International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2022

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Yao, Yufang and Hrnjak, Pega, "Effect of Tube Size and Oil on Developing Adiabatic Two-phase Flow" (2022). *International Refrigeration and Air Conditioning Conference.* Paper 2395.
https://docs.lib.purdue.edu/iracc/2395

Effect of Tube Size and Oil on Developing Adiabatic Two-Phase Flow

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ABSTRACT

It is well known that the developed two-phase flow is determined by the working conditions, tube size, and working media. For the developing two-phase flow, it is also affected by these factors. However, there are only a few studies about developing two-phase flow in the open literature. In this paper, the authors will compare the developing adiabatic two-phase flow after a thermostatic expansion valve in a 5 mm and an 8 mm tube to check the effect of tube size. The experiments are conducted in a real AC system with R134a and 1.3% POE 32 as the working medium. A previous study in the Hrnjak research group at the University of Illinois has investigated the developing two-phase flow of pure refrigerant after a needle valve. By comparing the results in current research with Bowers and Hrnjak (2009), it is possible to learn more about the effect of oil on developing two-phase flow. The authors found that the flow patterns near the expansion device are affected by both the addition of oil and the inner structure of the valve. When the flow is fully developed, the effect of the expansion device is negligible and the difference in flow pattern is mainly caused by oil. The developed flow pattern map with refrigerant and oil mixture in this paper is also compared with Wojtan *et al.* (2005) and Barbieri *et al.* (2008) flow pattern map to investigate the effect of oil on developed two-phase flow.

1. INTRODUCTION

Two-phase flow regimes and flow characteristics such as void fraction and the pressure drop have gotten a lot of attention and have been investigated thoroughly. But most of the research in open literature focused on the developed flow (Kattan *et al.*, 1998; Wojtan *et al.*, 2005a; Qian & Hrnjak, 2019, 2020, 2021a). In fact, when the two-phase flow passes through a singularity, such as the sudden change in flow area, bending, tube fittings, or valves, the flow regime will be disturbed, and the flow characteristics will change as well. This region of the flow before it is fully developed is called developing two-phase flow. The open literature regarding developing two-phase flow is very limited compared to developed flow, among which the majority focused on developing two-phase flow after a sudden change in flow area.

Aloui and Souhar (1996) and Bottin *et al.* (2014) examined the two-phase flow characteristics after a mixing chamber. The two-phase flow was created by mixing two streams of liquid and vapor flow. Salcudean *et al.* (1983) and Ahmed *et al.* (2008) studied the changes in two-phase flow after a sudden expansion/contraction in the flow area. Ahmed *et al.* (2008) also reported the effect of expansion ratio on developing two-phase flow. To the best of our knowledge, there is no research in open literature regarding the developing two-phase flow after an expansion device but for two studies in our group (Fei & Hrnjak, 2004; Bowers & Hrnjak, 2009). Both use R134a as the working fluid, instead of the commonly used two-component air-water or air-oil flow.

In this paper, R134a with 1.3% POE 32 is used as the working fluid to relate the developing flow regime to real application. Currently, the effect of oil was only studied for fully developed flow or boiling/condensation flow patterns. Manwell (1990) investigated the developed two-phase flow regimes of refrigerant and oil mixtures and claimed that the addition of oil causes the formation of foaming. The foaming can wash the sidewall and facilitate the transition to annular flow at lower mass flux. Kim and Hrnjak (2012) studied the influence of oil on boiling flow patterns of CO2. They reported an increase in the wetted area around the circumference of the tube due to the foaming.

Jige *et al.* (2020) examined the boiling flow of R32 and oil in a multiport tube. The most obvious impact of oil is the foaming in liquid slugs for intermittent flow, while for other flow patterns, no significant effect was observed.
This paper presents the developing adiabatic two-phase flow after a thermostatic expansion valve in two glass tubes with different diameters. The impact of tube size on two-phase flow patterns along the 600 mm-long tubes is analyzed. The authors also examined the effect of oil on developing two-phase flow by comparing the results in current research (R134a with 1.3% of POE 32) with those of pure refrigerant by Bowers and Hrnjak (2009). The developed flow patterns with refrigerant and oil mixture are also compared with an existing flow pattern map.

2. EXPERIMENTAL FACILITY

The facility used in this paper is shown schematically in Figure 1. It is a typical AC system including a compressor, a condenser, an expansion device, and an evaporator. A full description of the facility could be found in Yao and Hrnjak (2021). There are two major modifications to the facility for the purpose of developing two-phase flow study. First, a 600 mm-long straight tube is added between the TEV and the distributor, as shown in Figure 2. The other modification is the circulation heater before the TEV. This heater is added to adjust the refrigerant quality at the TEV exit at a wide range in collaboration with the sub-cooler.

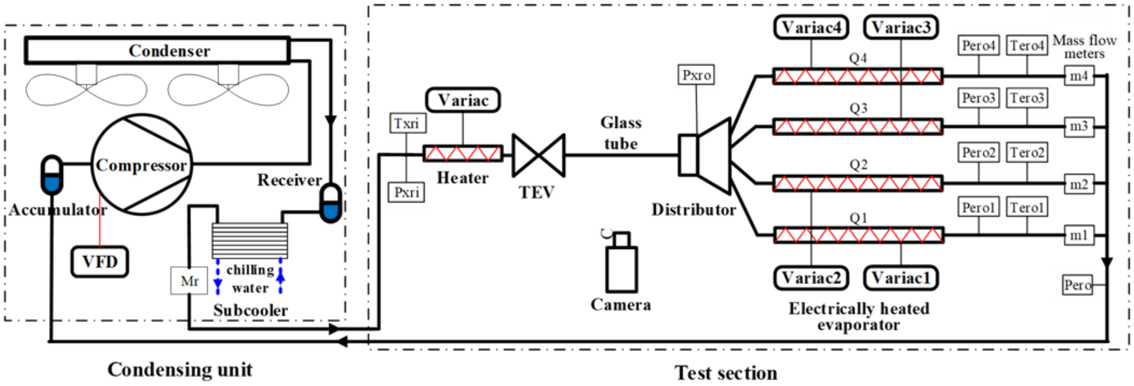


Figure 1: Schematic of the facility

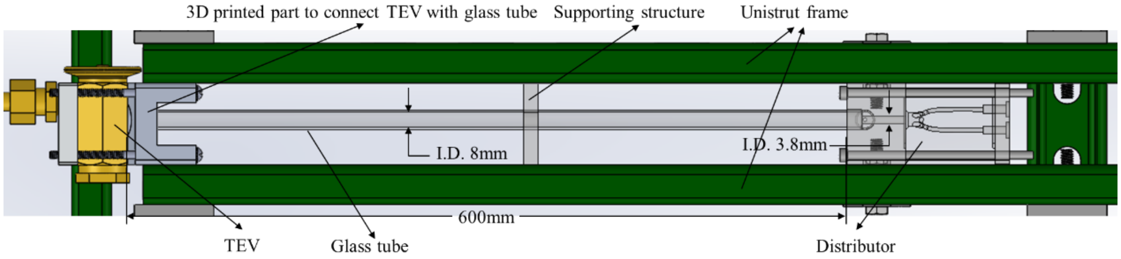


Figure 2: TEV and distributor assembly

In this paper, two glass tubes with different diameters are used to get developing adiabatic two-phase flow. Table 1 summarizes the operating conditions for all the experiments. The control strategies for all the parameters were also introduced in detail in Yao and Hrnjak (2021). The saturation pressure in the glass tube is not a constant for different working conditions. This is because of the large pressure drop of vapor flow through the mass flow meters. In general, the saturation pressure is higher as the mass flow rate increases.

Table 1: Experimental conditions

Working fluid	Tube geometry [mm]	Mass flux [kg m-2 s-1]	Distributor inlet quality [-]	Orientation	Pressure in glass tube [kPa]
R134a with 1.3% POE32	L=600 D=5 ang 8	100 - 1000	0.002 - 0.50	Horizontal	410-680

3. THE EFFECT OF TUBE DIAMETER ON DEVELOPING TWO-PHASE FLOW

In a companion paper in the same conference (Yao and Hrnjak, 2022), the authors have analyzed the developing adiabatic two-phase flow after a thermostatic expansion valve in an 8 mm straight tube. The two-phase flow right after the expansion device is usually well-mixed. As flow progresses along the tube, liquid and vapor will separate from each other and the flow structure will get stable gradually. Based on the flow characteristic, the developing two-phase flow can be classified into four regions: well-mixed, separating, separated but developing, and fully developed flow. This is consistent with what was found by Bowers and Hrnjak (2009). To get a further understanding of the effect of tube size on developing and developed two-phase flow, the developing flow regimes along a 5 mm inner diameter tube are visualized and compared with the results in an 8 mm tube.

3.1 Well-mixed Region

When two-phase flow is created after sudden expansion inside the TEV, the liquid and vapor phases should be well-mixed. This well-mixed structure may or may not last to the location where the visualization begins in our experiments. It is more likely to get well-mixed flow when the mass fluxes are relatively high. At low mass fluxes, it could be in the separating region at the beginning of the visualization (The separating region will be discussed later). When the single-phase liquid flow passes through the TEV, the sudden expansion will evaporate part of the liquid, accompanied by bubble generation. As the bubbles grow, coalesce, and finally break up, the liquid filling among the gap of bubbles becomes droplets or liquid ligaments. These small particles (bubbles, droplets, and liquid ligaments) are dispersed uniformly in a continuous phase in the well-mixed region. This region can last for a certain distance, depending on the working conditions and tube diameter.

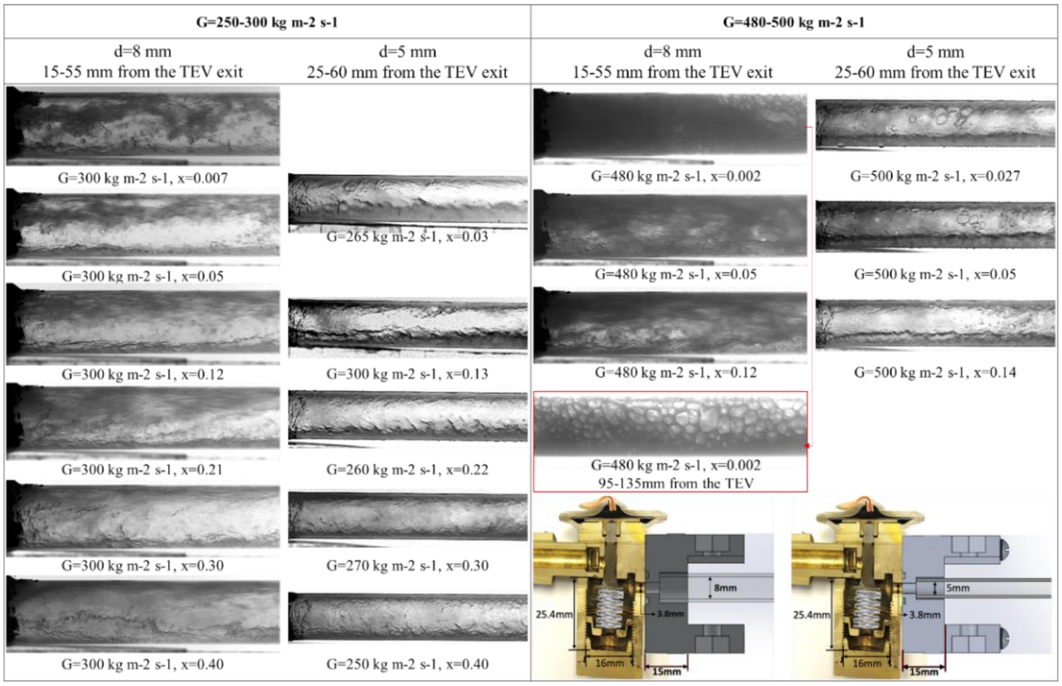


Figure 3: Flow patterns at the TEV exit: 5 mm vs. 8 mm (similar mass flux)

Figure 3 compares flow patterns at the TEV exit in two tubes with different diameters (at similar mass flux). There are always more bubbles, droplets, or liquid ligaments in the 8 mm tube, while in the 5 mm tube, the two phases are almost separated from each other. Only a few bubbles or droplets are observed in the upper part of the tube and the liquid layer at the bottom is much thicker. With similar mass fluxes in the glass tube, the mass flow rate is lower for the smaller tube. For the same TEV, a lower mass flow rate means the mass flux inside the TEV is lower. As shown in Figure 3, there is a relatively large chamber inside the TEV (d=16 mm, h=25.4 mm) after the throttle. The bubbles generated from flash evaporation can grow faster in this large space and the separation of the two phases will begin earlier when the mass flux is low. In this case, the well-mixed region may only exist inside the TEV or at the very beginning of the tube before visualization.

Figure 4 demonstrates the effect of tube size on flow patterns at the TEV exit at similar mass flow rates. In this case, mass fluxes inside the TEV are the same. The difference in flow pattern between the two tubes is less significant compared to the results in Figure 3. This means the flow behavior inside the expansion device plays an important role in determining the flow patterns afterward. In other words, mass flux inside the TEV affects the degree of phase separation, which in turn affects the flow development along the tube.

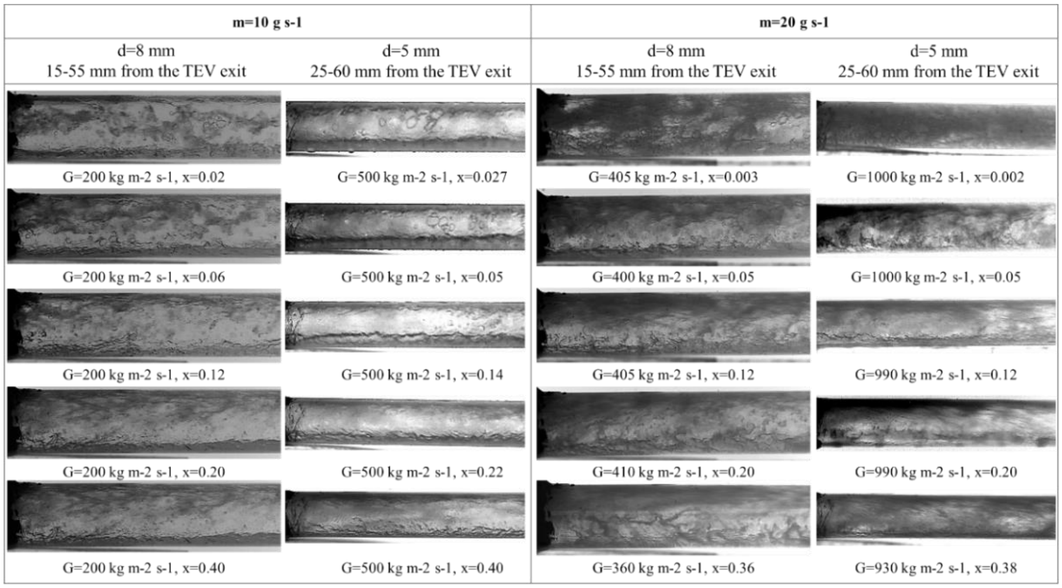


Figure 4: Flow patterns at the TEV exit: 5 mm vs. 8 mm (similar mass flow rate)

3.2 Separating Region

Based on the analysis in section 3.1, the flow patterns right after the expansion device show a significant difference for different tube sizes at similar mass fluxes. However, at similar mass flow rates, the difference is much smaller. In order to get further understanding of the effect of tube diameter on the separation of two phases, it is preferable to keep a similar flow pattern at the beginning of the tube. Therefore, the developing two-phase flow at similar mass flow rates is chosen to compare in Figure 5.

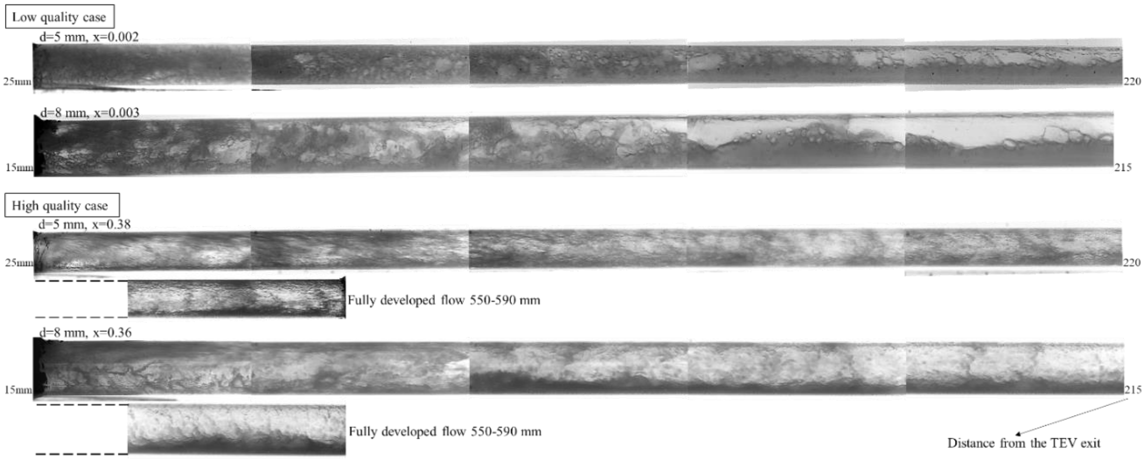


Figure 5: Effect of tube diameter on separating of two-phase flow (m=20 g s-1)

When the vapor quality is relatively low, a discernible interface is observed at a shorter distance in the large tube because of the low mass flux. This conclusion still holds as the vapor quality increases. It is difficult to recognize the liquid-vapor interface in the small tube even in the fully developed region. Because the mass flux is pretty high (1000 kg m-2 s-1 at 20 g s-1). The strong shear stress results in a turbulent interface and part of the liquid is entrained in the vapor phase in form of droplets or ligaments due to the high-velocity vapor flow. As for the large-diameter tube, the entrained liquid is falling to the bottom of the tube gradually, indicated by the less greyness in the vapor phase. At the same time, the interface becomes more and more traceable with the separation of the two phases.

3.3 Separated but Developing Region

The separated but developing region is marked by a distinct interface and accompanied by some minor changes in flow characteristics, indicating the end of phase separation but not fully developed flow yet. For instance, in the 8 mm tube, we have observed the transition from stratified-wavy flow to intermittent flow, with an increase in liquid level and more turbulent liquid waves (Yao and Hrnjak, 2022). Similar phenomena are also found in the 5 mm tube.

3.4 Developed Region

The final region of flow development is the fully developed region. Flow patterns in the developed region do not change significantly and the average void fraction is nearly constant. Figure 6 presents the developed flow pattern map in a 5 mm tube and compares it with the map of the 8 mm tube. As discussed in Yao and Hrnjak (2022), the two-phase flow at the end of the tube (600 mm after the TEV) is fully developed for most of the operating conditions, with only a few exceptions (7% of total tests) at extremely low mass flux and low vapor quality. For simplicity, the flow patterns in Figure 6 are considered to be fully developed.

For both tubes, it is intermittent flow at low vapor quality and annular flow at high quality and high mass flux. However, the flow patterns in between are different. Intermittent/Annular flow is observed for most cases in the 5 mm tube, with one exception of intermittent/wavy flow at low mass flux. As for the 8 mm tube, it is intermittent/wavy and stratified-wavy flow in between. This difference indicates that it is more likely to have a wetted wall in a smaller tube, while it is prone to have stratification in the larger tube. This conclusion is also supported by the phenomenon that the transition to annular flow occurs at a lower vapor quality in the smaller tube.

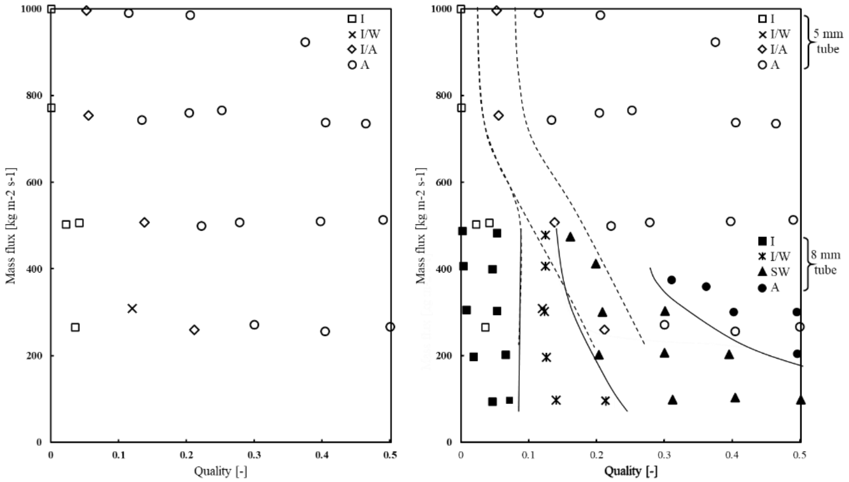


Figure 6: Developed flow pattern map in a 5 mm tube (left) and the effect of tube diameter on the developed flow pattern map (right) with R134a and 1.3% POE 32 (fully developed flow for most cases)

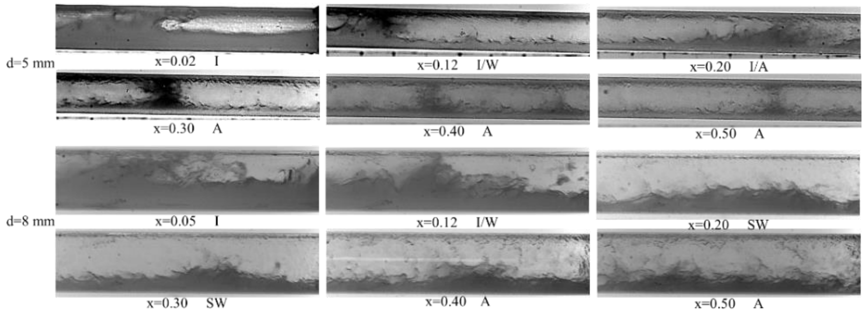


Figure 7: Flow patterns in the developed region: 5 mm vs. 8 mm (G=260-300 kg m-2 s-1)

Another effect of tube size on the developed flow pattern is the wave structure. As shown in Figure 7, there are always obvious liquid waves in the 5 mm tube regardless of the flow patterns, and the waves almost reach the top of the tube for all the conditions. However, in the 8 mm tube, the waves in stratified-wavy and annular flow have much lower amplitude and cannot touch the upper wall. This is logical because the effect of gravity is less significant in small tubes, and it is known that gravity can stabilize the flow.

3.5 3D Flow Pattern Map

As far as we know, all the flow pattern maps in open literature were proposed for developed two-phase flow. The flow patterns are predicted based on mass flux and vapor quality (Kattan *et al.*, 1998; Wojtan *et al.*, 2005a), or liquid and vapor superficial velocity (Baker, 1954; Mandhane *et al.*, 1974). For developing two-phase flow, in addition to mass flux and vapor quality, the flow pattern is also affected by the distance after the expansion device or other types of singularities. In Yao and Hrnjak (2022), we have defined developing two-phase flow patterns and proposed a 3D flow pattern map based on the experimental results in an 8 mm straight tube. To investigate the effect of the tube size on flow development, the 3D flow pattern map for the 8 mm tube is compared with that of the 5 mm tube in Figure 8.

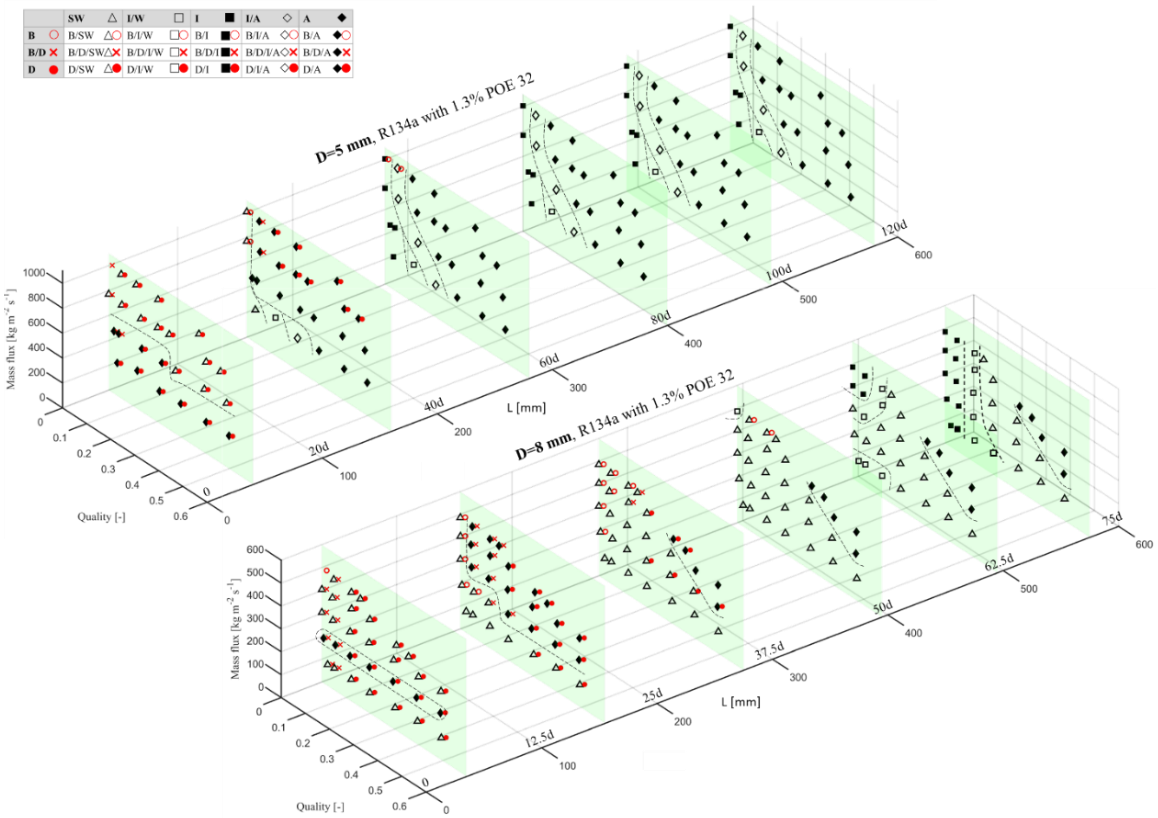


Figure 8: 3D flow pattern map of adiabatic two-phase flow in horizontal tubes: 5 mm vs. 8 mm

Figure 8 shows that the bubbles or droplets (the second symbol in flow patterns) can exist for a longer distance in the larger tube under the same working conditions. As discussed in section 3.1, the two-phase flow right after the expansion device is more homogeneous in the large tube. A well-mixed two-phase flow at the beginning means that a longer distance is required for phase separation. Therefore, the bubbles or droplets last longer. The dash lines in Figure 8 are the transition lines between different flow patterns when neglecting the bubbles and droplets. For both tubes, only stratified-wavy and annular flow are observed at the beginning. All the other flow patterns (I, I/W, I/A, and A) are transformed from these two types. The fully developed annular flow is formed earlier than intermittent flow. As the tube diameter increases, the distance to get fully developed intermittent flow also increases. Because in a small tube, the wall shear stress is stronger. When the well-mixed two-phase flow develops along the tube, the wall shear stress will slow down the liquid faster. On the other hand, the liquid waves can reach the top of the tube and become liquid slugs easier in a small tube.

4. THE EFFECT OF OIL ON DEVELOPING TWO-PHASE FLOW

The lubricant is nearly inevitable for real AC systems. However, two-phase flow regimes of refrigerant and oil mixture have not been studied extensively. In this paper, we examine the developing two-phase flow of R134a with 1.3% POE 32 after an expansion device. To understand the effect of oil on developing flow patterns, experimental results in the current study are compared with Bowers and Hrnjak (2009). They also studied the developing two-phase flow after an expansion valve, but the working media is pure R134a. A needle valve was used as the expansion device instead of TEV.

4.1 Flow Patterns Near the Expansion Device

Figure 9 compares the flow patterns near the expansion device in the current study with Bowers and Hrnjak (2009) at similar mass flux and vapor quality. The tube diameter and saturation temperature are also similar. At the quality of 0.05, Bowers and Hrnjak (2009) observed plenty of bubbles in the upper part of the tube and a liquid layer at the bottom with increasing thickness, while in the current study, the upper part of the tube is occupied by a continuous vapor phase, carrying some liquid droplets/ligaments. It is speculated that the difference in flow patterns in this region is caused mainly by the different expansion devices rather than the addition of oil. In Figure 9 (right), there is a large space (d=16 mm, h=25.4 mm) inside the TEV, while it is a small passage (d=2.65 mm) in the needle valve. Bubbles generated from flash evaporation may coalesce and break up inside the TEV before the two-phase flow enters the glass tube. If the same valve was used in these two studies, more bubbles would be expected for two-phase flow with oil. Because oil has higher surface tension than the refrigerant. It is much more difficult for the bubbles to grow larger and break up. More effort is needed to examine the effect of expansion device and oil separately. As the refrigerant quality increases, both studies have droplets flow at the exit of the expansion valve. The flow patterns are much more similar.

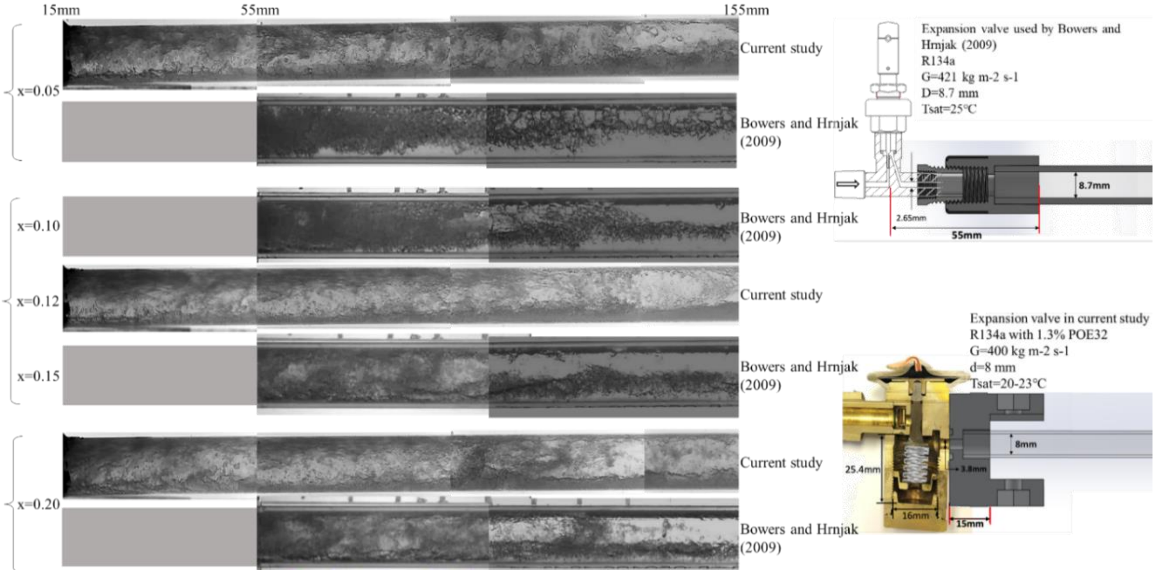


Figure 9: Flow patterns near the TEV exit in the current study compared to Bowers and Hrnjak (2009)

4.2 Fully Developed Flow

The flow patterns near the expansion valve are affected by both the working media and the valve structure. However, when the flow is fully developed after a long distance, the flow pattern is only determined by working media. Figure 10 (top) compares the developed flow pattern map in the current study with Bowers and Hrnjak (2009) to check the effect of the oil. As mentioned earlier, the saturation temperature in the current study is not constant. As the mass flux increases, the saturation temperature also increases. At mass flux around 400 kg m-2 s-1, the saturation temperature is similar to the working conditions of Bowers and Hrnjak (2009). Therefore, the flow patterns at this specific mass flux are compared in Figure 10 (bottom). There is no significant difference in flow patterns when the quality is below 0.2. As the quality increases, the transition from stratified-wavy to annular flow happens at 0.3 for refrigerant and oil mixture, while it is still stratified-wavy flow for the pure refrigerant. In other words, oil can promote the formation of annular flow. It is known that oil has a higher surface tension than refrigerants. Hence, the refrigerant and oil mixture is more likely to wet the periphery of the tubes. Similar conclusions were reported by Worsoe-Schmidt (1960), Wongwises *et al.* (2002), and some other research for developed flow.

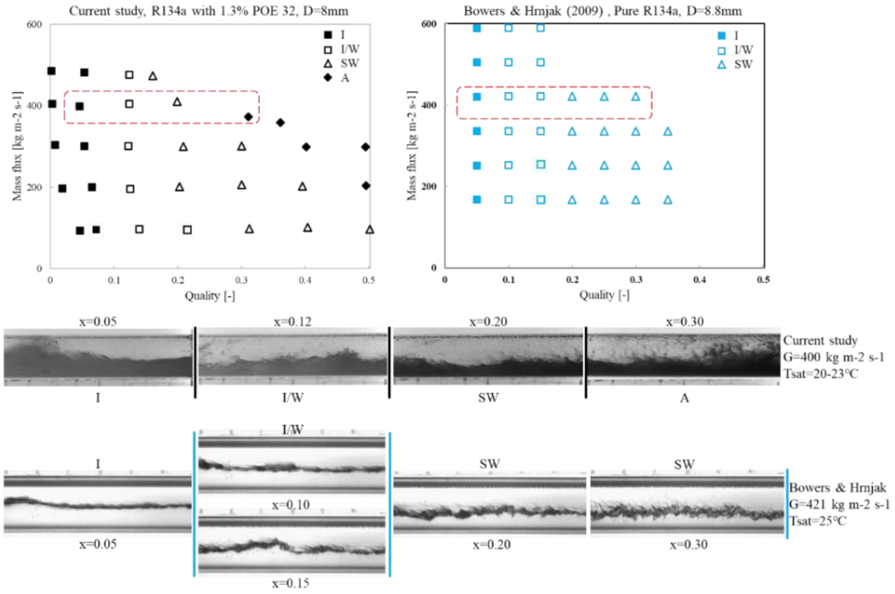
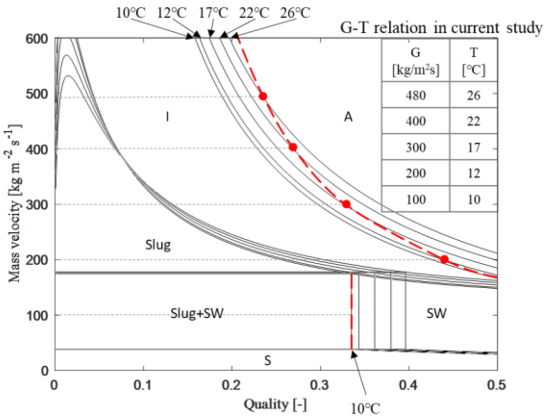


Figure 10: The effect of oil on fully developed flow: current study vs. Bowers and Hrnjak (2009)

5. COMPARISON WITH EXISTING DEVELOPED FLOW PATTERN MAP

To predict flow patterns under given working conditions, numerous flow pattern maps have been proposed. One of the best-known flow pattern maps for refrigerant two-phase flow is that of Kattan *et al.* (1998). Then, Wojtan *et al.* (2005a) modified it by subdividing the stratified-wavy flow into three subzones: slug, slug/stratified-wavy, and stratified-wavy. Barbieri *et al.* (2008) upgraded it further by proposing a new transition line between the intermittent and annular flow. The flow patterns observed in this paper are compared to the map of Kattan *et al.* (1998) with modifications from both Wojtan *et al.* (2005a) and Barbieri *et al.* (2008) (Wojtan-Barbieri map). Since the saturation temperature in current research is not constant for all the tested working conditions, it is necessary to check the effect of temperature on the flow pattern map to make a fair comparison. Figure 11 presents the transition lines in the Wojtan-Barbieri flow pattern map at different temperatures. The temperature mainly influences the transition lines of intermittent to annular flow and stratified-wavy to slug+stratified-wavy flow. An adjustment is made (dash lines in Figure 11) based on the temperature-mass flux relation to get a special map to compare with the results in this paper.
Figure 12 presents the observed flow patterns in the fully developed region overlapped on the Wojtan-Barbieri map with modification for temperature effect. All the annular flows are well predicted by the map for both tubes. But the maps are plotted for the pure refrigerant. Considering the conclusion that the oil will make the transition to annular flow occur at a lower quality, this transition line (intermittent to annular) should move to the right. On the other hand, it is common to have a semi-annular region (intermittent/annular or wavy/annular) at the left side of the annular flow. It is also reasonable if the transition line locates inside this semi-annular region. For the 5 mm tube, the major difference with the Wojtan-Barbieri map is the intermittent/annular and one intermittent/wavy flow between the intermittent and annular flow regimes. It is not a big surprise since the transition from one flow pattern to another occurs gradually instead of sharply. The flow pattern in between will share similarities with all the neighboring flow patterns. The discrepancy with the Wojtan-Barbieri map is more obvious for the 8 mm tube. The stratified-wavy flow is observed at lower quality and intermittent/wavy flow can exist at higher mass flux than predicted by the map. Bowers and Hrnjak (2009) got similar results with pure refrigerant (Figure 10 top). The so-called ‘stratified-wavy’ flow at high mass fluxes (Figure 12, inside the triangle) also resembles annular and intermittent-wavy flow at the same time. It is more like a transitional region.

The above-mentioned discrepancy with the Wojtan-Barbieri map is possibly a result of the ambiguity of definitions for intermittent/slug/plug flow. Wojtan *et al.* (2005a) divided the stratified-wavy flow of Kattan *et al.* (1998) map into three subzones: slug, slug+stratified-wavy, and stratified-wavy flow. In the original version of the Kattan *et al.* (1998) map, the intermittent flow includes both plug and slug flow. But in Wojtan *et al.* (2005a) map, the slug flow is independent of intermittent flow and belongs to the stratified-wavy flow in Kattan *et al.* (1998) map. This indicates the difficulty in defining the flow patterns near the intersection of stratified-wavy, slug, plug, or intermittent flow accurately. Actually, several transitional regions may exist near the transition lines in the Wojtan-Barbieri flow pattern map. But these transitional regions are not the same for tubes of different sizes. For instance, in the 5 mm tube, the flow pattern between intermittent and annular flow is dominated by intermittent/annular flow. Because the tube wall is more likely to be wetted when the diameter is small. In contrast, intermittent/wavy and intermittent/wavy/annular flow is observed in the 8 mm tube between intermittent and annular flow, indicating a stronger effect of gravity over inertia and surface tension.



G [kg/m²s]	T [°C]
480	26
400	22
300	17
200	12
100	10

Figure 11: Effect of temperature on Wojtan-Barbieri flow pattern map (R134a, d=8 mm)

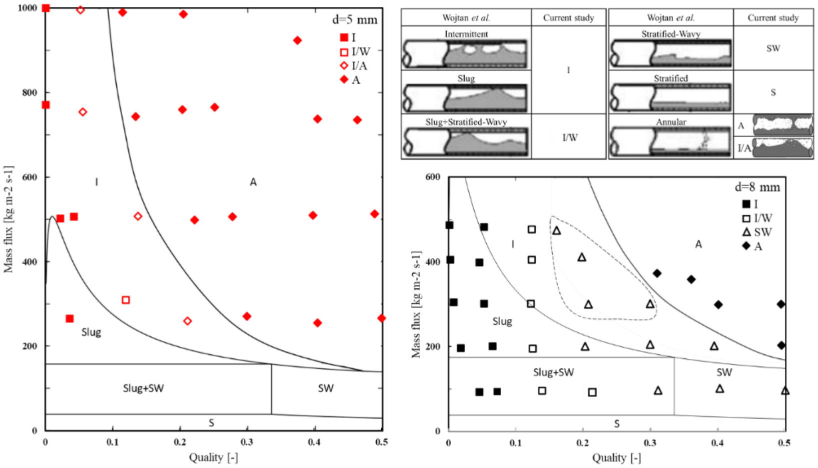


Figure 12: Observed flow patterns compared to Wojtan-Barbieri flow map for Pure R134a

6. SUMMARY AND CONCLUSIONS

This paper compares the developing adiabatic two-phase flow in a 5 mm and 8 mm straight tube after an expansion valve. With similar mass flux, the flow patterns near the TEV exit are much more similar to homogeneous flow in the larger tube (Figure 3), indicating less phase separation inside the TEV because of the higher mass flow rate. Given a similar flow pattern at the beginning of the tube, a discernible interface is expected at a longer distance in the smaller tube (Figure 5). Because gravity, which is believed to promote phase separation, exerts more effect as the tube diameter increases. When the two-phase flow is fully developed, it is more likely to have a partially wetted or fully wetted wall in the smaller tube due to the stronger surface tension.

This paper also reveals the effect of oil on developing adiabatic two-phase after the expansion device. Flow patterns at the beginning of the tube are significantly affected by the valve structure. A valve with a large inner space after the throttle is speculated to accelerate the phase separation, while a compact space is favorable to create a more homogeneous flow. The effect of oil is inconspicuous compared to the valve structure on flow patterns near the expansion valve. However, for fully developed flow, the addition of oil can promote the transition from intermittent to annular flow.

The fully developed flow in the current study is compared to the flow pattern map of Wojtan-Barbieri. This map gives a good prediction for annular flow. However, the transition between intermittent, stratified-wavy, and annular flow is more complicated. More effort is needed to get an accurate flow pattern map covering a wide range of tube diameters, working fluids, and operating conditions. Characterization of flow patterns by other tools (Wojtan *et al.*, 2005b; Qian & Hrnjak, 2021b, 2021c) is also important to improve the accuracy of flow pattern map for future study.

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