3. It is noted that the higher wall superheat and imposed heat flux are needed to achieve ONB for lower saturated temperature. This is attributed to the fact that at a lower $T_{\text{sat}}$ the surface tension of R-407C is higher (Table 2.2). At the higher surface-tension the liquid refrigerant is more difficult to completely flood the cavities, which in turn retards the bubbles to nucleate from the cavities on the heated surface. Thus a higher wall superheat is needed to activate the cavities. Otherwise, the effect of $T_{\text{sat}}$ on the boiling curves is rather slight.

Finally, the effects of the duct gap on the boiling curves are shown in Figure 5.4. It is noted that somewhat lower wall superheat and imposed heat flux are needed to initiate the boiling on the heated surface for a smaller $\delta$. This mainly results from the fact that for given $G$, $q$, $T_{\text{sat}}$ and $\Delta T_{\text{sub}}$ the mass flow rate through the duct is lower for a smaller $\delta$. Thus the axial temperature rise of the refrigerant flow is larger for a smaller $\delta$. It results in a required lower wall superheat and imposed heat flux at ONB. It is also noted that the boiling curves are shifted significantly to the left in the nucleate boiling region as the gap size is decreased, which indicates that the boiling heat transfer in the duct with a small gap is much better.

5.2 Subcooled Flow Boiling Heat Transfer Coefficient

The effects of the four experimental parameters on the subcooled flow boiling heat transfer coefficient measured at the middle axial location ($z = 80$ mm) of the annular duct are shown in Figures 5.5-5.8 by presenting the subcooled flow boiling heat transfer coefficients against the imposed heat flux for various $G$, $\Delta T_{\text{sub}}$, $T_{\text{sat}}$ and $\delta$.

The results in Figures 5.5-5.8 indicate that the increase of the subcooled flow boiling heat transfer coefficient with the imposed heat flux is relatively significant for all cases. We note from Figure 5.5 that the refrigerant mass flux exhibits only a slight effect on the boiling heat transfer coefficient for $\delta = 1.0$ & 2.0 mm. Next, the boiling heat transfer is much better for a smaller inlet liquid subcooling especially at low imposed heat flux (Figure 5.6). For instance, at $q = 40 \text{ kw/m}^2$, $T_{\text{sat}} = 15 ^\circ \text{C}$, $G = 500 \text{ kg/m}^2\text{s}$ and $\delta = 2.0 \text{ mm}$, $h_r$ for $\Delta T_{\text{sub}} = 3 ^\circ \text{C}$ is about 18% higher than that for $\Delta T_{\text{sub}} = 6 ^\circ \text{C}$ (Figure 5.6(a)). Then, the refrigerant saturated temperature shows relatively slight effects on the boiling heat transfer...
coefficient (Figure 5.7). It is of interest to note from the data in Figure 5.8 that reducing the duct size can effectively enhance the subcooled boiling heat transfer in the duct. For the specific case with $q = 40 \text{ kW/m}^2$, $T_{\text{sat}} = 15^\circ\text{C}$, $G = 500 \text{ kg/m}^2\text{s}$ and $\Delta T_{\text{sub}} = 3^\circ\text{C}$, $h_r$ for $\delta = 1.0 \text{ mm}$ is about 40% higher than that for $\delta = 2.0 \text{ mm}$ (Figure 5.8(a)). This is considered to mainly result from the fact that in the narrower duct the radial gradient of the liquid axial velocity is larger, which in turn exerts higher shear force on the bubbles nucleated from the wall and causes them to depart from the heating surface at a higher rate.

### 5.3 Bubble Behavior in Subcooled Flow Boiling

When the wall superheat exceeds the incipient boiling temperature, it is noted from the experiment that tiny bubbles form on the active cavities and grow continuously until they depart from the heating surface. The bubble growth and departure are somewhat regular and the bubbles are nearly spherical in shape at a low imposed heat flux. The bubble formation, growth and detachment processes in the duct obviously depend on the flow and thermal conditions and on the geometry of the cavities.

The characteristics of bubbles in the subcooled flow boiling in a small section around the middle axial location ($z = 80 \text{ mm}$) of the annular duct are illustrated in Figure 5.9 by showing the side view photos taken from the cases at $\delta = 1.0 \text{ mm}$ for different imposed heat fluxes, refrigerant mass fluxes, inlet subcoolings and saturation temperature. First of all, the bubbles at the low $q$ of $25 \text{ kW/m}^2$ for the case at $T_{\text{sat}} = 15^\circ\text{C}$, $G = 500 \text{ kg/m}^2\text{s}$, $\delta = 1.0 \text{ mm}$ and $\Delta T_{\text{sub}} = 3^\circ\text{C}$ can be seen from Figure 5.9(a). Checking with the video tapes recording the bubble motion reveals that the bubbles form and grow at the active nucleation sites while they experience a short period of stationary growth to a certain size. And then the bubbles detach from the heating surface and accelerate into the subcooled liquid. As the imposed heat flux is increased slightly to $q = 35 \text{ kW/m}^2$ (Figure 5.9(b)), more bubbles are nucleated and bubbles are observed to collide and coalesce occasionally. The coalescence bubbles rise faster than the tiny bubbles due to the larger buoyancy force associated with them. As the heat flux is raised to $q = 45 \text{ kW/m}^2$ (Figure 5.9(c)), coalescence of the bubbles occurs more frequently and irregularly. In general, increasing the imposed heat flux directly provides more energy to the cavities and more cavities on the heating surface can be activated. Besides, the higher buoyancy and shear force from higher wall superheat cause the bubble departure frequency to increase substantially with the imposed
heat flux. Moreover, the bubble departure diameter increases slightly with the imposed heat flux due to the higher wall superheat.

Next, Figures 5.9(d)~(f) show the bubble characteristics around the middle axial location affected by the refrigerant mass flux by presenting the photos for the higher mass flux of 600 kg/m$^2$s but at the same $q$, $T_{\text{sat}}$, $\delta$ and $\Delta T_{\text{sub}}$ as that for Figures 5.9(a)~(c). The higher liquid speed for a higher $G$ can sweep the bubbles more quickly away from the cavities resulting in a higher bubble departure frequency and the smaller bubble departure diameter. Hence bubbles are smaller at a high mass flux. Besides, at a higher $G$ the liquid temperature is lower for a given imposed heat flux at a given $\Delta T_{\text{sub}}$. Thus less bubble nucleation is activated on the heated wall and the bubble nucleation density is lower.

Then, the effects of the inlet liquid subcooling on the bubble characteristics around the middle axial location are illustrated by comparing the photos shown in Figures 5.9(g)~(i) with Figures 5.9(a)~(c) respectively for $\Delta T_{\text{sub}}=6\degree C$ and $3\degree C$ at $q=25$~$45$ kW/m$^2$, $G=500$ kg/m$^2$s, $\delta=1.0$ mm and $T_{\text{sat}}=15\degree C$. In general, the mean bubble diameter is larger at a lower liquid subcooling. The larger bubbles are due to the weaker vapor condensation and more bubble coalescence at a lower inlet liquid subcooling. In addition, an increase in the inlet subcooling results in the reduction in the bubble departure frequency and active nucleation sites. This is due to the fact that at a higher inlet liquid subcooling the liquid R-407C temperature at the subcooled liquid-vapor interface is relatively low compared to the hot heated surface. Hence at the same imposed heat flux, the wall superheat is not high enough to sustain the continuing growth of the bubbles when the inlet liquid subcooling is high.

Finally, the effects of the refrigerant saturation temperature on the bubble characteristics around the middle axial location are illustrated by comparing the photos shown in Figures 5.9(j)~(l) with Figures 5.9(a)~(c) respectively for $T_{\text{sat}}=10\degree C$ and $15\degree C$ at $q=25$~$45$ kW/m$^2$, $G=500$ kg/m$^2$s, $\delta=1.0$ mm and $\Delta T_{\text{sub}}=3\degree C$. In general, bubbles are larger at a lower saturation temperature. The larger bubbles are due to the higher surface tension and more bubble coalescence at a lower saturation temperature. Besides, the active nucleation sites increase with increasing saturation temperature due to lower surface tension and enthalpy of vaporization.

The bubble characteristics around the middle axial location affected by the duct
size are shown in Figures 5.10(a)–(f). It is noted that the bubbles in the smaller duct size are slightly bigger. As the imposed heat flux is increased, the bubble departure frequency and diameter are higher and the bubbles collide and coalesce more frequently in the smaller duct size. It is due to the axial temperature rise of the refrigerant flow is larger for a smaller gap, which in turn results in a higher liquid temperature on the interface between gas and liquid. Then, more large bubbles are formed from the coalescence of the small bubbles in the smaller ducts at higher imposed heat flux. As the heat flux is raised to $q=45$ kW/m$^2$ (Figures 5.10(c) and (f)), the bubbles in the smaller duct coalesce more easily and form bigger bubbles. The large bubbles somewhat deform due to the space limitation.

To be quantitative on the bubble characteristics, we move further to estimate the mean bubble departure diameter and frequency and the active nucleation site density in the bubbly flow by carefully tracing the motion of the bubbles from the images of the boiling flow stored in the video taps. These quantitative data illustrating the bubble behavior are examined in the following. The effects of the four experimental parameters on the mean bubble departure diameter for the subcooled flow boiling of R-407C at the middle axial location ($z=80$ mm) of the annular duct are shown in Figures 5.11-5.14 by presenting the average bubble departure diameter against the imposed heat flux for various $G$, $\Delta T_{\text{sub}}$, $T_{\text{sat}}$ and $\delta$. Note that the increase of the bubble departure size with the heat flux is very significant for all cases presented here. First, the effects of the refrigerant mass flux on the mean bubble departure diameter are shown in Figure 5.11. The results indicate that the average bubble departure diameter is slightly larger for a smaller refrigerant mass flux. For example, at $q=35$ kw/m$^2$, $T_{\text{sat}}=15^\circ$C, $\Delta T_{\text{sub}}=3^\circ$C and $\delta=1.0$ mm, the average bubble departure diameter for $G=500$ kg/m$^2$s is only about 13 % larger than that for $G=600$ kg/m$^2$s (Figure 5.11(b)). Next, the effects of the inlet subcooling on the R-407C subcooled flow boiling average bubble departure diameter are shown in Figure 5.12. Note that the average bubble departure diameter is somewhat larger for a smaller liquid subcooling. For example, at $q=35$ kw/m$^2$, $T_{\text{sat}}=15^\circ$C, $G=500$ kg/m$^2$s and $\delta=1.0$ mm, the average bubble departure diameter for $\Delta T_{\text{sub}}=3^\circ$C is about 14 % larger than that for $\Delta T_{\text{sub}}=6^\circ$C (Figure 5.12(b)). Then, the effects of the refrigerant saturated temperature on the subcooled flow boiling average bubble departure diameter are shown in Figure 5.13. The results show that at a higher $T_{\text{sat}}$ the average departing bubble is slightly smaller. Finally, the effects of the duct size on the subcooled flow boiling average bubble departure diameter are shown in
Figure 5.14. The results indicate that the average departing bubbles are slightly larger in the smaller duct especially at high imposed heat flux. For instance, at \( q = 35 \text{ kw/m}^2 \), \( T_{\text{sat}} = 15^\circ \text{C} \), \( G = 500 \text{ kg/m}^2\text{s} \) and \( \Delta T_{\text{sub}} = 3^\circ \text{C} \), the average bubble departure diameter for \( \delta = 1.0 \) mm is about 6% higher than that for \( \delta = 2.0 \) mm (Figure 5.14(a)).

How the refrigerant mass flux, inlet subcooling, refrigerant saturated temperature and duct size affect the measured mean bubble departure frequency for the subcooled flow boiling of R-407C at the middle axial location (\( z = 80 \) mm) of the annular duct are illustrated in Figures 5.15-5.18 by presenting the average bubble departure frequency against the imposed heat flux for various \( G \), \( \Delta T_{\text{sub}} \), \( T_{\text{sat}} \) and \( \delta \). The increase of the bubble departure frequency with the imposed heat flux is clearly seen from the data in Figures 5.15-5.18. First, the effects of the refrigerant mass flux on the subcooled flow boiling mean bubble departure frequency are shown in Figure 5.15. The results indicate that the average bubble departure frequency is somewhat higher for a larger refrigerant mass flux especially at high imposed heat flux. For example, at \( q = 35 \text{ kw/m}^2 \), \( T_{\text{sat}} = 15^\circ \text{C} \), \( \Delta T_{\text{sub}} = 3^\circ \text{C} \) and \( \delta = 1.0 \) mm, the average bubble departure frequency for \( G = 600 \text{ kg/m}^2\text{s} \) is about 15% higher than that for \( G = 500 \text{ kg/m}^2\text{s} \) (Figure 5.15(b)). Next, the effects of the inlet subcooling on the subcooled flow boiling average bubble departure frequency are shown in Figure 5.16. Note that the average bubble departure frequency is also somewhat higher for a smaller liquid subcooling. For instance, at \( q = 35 \text{ kw/m}^2 \), \( T_{\text{sat}} = 15^\circ \text{C} \), \( G = 500 \text{ kg/m}^2\text{s} \) and \( \delta = 1.0 \) mm, the average bubble departure frequency for \( \Delta T_{\text{sub}} = 3^\circ \text{C} \) is about 17% higher than that for \( \Delta T_{\text{sub}} = 6^\circ \text{C} \) (Figure 5.16(b)). Then, the effects of the refrigerant saturated temperature on the subcooled flow boiling average bubble departure frequency are shown in Figure 5.17. The results indicate that the average bubble departure frequency is slightly higher for a higher refrigerant saturation temperature. As an example, at \( q = 35 \text{ kw/m}^2 \), \( G = 500 \text{ kg/m}^2\text{s} \), \( \delta = 1.0 \) mm and \( \Delta T_{\text{sub}} = 3^\circ \text{C} \), the average bubble departure frequency for \( T_{\text{sat}} = 15^\circ \text{C} \) is about 11% higher than that for \( T_{\text{sat}} = 10^\circ \text{C} \) (Figure 5.17(b)). Finally, the effects of the duct size on the subcooled flow boiling average bubble departure frequency are shown in Figure 5.18. The results indicate that the average bubble departure frequency is noticeably higher for a smaller duct. For instance, at \( q = 35 \text{ kw/m}^2 \), \( T_{\text{sat}} = 15^\circ \text{C} \), \( G = 500 \text{ kg/m}^2\text{s} \) and \( \Delta T_{\text{sub}} = 3^\circ \text{C} \), the average bubble departure frequency for \( \delta = 1.0 \) mm is about 14% higher than that for \( \delta = 2.0 \) mm (Figure 5.18(a)).
The effects of the refrigerant mass flux, inlet subcooling, refrigerant saturated temperature and duct size on the number density of the active bubble nucleation sites in the subcooled flow boiling of R-407C at the middle axial location (z =80mm) of the annular duct are shown in Figures 5.19-5.22. For all cases the increase of the active nucleation site density with the imposed heat flux is rather pronounced. The results also indicate that the average active nucleation site density is significantly higher for a smaller refrigerant mass flux. For example, at \(q =35 \text{ kw/m}^2\), \(T_{\text{sat}} =15^\circ \text{C}\), \(\Delta T_{\text{sub}} = 3^\circ \text{C}\) and \(\delta = 1.0 \text{ mm}\), the average active nucleation site density for \(G =500 \text{ kg/m}^3\text{s}\) is about 25% higher than that for \(G =600 \text{ kg/m}^3\text{s}\) (Figure 5.19(b)). Next, the effects of the inlet liquid subcooling on the subcooled flow boiling average active nucleation site density shown in Figure 5.20 indicate that the average active nucleation site density is somewhat higher for a smaller liquid subcooling. As an example, at \(q =35 \text{ kw/m}^2\), \(T_{\text{sat}} =15^\circ \text{C}\), \(G =500 \text{ kg/m}^3\text{s}\) and \(\delta = 1.0 \text{ mm}\), the average active nucleation site density for \(\Delta T_{\text{sub}} = 3^\circ \text{C}\) is about 11% higher than that for \(\Delta T_{\text{sub}} = 6^\circ \text{C}\) (Figure 5.20(b)). Then, the data shown in Figure 5.21 indicate that the average active nucleation site density is noticeably higher for a higher refrigerant saturation temperature. As an example, at \(q =35 \text{ kw/m}^2\), \(G =500 \text{ kg/m}^3\text{s}\), \(\delta = 1.0 \text{ mm}\) and \(\Delta T_{\text{sub}} = 3^\circ \text{C}\), the average active nucleation site density for \(T_{\text{sat}} =15^\circ \text{C}\) is about 18% higher than that for \(T_{\text{sat}} =10^\circ \text{C}\) (Figure 5.21(b)). Then, the results in Figure 5.22 show that the influence of duct size for average active nucleation site density is insignificant.

### 5.4 Comparison between R-407C and R-134a Flow Boiling

We move further to compare the present data for the R-407C subcooled 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 5.23-5.28. The results in Figure 5.23 indicate that a higher wall superheat is needed to initiate boiling for R-134a. 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 \(\delta =1.0 \text{ mm}\), suggesting the subcooled flow boiling heat transfer for R-407C is much better. Indeed, the data in Figure 5.24 manifest that R-407C has a much higher boiling heat transfer coefficient except at the low heat flux near ONB. For example, at \(T_{\text{sat}} =15^\circ \text{C}\), \(\Delta T_{\text{sub}} = 3^\circ \text{C}\), \(G =500 \text{ kg/m}^3\text{s}\), \(\delta =1.0 \text{ mm}\) and \(q = 45 \text{ kW/m}^2\), the subcooled boiling heat transfer
coefficient for R-407C is about 41% higher than that for R-134a (Figure 5.24(b)).

The bubble characteristics in the narrow duct around the middle axial location at $T_{\text{sat}} = 15^\circ C$, $\triangle T_{\text{sub}} = 3^\circ C$, $G = 500$ kg/m$^2$s and $\delta = 1.0$ mm for refrigerants R-407C and R-134a are illustrated by the photos in Figure 5.25. By checking the video tape, the departing bubbles are smaller for R-407C due to lower surface tension force. And the bubble departure frequency of R-407C is higher than R-134a resulting from the lower surface tension force and smaller bubble departure diameter. Note that the active nucleation site density for R-407C is substantially higher than R-134a, and there are more coalescence bubbles seen in the photos. Then, the mean bubble departure diameters for the two refrigerants are shown in Figure 5.26. It is noted that the mean bubble departure diameter for R-407C is significantly smaller than R-134a, resulting from the lower surface tension force. For example, at $T_{\text{sat}} = 15^\circ C$, $\triangle T_{\text{sub}} = 3^\circ C$, $G = 500$ kg/m$^2$s and $q = 35$ kw/m$^2$, the average bubble departure diameter for R-134a is only about 45% larger than that for R-407C (Figure 5.26(b)). Next the effect of the refrigerants on the mean bubble departure frequency is shown in Figure 5.27. It is noted that the mean bubble departure frequency for R-407C is higher than R-134a, especially at high imposed heat flux. For example, at $T_{\text{sat}} = 15^\circ C$, $\triangle T_{\text{sub}} = 3^\circ C$, $G = 500$ kg/m$^2$s and $q = 35$ kw/m$^2$, the average bubble departure frequency for R-407C is only about 24% larger than that for R-134a (Figure 5.27(b)). Finally, the mean active nucleation site densities for the two refrigerants are shown in Figure 5.28. The results indicate that the mean active nucleation site density for R-407C is substantially higher than R-134a, especially at high imposed heat fluxes. For example, at $T_{\text{sat}} = 15^\circ C$, $\triangle T_{\text{sub}} = 3^\circ C$, $G = 500$ kg/m$^2$s and $q = 35$ kw/m$^2$, the mean active nucleation site density for R-407C is only about 31% larger than that for R-134a (Figure 5.28(b)).

5.5 Comparison with Existing Correlations

Moreover, the present data for the R-407C subcooled 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 5.29. 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] also overpredict our data to some degree. However, our
data are well correlated by the correlation of Fujita et al. [5] (Figure 5.25(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 5.1.

### 5.6 Correlation Equations

An empirical equation to correlate the present data of the heat transfer coefficient in the subcooled flow boiling of R-407C in the horizontal annular duct with a narrow gap is proposed here when the bubbly flow dominates in the duct. Based on the present data, the total heat flux input to the boiling flow $q_t$ is considered to consist of two parts: one resulting from the bubble nucleation $q_b$ and another due to the single-phase forced convection $q_c$. Thus

$$q_t = q_b + q_c$$

(5.1)

Here $q_b$ and $q_c$ can be calculated from the quantitative data for the bubble characteristics examined in section 5.3 and single phase forced convection as

$$q_b = \rho_d V_g f N_{ac} i_{fg}$$

(5.2)

and

$$q_c = E h_f (T_w - T_f)$$

(5.3)

Note that in the above equation an enhancement factor $E$ is added to $q_c$ to account for the agitating motion of the bubbles which can enhance the single-phase convection heat transfer. Empirically, $E$ and $h_f$ can be correlated as

$$E = \max(1, N_{conf}^{0.2} F_{fr}^{0.01} (1 + 200 Bo)^{5})$$

(5.4)

and

$$h_f = \frac{N_{ac} \cdot k}{D_h}$$

(5.5)

Note that $N_{ac}$ is estimated from the Gnielinski correlation [42],

$$N_{ac} = \frac{f_f / 8}{1 + 12.7 Re^{1/2} Pr^{1/3} - 1}$$

(5.6)

Here $f_f$ is the friction factor evaluated from the relation [42] and is correlated as

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

(5.7)

Where $\rho_d$ is the vapor density, $V_g$ is the mean vapor volume of the departing bubble which is equal to

$$V_g = \frac{4\pi}{3} \left( \frac{d_p}{2} \right)^3$$

$f$ is the mean bubble departure frequency, $N_{ac}$ is the mean active nucleation site density, $i_{fg}$ is the enthalpy of vaporization. Because the experimental $Re_l$
ranges from 5400 to 11500, we use the Gnielinski correlation for $\text{Re}_l > 2,300$ to evaluate the single-phase forced convection heat transfer. 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 $q > 40 \text{kW/m}^2$.

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

$$
\frac{d_p}{\sqrt{\sigma/(g\Delta \rho)}} = \frac{160N_{\text{conf}} (\rho_l/\rho_g)^{0.6}}{\text{Re}^{0.5} \left[ J_{a2} + \frac{150(\rho_l/\rho_g)^{0.8}}{\text{Bo} \text{Re}^{1.4}} \right]}
$$

(5.8)

Here $J_{a2}$ is Jakob number defined as

$$
J_{a2} = \frac{\rho_l \cdot C_p \cdot \Delta T_{\text{sub}}}{\rho_g \cdot i_{\text{fg}}}
$$

(5.9)

Figure 5.30 shows that almost all the present experimental data for $d_p$ fall within $\pm 25\%$ of the above correlation and the mean absolute error is 13.3\%. Besides, an empirical equation is proposed for the product of the mean bubble departure diameter and frequency as

$$
\frac{f \cdot d_p}{\mu_l/(\rho_l D_h)} = 1600 \cdot \text{Re}_l^{0.887} \cdot J_{a2}^{-0.05} \cdot \text{Bo}^{0.887} \cdot N_{\text{conf}}^{0.3}
$$

(5.10)

Note that almost all the experimental data for $f \cdot d_p$ collected in this study can be correlated within $\pm 20\%$ by Equation (5.10) and the mean absolute error is 10\% (Figure 5.31). Finally, we propose an empirical correlation for the average active nucleation site density in the subcooled flow boiling of R-407C as

$$
N_{\text{ac}} d_p^2 = -0.035 + 1700 \text{Bo}^{-0.25} \text{Re}_l^{-0.25} J_{a2}^{-0.25} N_{\text{conf}}^{-0.05}
$$

(5.11)

Figure 5.32 shows that nearly all the present experimental data fall within $\pm 30\%$ of the above correlation and the mean absolute error is 14.8\%.
When the correlations for \( d_p \), \( f \), and \( N_{ac} \) given in Equations (5.8)-(5.11) are combined with Equations (5.1)-(5.7) for \( q_i \), more than 90% of the heat transfer data for the bubbly flow regime measured in the present study fall within ±30% of the correlation proposed here with a mean deviation of 17.3% (Figure 5.32).

5.7 Concluding Remarks

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

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

2. The subcooled boiling heat transfer coefficient increases with a decrease in the duct size, but decreases with an increase the inlet subcooling. Besides, raising the imposed heat flux can cause a significant increase in the boiling heat transfer coefficients. However, the effects of the refrigerant mass flux and saturated temperature on the boiling heat transfer coefficient are small.

3. Visualization of the bubble motion in the boiling flow reveals that the bubbles are suppressed by raising the refrigerant mass flux and inlet subcooling. The mean bubble departure diameter, mean bubble departure frequency and active nucleation site density are lower with increasing inlet subcooling. Moreover, raising the imposed heat flux produces positive effects on the bubble population, coalescence and departure frequency.

4. The comparison of the subcooled flow boiling data for R-407C and R-134a measured in the same duct shows that R-407C has higher heat transfer coefficient particularly at high imposed heat flux. The mean bubble departure diameter of R-407C is smaller
than R-134a. The mean bubble departure frequency and the active nucleation site density for R-407C are higher than R-134a especially at high imposed heat flux.
Table 5.1 Comparison between various heat transfer correlations and present experimental data sets

<table>
<thead>
<tr>
<th>correlating method</th>
<th>ε(%)</th>
<th>λ(%)</th>
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<tr>
<td>Lazarek and Black [4]</td>
<td>105</td>
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<td>Fujita et al. [5]</td>
<td>16</td>
<td>88</td>
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<td>Bao et al. [6]</td>
<td>64</td>
<td>7</td>
</tr>
<tr>
<td>Tran et al. [17]</td>
<td>82</td>
<td>17</td>
</tr>
<tr>
<td>Liu and Winterton [37]</td>
<td>48</td>
<td>43</td>
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<tr>
<td>Kandlikar [38]</td>
<td>56</td>
<td>12</td>
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Fig. 5.1 Subcooled flow boiling curves for R-407C for various refrigerant mass fluxes at (a) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$, $\delta=2.0$ mm and (b) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$, $\delta=1.0$ mm. (ONB(300) denotes the ONB for $G=300$ kg/m$^2$s)
Fig. 5.2 Subcooled flow boiling curves for R-407C for various inlet subcoolings at (a) $T_{\text{sat}} = 15^\circ C$, $G = 500$ kg/m$^2$s & $\delta = 2.0$ mm and (b) $T_{\text{sat}} = 15^\circ C$, $G = 500$ kg/m$^2$s & $\delta = 1.0$ mm.
Fig. 5.3 Subcooled flow boiling curves for R-407C for various refrigerant saturated temperatures at (a) $G = 500 \text{ kg/m}^2\text{s}$, $\Delta T_{\text{sub}} = 3 \degree C$ & $\delta = 2.0 \text{ mm}$ and (b) $G = 500 \text{ kg/m}^2\text{s}$, $\Delta T_{\text{sub}} = 3 \degree C$ & $\delta = 1.0 \text{ mm}$. 
Fig. 5.4 Subcooled flow boiling curves for R-407C for various gap sizes at (a) $T_{\text{sat}}=15^\circ \text{C}$, $G=500 \text{ kg/m}^2\text{s}$ & $\Delta T_{\text{sub}}=3^\circ \text{C}$ and (b) $T_{\text{sat}}=15^\circ \text{C}$, $G=500 \text{ kg/m}^2\text{s}$ & $\Delta T_{\text{sub}}=6^\circ \text{C}$. 

88
Fig. 5.5 Subcooled flow boiling heat transfer coefficient for R-407C for various refrigerant mass fluxes at (a) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$ & $\delta=2.0\text{ mm}$ and (b) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$ & $\delta=1.0\text{ mm}$. 
Fig. 5.6 Subcooled flow boiling heat transfer coefficient for R-407C for various inlet subcoolings at (a) $T_{sat} = 15^\circ C$, $G = 500 \text{ kg/m}^2\text{s}$ & $\delta = 2.0 \text{ mm}$ and (b) $T_{sat} = 15^\circ C$, $G = 500 \text{ kg/m}^2\text{s}$ & $\delta = 1.0 \text{ mm}$.
Fig. 5.7 Subcooled flow boiling heat transfer coefficient for R-407C for various refrigerant saturated temperatures at (a) $G = 500$ kg/m$^2$s, $\Delta T_{sub}=3^\circ$C & $\delta = 2.0$ mm and (b) $G= 500$ kg/m$^2$s, $\Delta T_{sub}=3^\circ$C & $\delta = 1.0$ mm.
Fig. 5.8 Subcooled flow boiling heat transfer coefficient for R-407C for various gap sizes at (a) $T_{sat}=15^\circ C$, $G=500\ kg/m^2s$ & $\Delta T_{sub}=3^\circ C$ and (b) $T_{sat}=15^\circ C$, $G=500\ kg/m^2s$ & $\Delta T_{sub}=6^\circ C$. 

For subcooled flow boiling, the heat transfer coefficient $h_f$ is a function of the quality $x$, the mass velocity $G$, and the subcooling temperature $\Delta T_{sub}$. The data points in the graphs represent different gap sizes $\delta$, with $\delta = 2.0\ mm$ and $\delta = 1.0\ mm$. The graphs show a clear trend of increasing $h_f$ with increasing $q$ (heat flux).
<table>
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<th>G (kg/m²s), T_{sat} (°C), ΔT_{sub} (°C)</th>
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</thead>
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<td>a</td>
<td>d</td>
<td>g</td>
<td>j</td>
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<td>(a)</td>
<td>(d)</td>
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<tr>
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<td>b</td>
<td>e</td>
<td>h</td>
<td>k</td>
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<tr>
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<td>c</td>
<td>f</td>
<td>i</td>
<td>l</td>
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</table>

Fig. 5.9 Photos of bubbles in the subcooled flow boiling of R-407C in a small region around middle axial location for δ= 1 mm for various imposed heat flux, mass fluxes, inlet liquid subcoolings and saturated temperature.
Fig. 5.10 Photos of bubbles in the subcooled flow boiling of R-407C in a small region around middle axial location at $T_{\text{sat}}=15^\circ \text{C}$, $G=500\text{kg/m}^2\text{s}$ & $\Delta T_{\text{sub}}=3^\circ \text{C}$ for various imposed heat fluxes and gap sizes.
Fig. 5.11 Subcooled flow boiling mean bubble departure diameter for various refrigerant mass fluxes at (a) $T_{\text{sat}} = 15^\circ\text{C}$, $\Delta T_{\text{sub}} = 3^\circ\text{C}$ & $\delta = 2.0$ mm and (b) $T_{\text{sat}} = 15^\circ\text{C}$, $\Delta T_{\text{sub}} = 3^\circ\text{C}$ & $\delta = 1.0$ mm.
Fig. 5.12 Subcooled flow boiling mean bubble departure diameter for various inlet subcoolings 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. 5.13 Subcooled flow boiling mean bubble departure diameter for various refrigerant saturated temperatures at (a) $G = 500 \text{ kg/m}^2\text{s}$, $\Delta T_{\text{sub}} = 3^\circ \text{C}$ & $\delta = 2.0 \text{ mm}$ and (b) $G = 500 \text{ kg/m}^2\text{s}$, $\Delta T_{\text{sub}} = 3^\circ \text{C}$ & $\delta = 1.0 \text{ mm}$. 
Fig. 5.14 Subcooled flow boiling mean bubble departure diameter for various duct sizes at (a) $T_{\text{sat}} = 15^\circ\text{C}$, $G = 500 \text{ kg/m}^2\text{s}$ & $\Delta T_{\text{sub}} = 3^\circ\text{C}$ and (b) $T_{\text{sat}} = 15^\circ\text{C}$, $G = 500 \text{ kg/m}^2\text{s}$ & $\Delta T_{\text{sub}} = 6^\circ\text{C}$. 
Fig. 5.15 Subcooled flow boiling mean bubble departure frequency for various refrigerant mass fluxes at (a) $T_{\text{sat}} = 15^\circ\text{C}$, $\Delta T_{\text{sub}} = 3^\circ\text{C}$, $\delta = 2.0$ mm and (b) $T_{\text{sat}} = 15^\circ\text{C}$, $\Delta T_{\text{sub}} = 3^\circ\text{C}$, $\delta = 1.0$ mm.
Fig. 5.16 Subcooled flow boiling mean bubble departure frequency for various inlet subcoolings at (a) $T_{\text{sat}} = 15^\circ\text{C}$, $G = 500$ kg/m$^2$s & $\delta = 2.0$ mm and (b) $T_{\text{sat}} = 15^\circ\text{C}$, $G = 500$ kg/m$^2$s & $\delta = 1.0$ mm.
Fig. 5.17 Subcooled flow boiling mean bubble departure frequency for various refrigerant saturated temperatures at (a) $G = 500 \text{ kg/m}^2\text{s}$, $\Delta T_{sub} = 3^\circ C$ & $\delta = 2.0 \text{ mm}$ and (b) $G = 500 \text{ kg/m}^2\text{s}$, $\Delta T_{sub} = 3^\circ C$ & $\delta = 1.0 \text{ mm}$. 
Fig. 5.18 Subcooled flow boiling mean bubble departure frequency for various duct sizes at (a) $T_{\text{sat}} = 15^\circ\text{C}$, $G = 500 \text{ kg/m}^2\text{s}$ & $\Delta T_{\text{sub}} = 3^\circ\text{C}$ and (b) $T_{\text{sat}} = 15^\circ\text{C}$, $G = 500 \text{ kg/m}^2\text{s}$ & $\Delta T_{\text{sub}} = 6^\circ\text{C}$.
Fig. 5.19 Subcooled flow boiling mean active nucleation site density for various refrigerant mass fluxes at (a) $T_{\text{Sat}} = 15^\circ C$, $\Delta T_{\text{sub}} = 3^\circ C$ & $\delta = 2.0$ mm and (b) $T_{\text{Sat}} = 15^\circ C$, $\Delta T_{\text{sub}} = 3^\circ C$ & $\delta = 1.0$ mm.
Fig. 5.20 Subcooled flow boiling mean active nucleation site density for various inlet subcoolings at (a) $T_{\text{Sat}} = 15^\circ\text{C}$, $G = 500$ kg/m$^2$s & $\delta = 2.0$ mm and (b) $T_{\text{Sat}} = 15^\circ\text{C}$, $G = 500$ kg/m$^2$s & $\delta = 1.0$ mm.
Fig. 5.21 Subcooled flow boiling mean active nucleation site density for various refrigerant saturated temperatures at (a) $G = 500$ kg/m$^2$s, $\Delta T_{\text{sub}} = 3^\circ$C & $\delta = 2.0$ mm and (b) $G = 500$ kg/m$^2$s, $\Delta T_{\text{sub}} = 3^\circ$C & $\delta = 1.0$ mm.
Fig. 5.22 Subcooled flow boiling mean active nucleation site density for various duct sizes at (a) $T_{sat} = 15\,^\circ C$, $G = 500\, kg/m^2s$ & $\Delta T_{sub} = 3\, ^\circ C$ and (b) $T_{sat} = 15\, ^\circ C$, $G = 500\, kg/m^2s$ & $\Delta T_{sub} = 6\, ^\circ C$. 
Fig. 5.23 Subcooled flow boiling curves for various refrigerants at (a) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$, $G=400$ kg/m$^2$s & $\delta = 2.0$ mm and (b) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$, $G=500$ kg/m$^2$s & $\delta = 1.0$ mm.
Fig. 5.24 Subcooled flow boiling heat transfer coefficient for various refrigerants at (a) $T_{\text{sat}}=15^\circ$C, $\Delta T_{\text{sub}}=3^\circ$C, $G=400$ kg/m$^2$s & $\delta=2.0$ mm and (b) $T_{\text{sat}}=15^\circ$C, $\Delta T_{\text{sub}}=3^\circ$C, $G=500$ kg/m$^2$s & $\delta=1.0$ mm.
Fig. 5.25 Photos of bubbles in the subcooled flow boiling in a small region around middle axial location at $T_{sat}=15\,^{\circ}\mathrm{C}$, $G=500\mathrm{kg/m}^2\mathrm{s}$, $\Delta T_{sub}=3\,^{\circ}\mathrm{C}$ & $\delta=1.0\,\mathrm{mm}$ for various imposed heat fluxes and refrigerants.
Fig. 5.26 Subcooled flow boiling mean bubble departure diameter for various refrigerants at (a) $T_{\text{sat}}=15\,^\circ\text{C}$, $\Delta T_{\text{sub}}=3\,^\circ\text{C}$, $G=500$ kg/m$^2$s & $\delta=2.0$ mm and (b) $T_{\text{sat}}=15\,^\circ\text{C}$, $\Delta T_{\text{sub}}=3\,^\circ\text{C}$, $G=500$ kg/m$^2$s & $\delta=1.0$ mm.
Fig. 5.27 Subcooled flow boiling mean bubble departure frequency for various refrigerants at (a) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$, $G=500$ kg/m$^2$/s & $\delta=2.0$ mm and (b) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$, $G=500$ kg/m$^2$/s & $\delta=1.0$ mm.
Fig. 5.28 Subcooled flow boiling mean active nucleation site density for various refrigerants at (a) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$, $G=500$ kg/m$^2$s & $\delta=2.0$ mm and (b) $T_{\text{sat}}=15^\circ\text{C}$, $\Delta T_{\text{sub}}=3^\circ\text{C}$, $G=500$ kg/m$^2$s & $\delta=1.0$ mm.
Fig. 5.29 Comparison of the present data for heat transfer coefficient in the subcooled 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. 5.29 Continued.
Fig. 5.29 Continued.
Fig. 5.30 Comparison of the measured data for mean bubble departure diameter in the subcooled flow boiling of R-407C with the proposed correlation.
Fig. 5.31 Comparison of the measured data for mean bubble departure frequency in the subcooled flow boiling of R-407C with the proposed correlation.
Fig. 5.32 Comparison of the measured data for mean active nucleation site density in the subcooled flow boiling of R-407C with the proposed correlation.
Fig. 5.33 Comparison of the measured data for heat transfer coefficient in the subcooled flow boiling of R-407C in the bubbly flow regime with the proposed correlation.