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Visualization of R410A Flow Boiling in Diabatic Conditions inside Horizontal Round Tubes

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\textbf{ABSTRACT}

The objective of this paper is to present the mechanism of flow boiling in horizontal smooth and micro-finned tubes through visualization in diabatic conditions. In most of the literature, the flow regime of flow boiling in the micro-finned evaporator tube is visualized by the sight glass at the exit of the test section under adiabatic condition. In order to better understand effect of micro-fins in flow boiling in the visualization test section, a novel technique to visualize flow of evaporation under diabatic condition has been developed and presented. R410A flow boiling experiments are conducted at 10 °C saturation temperature in both of the smooth and micro-finned tubes with the inner diameter of 6.3 mm. The bubble generation in the liquid refrigerant is presented along with bubble departure diameter, bubble departure frequency, and nucleation sites. In addition, the flow regime of the flow boiling under adiabatic and diabatic conditions is compared.

1. INTRODUCTION

Micro-finned tubes are widely used for evaporators and condensers in refrigeration and air-conditioning systems. It was found that the micro-fin geometry significantly enhanced the heat transfer coefficient in round tubes with a minor additional pressure drop penalty. Investigating the change of the flow pattern in the micro-finned tube provides some evidences for the mechanism of heat transfer enhancement. A number of experimental studies concerned with the flow regimes of two-phase flow in micro-finned tubes have been reported. Yoshida et al. (1988) inserted a fiber scope into a spirally grooved tube to observe the flow behavior of R22 during flow boiling. Cavallini et al. (2006) visualized the flow patterns in a micro-finned tube that was cut at an angle around 45° at the final part inserted into a chamber with glass windows during condensation process. The above methods for visualization maybe influence the flow behavior or break the original flow field inside the tube, which are defined as intrusive techniques. Non-intrusive methods, where the flow field is not disturbed, such as X-ray tomography (Owen et al., 1975, Vince and Lahey, 1982, Harvel et al. 1995), ultrasonic tomography (Masala et al., 2007, Rahim et al. 2007), nuclear magnetic resonance imaging (Fukushima, 1999) are not broadly employed in this field because of the safety or cost issue.

The most common way to investigate the flow regimes in micro-finned tubes is using a sight glass for visualization at the exit of the tested micro-finned tube such as Fujii et al. (1995), Yu et al. (2002), Schael and Kind (2005), Chen et al. (2006), Olivier et al. (2007), Rollmann and Spindler (2015), and Sharar and Bar-Cohen (2016). The inner diameter of the glass tubes is approximately equal to that of the tested tube, and the connection portion between the tested tube and glass tube is short enough to reduce the influence on the flow. The observed flow pattern through the sight glass is assumed to fully represent the flow in the tested micro-finned tube. In this method, the sensor is not directly contact the fluid, so the flow field is not interfered. Although the flow behavior maybe slightly changes due to the different material or inner geometry from the tested micro-finned tube, this method can be seen as a semi-intrusive method, where flow field is not significantly disturbed.

Traditionally, the visualized flow regime in the glass tube is not heated or cooled, which is near adiabatic condition, but the adiabatic condition maybe affects the flow behavior of the two-phase flow such as the flow regime at the
onsite condensation and bubble generation process in evaporation. Palen et al. (1979) used concentric glass tubes to simulate the typical condenser and observed the continuous process of condensation from inlet to exit. Meyer and Hrnjak (2017) and Xiao and Hrnjak (2017) studied the condensation of R134a in smooth tube outside the two-phase region through visualization with the similar way. They built up a diabatic visualization section, which was composed of two concentric glass tubes and encased in a clear plastic shielding box. They stated that the behavior of the fluid in it was close to an actual condenser than typical adiabatic visualization experiments. Westheimer and Peterson (2001) visualized the flow boiling in a vertical glass annular heat exchanger under microgravity conditions and mainly discussed the gravity effect on the flow regime. To the best of our knowledge, there is no related work with the visualization of the evaporative flow regime in the transparent micro-finned tube under diabatic condition.

This paper is aim at investigating the effect of diabatic condition on flow regime of R410A in smooth and micro-finned tubes during evaporation. Flow boiling in transparent axial micro-finned and smooth tubes made by 3D printer were visualized. In addition, the bubble generation in the liquid refrigerant is presented and discussed.

2. EXPERIMENTS

2.1 Test apparatus

Figure 1 shows a schematic drawing of the test apparatus used for measuring heat transfer coefficient, pressure drop and visualization during flow boiling. The experimental set-up consists of two major flow loops: a refrigerant loop and a secondary-fluid loop. In the refrigerant loop (blue solid line in the schematic drawing), R410A without oil is pumped around using a gear pump and its mass flow rate is measured with a Coriolis mass flow meter. The inlet condition of the heat transfer test section is controlled through a calorimeter. The calorimeter heats the subcooled liquid refrigerant to a desired vapor quality by electric heaters. The heat transfer test section is composed of the tested tube (smooth or micro-finned tubes), brass jackets, and tube circuits for water, whose details are described in Yang and Hrnjak’s (2018) earlier work. A diabatic visualization section for observing flow regime is located at the downstream of the heat transfer test section. After the visualization section, horizontal and vertical pressure drops of the tested tubes are measured by differential pressure transducers under near adiabatic condition. A control heater regulated by a PID controller is located at top of the facility for maintaining a desired saturation temperature in the test section. After the control heater is a plate heat exchanger connected to a R404A cooling unit for condensing the refrigerant, and the liquid refrigerant is stored in a receiver. In the secondary-fluid loop (red broken line in the schematic drawing), water is used in this test to provide heat to the heat transfer test section and the diabatic visualization section. The water is circulated with a micro pump and the mass flow rate is measured with a Coriolis mass flow meter. Prior to entering the heat transfer test section, the water is heated to desired temperature by a cartridge heater. Since the water is cooled after passing through the heat transfer test section, an additional cartridge heater is installed to heat it again for the evaporation process in the visualization section.

![Figure 1: Schematic of test facility](image-url)
Temperatures in the facility are measured using T-type thermocouples with a calibrated accuracy of ±0.1 °C. The absolute pressure of R410A is determined with an absolute pressure transducer with an uncertainty of ±5.17 kPa. The mass flow rate of R410A and the water are measured by a Coriolis Effect mass flow meter with an accuracy of ±0.10% of the reading. Watt transducers with 0.2 % reading accuracy are used to determine electrical power inputs for the calorimeter and the water heater.

2.2 Diabatic visualization section
The visualization section in this work is special and there are two distinguishing characteristics. First, the visualized clear tube is heated by the secondary fluid, so the more realistic evaporative condition than the typical adiabatic one is simulated. Second, 3D printed tubes with internal micro-fins are used to further investigate the geometry effect. The visualization section is a transparent heat exchanger which consists of two concentric tubes, as shown in Figure 2(a). The outer tube is a 10 cm long glass tube, whose inner and outer diameter are 15.75 mm and 19.05 mm, respectively. The inner tube is a 21 cm clear resin tube with internal fin geometry made by 3D printer, whose outer diameter is 9.525 mm. Figure 2(b) demonstrates the schematic of the components in the visualization section. Refrigerant flows in the inner tube, while the water flows between the inner resin tube and the outer glass tube. The water that exits the heat transfer test section in the closed water loop is heated by a cartridge heater and injected into the visualization section via circular manifold. For determining the heat flux provided to inner resin tube, the inlet and outlet of the water temperature are measured.

![Diagram of visualization section](image)

**Figure 2**: (a) Concentric tubes for diabatic flow visualization (b) Illustration of refrigerant and water flows in the visualization section.

In order to take the effect of micro-fin geometry on flow into account, the transparent tube with the internal fins was manufactured using a 3D printer and used in the visualization section. The 3D printer used here to make the sophisticated tube is a stereolithography system (SLA), which provides a beam diameter of 0.075±0.015 mm with a minimum feature size of 0.02 mm in High Resolution (HR) mode. Two types of transparent tubes were used for visualizing flow patterns: smooth tube and axial micro-finned tubes. The inner diameter and fin geometry in the 3D printed tube are similar to the aluminum tested tubes used in the facility, but the outer diameter is larger because the burst pressure for the resin tube is different from the aluminum tube. The geometry of the tube is measured through the microscopic pictures with CAD software. The transparent smooth tube has an inner diameter of 6.32 mm and an outer diameter of 9.525 mm. The transparent micro-finned tube has 58 fins with outer diameter of 9.525 mm and fin-tip diameter of 6.085 mm. Figure 3(a) and 3(b) compare the geometric shapes of the transparent micro-finned...
tube and the aluminum micro-fin tube. It is seen that the fin shape in the two tubes are a little bit different due to the resolution of 3D printer but is reasonably close enough. The fin height and fin width in the resin tube is 0.23 mm and 0.12 mm, whereas in the aluminum tube is 0.22 mm and 0.17 mm.

![Comparison of the geometry in the (a) 3D printed axial micro-fin tube and (b) aluminum micro-fin tube](image)

Figure 3: Comparison of the geometry in the (a) 3D printed axial micro-fin tube and (b) aluminum micro-fin tube

Two-phase flow behavior in diabatic visualization were captured with a Phantom V4.2 monochromatic high-speed camera with two different lenses. A 55-mm Nikon lens was used for recognizing the flow patterns in round tubes, while a microscope lens was utilized for characterizing the parameters such as bubble departure diameter and generation frequency. Quantification of the bubbles generated in the visualization section was conducted following the video processing method developed by Xu and Hrnjak (2017).

3. DATA REDUCTION

3.1 Heat flux

In the diabatic visualization section, the heat flux is provided by the water flowing through the transparent concentric tubes. The heat transfer to the refrigerant is based on the water temperature difference between the inlet and outlet of the visualization section times the mass flow rate of the water and the heat loss to the ambient. The heat flux is calculated as the following equation,

\[
q = \frac{Q_{R410A,vis}}{\pi D_i L} = \frac{\left(m_c \cdot C_{p,w} \cdot (T_{w,vis,i} - T_{w,vis,o}) - \dot{Q}_{amb,vis}\right)}{\pi D_i L}
\]

where \(m_c\) is the mass flow rate of the water, \(C_{p,w}\) is the specific heat of the water at the constant pressure, \(T_{w,vis,i}\) and \(T_{w,vis,o}\) are the water temperature at the inlet and outlet of the visualization section, \(D_i\) is inner diameter or meltdown diameter of the resin tube, \(L\) is the length of the resin tube with heat exchange, and \(\dot{Q}_{amb,vis}\) is the heat loss to the environment from the visualization section, which is estimated through a calibration experiment.

3.2 Vapor quality

The inlet vapor quality of the heat transfer test section is controlled by the calorimeter as mentioned in the previous section. The subcooled R410A is pumped into the calorimeter and heated until the desired vapor quality is reached. The temperature and pressure at both inlet and outlet of the calorimeter are measured. The vapor quality at the inlet of the test section is given by:

\[
\chi_{ts,i} = \frac{\dot{Q}_{cal} - \dot{m}_r C_{p,r} (T_{cal,o} - T_{cal,i})}{\dot{m}_r h_{fg}}
\]

where \(\dot{Q}_{cal}\) is the heating power of the calorimeter, \(\dot{m}_r\) is the mass flow rate of the refrigerant, \(C_{p,r}\) is the specific heat of the refrigerant at the constant pressure, \(T_{cal,i}\) and \(T_{cal,o}\) are the temperature at the inlet and outlet of the calorimeter, and \(h_{fg}\) is the latent heat of the refrigerant.
During the evaporation in the heat transfer test section, the vapor quality slightly increases due to the heat transfer to the refrigerant. Since the connection portion of heat transfer section and visualization section is short enough, the vapor quality change between the heat transfer test section outlet and the visualization section inlet is assumed to be negligible. The vapor quality at the inlet of the visualization section is determined as the following equation.

\[ x_{vis,i} = x_{tr,i} + \frac{\dot{Q}_{R410A,ts}}{\dot{m}_h h_{fg}} \]  

(3)

The heat transfer rate to the refrigerant in the heat transfer test section is calculated based on the energy balance as shown in equation (4).

\[ \dot{Q}_{R410A,ts} = \left( \dot{m}_p C_p \right)_{w} \left( T_{w,i} - T_{w,o} \right) - \dot{Q}_{amb,ts} - \dot{Q}_{cond} \]  

(4)

In equation (4), the heat transfer rate from the water is determined from the water specific heat, mass flow rate of the water, and the temperature difference between the inlet and outlet of the heat transfer test section. \( \dot{Q}_{amb,ts} \) is the heat loss to the environment through the insulation, which is estimated through a calibration experiment. \( \dot{Q}_{cond} \) is the axially conductive heat loss through the pipe wall due to the higher wall temperature of the aluminum tube in the test section than that of the aluminum tube away from the test section, and it is estimated by a finite element method proposed by Jang and Hrnjak (2004).

Similarly, the evaporation in the diabatic visualization section increases the vapor quality. The vapor quality at the outlet of the visualization section is calculated as follows.

\[ x_{vis,o} = x_{vis,i} + \frac{\dot{Q}_{R410A,vis}}{\dot{m}_h h_{fg}} \]  

(5)

The mean vapor quality in the diabatic visualization section is calculated using the arithmetic mean value of outlet and inlet qualities given in equation (6).

\[ x_{avg} = \left( x_{vis,i} + x_{vis,o} \right) / 2 \]  

(6)

4. RESULTS AND DISCUSSION

The experimental results of the visualization of R410A flow boiling in transparent round tubes with and without internal micro-fin geometry under diabatic condition are presented. Compared to the traditional method (near adiabatic condition), the bubble generation near the tube wall is captured. Since the nucleate boiling is suppressed by raising the mass flux and vapor quality, the results shown here are mainly in the regions of stratified flow, slug flow, or subcooled flow boiling, where the bubble generation can be observed.

4.1 Comparison of visualization in adiabatic and diabatic conditions

To illustrate the effect of the diabatic condition on the flow regime, R410A flow boiling experiments were conducted in the transparent smooth tube under diabatic and near adiabatic conditions. In the case of adiabatic visualization, the 3D printed smooth tube was directly installed at the exit of the tested metal tube without any heating. Figure 4 (a) and (b) compare the side views of flow regime in the transparent smooth tube at \( G = 100 \) kg/m²s and \( T_{sat} = 10 \) °C under adiabatic condition and diabatic condition (\( q = 1.18 \) kJ/m²). The flow pattern under this mass flux and vapor quality is between stratified-wavy and slug flow. Through the diabatic visualization, it is seen that the evaporation is developing and many bubbles are presented in the visualization. Local heat flux provided to generate the bubbles can be estimated through this visualization, and more physics and mechanism of the flow boiling can be further investigated.
Figure 4: Side views of flow regime in the saturated flow boiling of R410A in the transparent smooth tube at $T_{sat} = 10^\circ$C, under (a) adiabatic condition and (b) diabatic condition ($q = 1.18$ kW/m$^2$). The numbers in the parenthesis represents the conditions of mass flux and vapor quality.

4.1 Diabatic visualization in transparent smooth tubes
The flow behavior of R410A during flow boiling in the transparent smooth tube under diabatic condition was captured through the high speed camera. For the case of $G = 100$ kg/m$^2$.s, $x=0.12$, $T_{sat} = 10^\circ$C and $q=1.7$ kW/m$^2$, the flow pattern was between stratified-wavy and slug flow. A Nikon 55 mm lens was utilized with a speed of 3000 frames per second (fps). Each image in Figure 5 consists of 512x256 pixels, and the corresponding image size is about 20 mmx10 mm. The photos show the side views of growing process for the slug flow due to Kelvin-Helmholtz instability in horizontal smooth. At $t=0$ ms, the flow pattern is stratified-wavy, and there is no bubble generated in the liquid refrigerant at the bottom of the tube. At $t=25$ ms, the liquid level is lifted up, and the crest of the roll-wave touches the upper part of the tube. Bubbles generation is seen at the upper and middle of the tube because of the relative higher wall temperature (higher superheat). At $t=82$ ms, the slug is formed, and the bubble generation is observed at the side of the tube. Then, the flow becomes stratified-wavy again and starts a new cycle.

Figure 5: Side views of flow regime in the saturated flow boiling of R410A in the transparent smooth tube at $G = 100$ kg/m$^2$.s, $x=0.12$, $T_{sat} = 10^\circ$C, and $q = 1.7$ kW/m$^2$ at different time: (a) $t=0$ ms (b) $t=25$ ms, and (c) $t=82$ ms.

A microscope lens was used to further observe more details of the bubble generation process. Figure 6 (a)-(d) show the pictures at the location near the liquid-vapor interphase. The image size in each photo of Figure 6 is 6.63 mm $\times$3.315 mm. At $t=0$ ms, the wave of the liquid-vapor interphase has not reached the location we focused, so there is no bubble generated. At $t=51$ ms, the liquid level is elevated, and bubble is consistently generated at the focused location. At $t=99$ ms, the wave at the liquid-vapor interphase becomes irregular and the steepness increases. The generated bubbles follow the growing wave and the bubble generated frequency is enhanced as the increase of the wave velocity. At $t=262$ ms, the liquid-vapor interphase goes down and the bubbles are gradually disappeared. In addition, some parameters for the generated bubbles are quantified through the video. Bubble departure diameter and bubble generation frequency are approximately 0.05 mm and 580 Hz~720Hz respectively. Moreover, it is observed that bubble generation frequency depends on the local liquid velocity, and it increases as the increase of the liquid velocity.
4.3 Diabatic visualization in transparent axial micro-finned tubes

The flow of R410A during evaporation in the transparent axial micro-finned tube was also investigated under diabatic conditions. Figure 7(a)-(c) show the case of the subcooled flow boiling at G=180 kg/m$^2$s and q=1.8 kW/m$^2$. and. In Figure 7(a), the photo was taken using Nikon 55 mm lens with the resolution of 512×256, and the length and the width of the photo are approximately 20 mm and 10 mm respectively. It is seen that bubbles are easily generated at the top and side of the tube. The active nucleation site density can also be estimated from the photo and is approximately $5.23\times10^5$ sites/m$^2$. To get a better look and characterize some parameters for generated bubbles, images are zoomed in with a microscope lens and presented in Figure 7(b) and (c). The bubbles are generated in the grooves of the micro-finned tube and grow as the flowing fluid. The bubbles flow along the grooves when their sizes are smaller than the groove width. The bubbles continue growing and escape from the confined channel as their sizes are larger than the groove width. Bubble departure diameter and bubble generation frequency are estimated from the video, which are approximately 0.051 mm and 125 Hz respectively.

The visualization of slug flow in the axial micro-finned tube is also captured and displayed in Figure 8. The experiment was conducted at $T_{\text{sat}}=10\ ^\circ\text{C}$, G=100 kg/m$^2$s, x=0.22, and q=1.26 kW/m$^2$. Figure 8(a) shows the side view of the flow that covers the whole tube diameter, and Figure 8(b) and (c) are the magnified images focusing on bubble generation. Similar to the slug flow in the smooth tube, there are a lot of bubbles generated as the crest of the roll-wave touches the upper part of the tube. Besides, it is found that bubbles are generated in the liquid film that is trapped in the groove of the tube. The bubble generation frequency is related to the liquid velocity in the groove and is estimated through the video. The bubble generation frequency is about 77.2 Hz as the velocity of the trapped liquid is slow and the frequency can be up to 900 Hz as the liquid flow (roll-wave) flushes the groove. The bubble departure diameter in the axial micro-finned tube is approximately 0.044 mm, and there is no significant difference from that in the smooth tube.
Figure 8: Diabatic visualization of slug flow in the axial micro-finned tube at $T_{sw}=10^\circ$C, $G=100$ kg/m$^2$s, $x=0.22$, and $q=1.26$ kW/m$^2$ captured with different lenses and magnifications: (a) Nikon 55 mm lens, (b) microscope lens (0.8×), and (c) microscope lens (1.5×).

5. CONCLUDING REMARKS

A novel technique for visualizing in-tube two-phase flow under diabatic condition was built. R410A flow boiling experiment were conducted in the 3D printed smooth and axial micro-finned tubes. The following conclusions can be drawn.

- Compared to the traditional adiabatic visualization technique, the more realistic evaporative condition is simulated and the developing evaporation process can be captured.
- When the roll-wave (slug) touches the upper part of the tube, many bubbles are generated at the liquid film near the tube wall.
- Bubble is easily generated at the top and side of the tube because of higher local wall temperature.
- The bubble generation frequency is not a constant value in the region of slug flow, and it increases as the local liquid velocity increases.
- There is no significant difference of the bubble departure diameter in the smooth and micro-finned tubes under the current experimental conditions.
- Bubble departure diameter, bubble generation rate, nucleation sites, and the partitioning of heat flux in the diabatic visualization will be analyzed and compared to the existing correlations and theoretical models.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>$C_p$</td>
<td>specific heat</td>
<td>(J/kg-K)</td>
</tr>
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<td>$D_i$</td>
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<td>(mm)</td>
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<td>$G$</td>
<td>mass flux</td>
<td>(kg/m$^2$s)</td>
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<td>$h_{fg}$</td>
<td>latent heat</td>
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<tr>
<td>$x$</td>
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Subscript

- amb: ambient
- avg: average
- cal: calorimeter
- cond: conduction

17th International Refrigeration and Air Conditioning Conference at Purdue, July 9-12, 2018
REFERENCES


ACKNOWLEDGEMENT

This study is supported by Air-Conditioning and Refrigeration Center (ACRC) at University of Illinois at Urbana-Champaign (UIUC). The authors would like to acknowledge the technical support from Creative Thermal Solutions Inc. (CTS). The authors are also grateful to MechSE RP Lab at UIUC for manufacturing 3D-printed tubes.