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Effect of Helix Angle on Flow of R410A during Evaporation inside Horizontal Round Tubes Based on Visualization in Diabatic Condition

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ABSTRACT

This paper presents the effect of the helix angle on flow boiling in micro-fin tubes supported by a novel visualization in diabatic conditions. Such visualization helps better understanding of the mechanism of boiling and heat transfer enhancement. In most of the literature, the flow regime of flow boiling in the micro-fin evaporator tube is visualized by the sight glass without internal fin geometry and at the exit of the test section. In order to better understand effect of micro-fins on flow regime in the visualization test section, transparent micro-fin tubes with different helix angles placed in outer glass tube with annular coolant flow were used to visualize flow during evaporation. R410A flow boiling experiments are conducted at 10 °C saturation temperature in smooth tube and micro-fin tubes of 0° and 18° helix angle. The visualization in flow boiling is presented. The results showed that the annular flow pattern in the helical micro-fin tube occurred at lower vapor quality than the smooth. This early transition was attributed to the capillary force from spiral grooves, which enabled the liquid to reach the top of the tube easily. For the axial micro-fin tube, the flow patterns were not significantly different from the smooth tube, but the liquid refrigerant was easily trapped in the grooves especially in the region of stratified-wavy or slug flow.

1. INTRODUCTION

Internally micro-fin tubes have been commonly used in modern air conditioning and refrigeration systems because of their outstanding thermal performance in two-phase flow. Helix angle is a crucial parameter in micro-fin tubes, which strongly influences heat transfer and pressure drop. Ito and Kimura (1979) studied the effect of helix angle on in-tube boiling heat transfer coefficient for R22. They tested 11.2 mm ID internally spiral-grooved tubes with the helix angle of 0°, 3°, 7°, 15°, 30°, 75°, and 90° under various mass flux and heat flux conditions. The results showed that the HTC increased as the helix angle increased until the angle was 7° and then decreased to a minimum value as the increase of helix angle. The minimum of HTC occurred at about 45°, and it increased again toward 90°. Kimura and Ito (1981) reported the experimental results concerned with the evaporative heat transfer for R12 in 4.75 mm ID micro-fin tubes with the helix angle of 4°, 7°, 15°, and 30°. They found that the mass flow rate considerably affected the optimal helix angle for the heat transfer. For the region of stratified flow region, how high the liquid refrigerant was pulled up due the capillary phenomenon determined the heat transfer enhancement. The heat transfer coefficient increased with the increase of helix angle. For the region of annular flow, the maximum heat transfer occurred at 15° helix angle, but did not change significantly with the helix angle between 4° and 30°. Oh and Bergles (1998) experimentally investigated the evaporative heat transfer for R134a in 9.52 mm OD micro-fin tubes with different helix angles (6°, 12°, 18°, 25°, and 44°). The authors mentioned that the optimal helix angle, where maximum HTC occurred, depended on mass flux, and 18° and 6° were the optimal one for G=50 kg/m²s for G=100 kg/m²s, respectively.

To better understand the behavior of two-phase flow in horizontal micro-fin tubes, flow visualization experiments were conducted in many studies. Yoshida et al. (1988) inserted a fiber scope into a spirally grooved tube to observe the flow behavior of R22 during flow boiling. At a low mass flux, where the liquid and vapor were separated in the lower and upper part of the tube, respectively, liquid existed in the grooves at the top of the tube and
flowed along the grooves with relatively slow speed. Oh and Bergles (2002) studied the effect of helix angle on the enhancement of evaporative heat transfer of R134a in the micro-finned tubes by visualizing the in-tube flow regime. A borescope was inserted into the heating test tube with connection of a custom-made uniform tee fitting. The author found that the increasing wetted area due to the climbing liquid flow at the top of the tube depended on the helix angle. Cavallini et al. (2006) and Doretti et al. (2013) built up a brass chamber with three glass windows to visualize the flow patterns in micro-finned tubes during condensation process. A small portion of the test tube was inserted into the chamber and cut at an angle around 45° at the final part. Colombo et al. (2012) used the similar method to investigate the evaporation and condensation of R134a in the helical micro-finned tubes. They mentioned that the transition between the intermittent and the annular flow was shifted to lower vapor quality than the smooth tube.

In addition to the intrusive method, the most common method to visualize the flow patterns is using a sight glass at the exit of the tested micro-finned tube. The observed flow pattern through the sight glass is assumed to represent the flow in the tested tube. Yu et al. (2002) found that the transitions of the flow patterns map for R134a in the micro-finned tubes with 18° helix angle occurred at lower mass flux and vapor quality than the smooth tubes. Rollmann and Spindler (2015) defined a new flow pattern, the helix flow, in the micro-finned. In this flow pattern, the refrigerant flow got a spin due the helical arrangement of the micro-fins and accelerated in the circumferential direction. More wetted surface led to an increase of heat transfer coefficient. To further study the effect of the micro-fins on two-phase flow, Shedd and Newell (2003) measured the liquid film thickness and its distribution in horizontal annular flow through clear PVC tubes with 20 internal microgrooves at three different helix angels (0°, 9° and 18°). The results showed that the thicker liquid of the film thickness profile in the 9° and 18° tubes rotated counterclockwise compared to the profile of the smooth tube. In addition, the helical micro-fins increased the amount of wetted tube periphery. In the lowest flow condition, about 81% of the 9° tube periphery and 94% of the 18° tube periphery was wetted (only 62% for the smooth tube). Namely, the helical microgrooves promote earlier transitions to annular flow. However, the geometry such as number of fin and fin shape of the PVC tube was different from that of the commercial micro-finned tube, this might affect the flow behavior.

Most of the works listed above have been focused on the flow patterns in the helical micro-finned tube instead of the axial one, and the literature concerned with the flow in the transparent micro-finned tube is limited. In this paper, one smooth tube and two micro-finned tubes (0° and 18°) made of clear resin by SLA 3D printer were studied to investigate the effect of helix angle on flow during evaporation. Visualization of R410A under diabatic conditions in the round tubes with different geometries are presented and discussed.

2. EXPERIMENTS

2.1 Test apparatus

The facility is designed to visualize the flow regime in round tubes with different inner geometries under diabatic conditions, as shown in Figure 1. There are two independent loops: one for refrigerant and the other for secondary fluid. In the refrigerant loop (blue solid line), refrigerant is circulated in an oil-free condition by a gear pump. Following the pump is a Coriolis mass flow meter (Micro Motion CMF 025) for measuring mass flow rate of the refrigerant. The calorimeter, located before the heat transfer test section, is used to heat the subcooled liquid refrigerant to a desired vapor quality. The test section for measuring heat transfer coefficient 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 transparent visualization is located right after the heat transfer test section to observe the two-phase flow patterns under the diabatic condition. Horizontal and vertical pressure drops are in turn measured by differential pressure transducers under near adiabatic condition. For maintaining a desired saturation temperature in the loop, there is a control heater regulated by a PID controller. A plate heat exchanger located after the control heat enables the refrigerant to condense by exchanging heat with a R404A cooling unit, and a receiver is set at the outlet of the condenser for storing the liquid refrigerant. For the secondary fluid loop (red broken line), water is used in this test to provide heat to the heat transfer test section and the diabatic visualization section. The water is pumped by a constant speed pump and the mass flow rate is measured with the Coriolis mass flow meter. In addition, there are two cartridge heaters for controlling the water temperature delivered to the heat transfer and visualization sections.
2.2 Visualization section
In most of the literature concerned with the flow visualization during evaporation in micro-finned tubes, the flow regime is visualized through the sight glass without internal fin geometry and at the exit of the test tube under near adiabatic condition. In other words, the flow regime in the smooth glass tube without any heating and fin geometry is assumed to represent the flow during evaporation in the copper micro-finned tubes. In order to improve the traditional method, a novel visualization section has been built to provide a more realistic evaporative condition to the visualized clear tube. The visualization section consists of two concentric transparent tubes with 10 cm long, as shown in Figure 2(a). The outer tube is made of glass, whose inner and outer diameter are 15.75 mm and 19.05 mm, respectively. The inner tube is clear resin tube with internal fin geometry, whose outer diameter is 9.525 mm. Figure 2(b) presents the schematic of the visualization section components. The tested refrigerant flows in the inner resin tube, and the water flows between inner and outer tube to provide heat to the refrigerant. The inlet and outlet of the water temperature are measured for calculating the heat flux in the visualization section.

(a)

(b)

Figure 2: (a) Concentric tubes for diabatic flow visualization. (b) Illustration of refrigerant and water flows in the visualization section.
For the purpose of visualizing the flow regime in transparent tubes with internal micro-fin geometry, 3D printing or additive manufacturing method is adopted to make complex and sophisticated shapes inside the tubes. The 3D printer used here is a stereolithography system (SLA), in which the liquid resin materials were cured in a photopolymerization process via ultraviolet laser. The beam diameter of 0.075±0.015 mm with a minimum feature size of 0.02 mm in High Resolution (HR) mode. Three types of 3D printed resin tubes were used for visualizing flow patterns: smooth, axial micro-fin (0° helix angle), and helical micro-fin (18° helix angle) tubes, as shown in Figure 3. To be mentioned that the transparent helical micro-fin tube was difficult to make since the tube was built up layer by layer in the 3D system. If the resolution of the 3D printer is not enough, the helical grooves will be zig-zag shape.

Figure 3: 3D printed transparent resin tubes: (a) smooth, (b) axial micro-fin (0° helix angle), and (c) helical micro-fin (18° helix angle)

Visualization of the flow patterns were captured with a Phantom V4.2 monochromatic high-speed camera using a 55-mm Nikon lens. Sampling rate was set as 3000 fps with a resolution of 512x256 pixels. The magnification is set such that a portion of tube approximately 2 cm long in the center of the visualization section is recorded. A 25 W cool white LED light panel was used to provide intense light located about 6 cm behind the tube.

2.3 Test conditions and instrumentation
Visualization of R410A flow boiling were conducted at a nominal condition of 10 °C saturation temperature. The mass flux varied from 100 to 300 kg/m²s, and a vapor quality ranged from 0.05 to 0.9. The heat flux in in the diabatic visualization section was about 1 kW/m². 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.

3. RESULTS AND DISCUSSION

3.1 Flow patterns in helical micro-fin tube
Figure 4 presents the flow patterns observed in the transparent resin tube with 18° helical micro-fins and they are characterized as follows: plug, stratified-smooth (SS), stratified-wavy (SW), slug, intermittent (I), wavy-annular (WA), and annular (A). At the very low vapor quality (void fraction is relatively low), the elongated bullet-shaped bubbles flow along upper part of the tube, which is called as plug flow. When both the liquid and vapor velocities are very low (low mass fluxes), the flow is characterized as stratified flow. Vapor flows at the top and liquid flows at the bottom of the tube due to gravity. This flow pattern can be subdivided into stratified-smooth (SS) and stratified-wavy (SW). The SS flow pattern occurs as the gas velocity is low enough, and the interface keeps smooth. As the vapor velocity increases, the interface becomes wavy attributed to Kelvin-Helmholtz instability. In the region of SW, the magnitude of the waves is not enough to reach the top of the tube. As the unstable waves grow until the tube is fully bridged, a slug is generated. Intermittent flow (I) is a transitional flow pattern as the main liquid level is not enough to wash the top of the tube but the waves at the interface are more irregular and turbulent than slug flow. In addition, some liquid films are formed around the tube due to the high vapor velocity. It is worthy to mention that the unsteady flow patterns like plug and slug are also grouped into the intermittent category in some literature. When the liquid film liquid wets all the tube periphery, the flow is characterized as annular flow. The annular flow can be further subdivided into way-annular (WA) and fully annular (A) according to the wave behavior. The differences in wave behavior between wavy-annular and fully annular are discussed in Schubring and Shedd’s (2008) work.
Figure 4: Flow patterns in 18° helical micro-finned tubes. (a) plug, (b) stratified-smooth, (c) stratified-wavy, (d) slug, (e) Intermittent, (f) Wavy-annular, and (g) Annular flow.
3.2 Flow pattern maps in helical micro-finned tubes

Figure 5 presents the flow pattern maps of R410 obtained by visualization as a function of vapor quality and mass flux in the transparent helical micro-finned tube with 18° helix angle. The results are compared with the flow pattern map of R410A in a smooth tube built up by Wojtan et al. (2005). The solid and open symbols are the visualization data in our experiments and the blue lines are the transition curves from the equations in the literature. To be note that the plug flow in the experiments is called slug flow in Wojtan et al.’s map, and the annular flow pattern here is subdivided into wavy-annular and annular flow. In general, our experimental data in helical micro-finned tube agree well with Wojtan et al.’s map except the transitions from slug + stratified-wavy flow to stratified wavy flow and from intermittent flow to annular flow. The transition from slug + SW flow to SW in Wojtan et al.’s map was based upon the I-A boundary in Kattan et al. (1998)’s map, and it was a constant value of vapor quality. However, there was no slug flow shown in the experiments as the vapor quality was over 0.3, so the transition from slug + SW flow to SW may be shift to the left. The major difference between our experimental data and the Wojtan et al’s map is the I-A transition. The visualization results showed that the annular flow in the helical micro-finned tube occurred at lower vapor quality. The capillary force from spiral grooves enables the liquid to reach the top of the tube easily, which lead to this earlier transition.

3.3 Comparison of flow regimes in smooth, axial micro-finned, and helical micro-finned tubes

Figure 6 compares the visualization results of R410A flow boiling at the saturation of 10°C for the mass flux of 180 kg/m²s in the smooth tube, axial micro-finned tube (0° helix angle), and helical micro-finned tube (18° helix angle). In Figure 6 (a)-(c), the vapor quality is 0.35. The flow pattern in the smooth and axial micro-finned tubes is stratified-wavy flow, where the wave exists at the liquid-vapor interphase and only few liquid films touched the top half of the tube. In the helical micro-finned tube, the flow pattern becomes intermittent, where the interface is more irregular and turbulent and more liquid films found at the top. When the vapor quality is increased to 0.6, the flow pattern in the smooth and axial micro-finned tubes is still stratified-wavy but it has become annular in the helical micro-finned tube, as shown in Figure 6 (d)-(f). For a higher vapor quality condition, x=0.8, the flow pattern in all the three tube is annular flow, as presented in Figure 6 (g)-(i).
The flow behaviors in the transparent tubes can be further explain the mechanism of heat transfer enhancement in the micro-finned tubes. For the axial micro-finned tube, Yang and Hrnjak (2018) stated that the enhancement factor of the 6.3 mm axial micro-finned tube with R410A was around 1.34, and the straight micro-fins have stronger influences as the mass flux and vapor quality is low. Based on the visualization data, the flow patterns in the axial micro-finned tube (0° helix angle) was generally similar to that in the smooth tube. In other words, the annular flow did not persist at lower mass fluxes or lower vapor quality than in the smooth tube. Although the straight micro-fins could not pull the liquid up to the tube, some liquid refrigerant was easily trapped in the grooves at the side of the tube due to the surface tension especially in the region of stratified wavy or slug flow. Therefore, the heat transfer enhancement in the axial micro-finned tube is mainly attributed to the additional liquid-phase refrigerant trapped in the grooves of the tube and the increasing surface area. For the helical micro-finned tube (18° helix angle), Kim et al. (2002) reported that the helical micro-fins significantly enhanced the heat transfer, and the enhancement factor with R410A was ranged from 1.1 to 2.5, which depended on the heat flux, mass flux, vapor quality, evaporative temperature and tube diameter. To give an explanation of this heat transfer enhancement, the change of the two-phase flow behavior observed in the helical micro-finned tube is illustrated. Compared to the smooth and axial micro-finned, more liquid film was found at the top of the tube in the helical micro-finned tube, since the capillary force enables the liquid refrigerant to climb up along the groove. In addition, the transition from SW or I to annular occurred at lower vapor quality and mass flux, which meant that the flow in the helical micro-finned tube was more annular. This mechanism explains why the helical micro-fins remarkably enhance the heat transfer of flow boiling in round tubes.

4. CONCLUSIONS

In this paper, the visualization of R410A flow boiling in smooth, axial micro-finned (0° helix angle), helical micro-finned (18° helix angle) tubes was experimentally investigated. The saturation temperature was fixed at 10°C, and the test range covered the vapor quality from 0.05 to 0.9, and mass flux from 100 to 300 kg/s·m². The following conclusions are obtained.

- Transparent helical micro-finned tubes were successfully made through a SLA 3D printer.
• Flow patterns observed in the transparent resin tube with 18° helical micro-fins are characterized as follows: plug, stratified-smooth (SS), stratified-wavy (SW), slug, intermittent (I), wavy-annular (WA), and annular (A).
• The annular flow in the helical micro-finned tube occurs at lower vapor quality. The liquid refrigerant flows along the grooves is easier to reach the top of the tube by the capillary force, which is beneficial to formation of the annular flow.
• In the axial micro-finned tube, the flow patterns are generally similar to that in the smooth tube, but liquid refrigerant is easily trapped in the grooves at the side of the tube.
• Transparent helical micro-finned tubes with 10° and 25° helix angle will be studied to investigate the effect of helix angle on flow during flow boiling in round tubes.

**NOMENCLATURE**

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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>D</td>
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<td>G</td>
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<td>q</td>
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**Subscript**

sat saturation

**REFERENCES**


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