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# Developing Adiabatic Two-phase Flow In An 8-mm Tube After An Expansion Valve

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# Developing Adiabatic Two-phase Flow in an 8-mm Tube After an Expansion Valve

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## ABSTRACT

Developed two-phase flow has been studied exhaustively in the open literature. However, there is limited research on developing two-phase flow. This paper investigates the developing adiabatic two-phase flow after a thermostatic expansion valve in an 8 mm straight tube with R134a and 1.3% POE 32 as the working medium. The flow patterns are visualized from the exit of the TEV until 595 mm afterward. To cover different types of flow patterns, the mass flux is changed from 100 to 480 kg m-2 s-1, and vapor quality is from 0.002 to 0.5. Based on the observations in our experiments, the developing two-phase flow patterns can be classified into four regions: well mixed, separating, separated but developing, and fully developed flow. At the exit of the expansion valve, liquid and vapor phases are well mixed due to the sudden expansion. The flow structure is similar to homogeneous flow and both phases have similar velocity. As flow progresses along the tube, the liquid velocity will decrease. As a consequence, the gravity/buoyancy force becomes more dominant over inertia and surface tension, resulting in the separating of bubbles/droplets with the main flow. The end of the separating region is characterized by a clear interface between the liquid and vapor phases. However, this does not mean a fully developed flow. The flow characteristics, such as void fraction and flow pattern may still change for a certain distance. This is called the separated but developing region, the last region before fully developed flow. All the flow patterns in developing two-phase flow are shown in a 3D flow pattern map. Compared to the traditional developed flow pattern map, the distance from the expansion valve is added as the third dimension. According to this 3D flow pattern map, as the distance increases, the flow patterns are changing gradually to fully developed flow.

## 1. INTRODUCTION

The two-phase flow pattern is of great importance to the performance of air-conditioning systems. Extensive research has been done to understand the behavior of the two-phase flow. Most of them focused on the fully developed region when the flow characteristics do not change anymore (Kattan *et al.*, 1998; Wojtan *et al.*, 2005; Barbieri *et al.*, 2008; Qian & Hrnjak, 2019, 2021a). However, developed flow is hardly found in real systems. When two-phase flow passes through a singularity in the flow path, such as contraction or expansion, the flow characteristics will change accordingly. The state before the flow is fully developed is called developing two-phase flow.

The literature regarding the developing two-phase flow is very limited. There is some research focused on developing two-phase flow after a sudden change in flow area or after a mixer. The working media were mostly air-water or air-oil flow. Salcudean *et al.* (1983) investigated the influence of obstructions in the flow area on the flow pattern transitions with air-water. The authors observed the flow regimes at 300 mm downstream from the obstruction and compared that with unobstructed channel results. They found the length of the flow regime affected by the obstruction is shorter for annular flow while it is longer for dispersed flow. Aloui and Souhar (1996) carried out an experimental study of gas-liquid bubbly flow in a flat duct with a sudden expansion in the flow area. The local void fraction downstream of the sudden expansion first increases to a maximum in the recirculation region and then decreases to a plateau value. Ahmed *et al.* (2008) studied the characteristics of air-oil flow upstream and downstream of a sudden expansion. They found that developing length is determined by liquid Reynolds number and area ratio.

Aside from the above-mentioned developing two-phase flow of two non-mixing fluids, there is another type: developing two-phase flow of a single fluid after the expansion device. For AC systems, it is known that the two-phase distribution in multi-channel evaporators is affected by the flow pattern at the evaporator inlet. Therefore, it is important to understand the development of refrigerant two-phase flow after the expansion device. To the best of our knowledge, there is no research in the open literature about this topic except in two studies in our group (Fei & Hrnjak, 2004; Bowers & Hrnjak, 2009). They used pure R134a as the working medium for most of the experiments, but Bowers and Hrnjak (2009) also did some initial work with refrigerant and oil mixture. It was found the addition of oil affects the development of the two-phase flow significantly.
This paper presents the developing adiabatic two-phase flow after a thermostatic expansion valve in a real AC system with R134a and 1.3% of POE 32. A high-speed camera visualized the flow patterns along a 600 mm-long straight tube between the TEV and distributor. Based on the observed flow patterns, a three-dimensional flow pattern map is proposed with mass flux, quality, and the distance from the expansion valve as X, Y, and Z axes.

## 2. EXPERIMENTAL FACILITY

Figure 1 shows the facility used in this study. It includes four major parts: a compressor, a condenser, a thermostatic expansion valve, and an evaporator. A detailed description of this facility can be found in Yao and Hrnjak (2021). But a few modifications are made for the study of the developing two-phase flow. One of the major differences is that a 600 mm-long glass tube is added between the TEV and distributor, as shown in Figure 2. This relatively long straight tube is used as an attempt to get developed flow near the end of the tube. Another modification is the circulation heater added before the TEV. This electrical heater and the water-cooled sub-cooler are used together to adjust the vapor quality at the TEV exit in a wide range. The mass flow rate, temperature, and pressure of each circuit of the evaporator are also measured, but these parameters are used for the investigation of two-phase flow distribution, which will not be discussed in this paper.

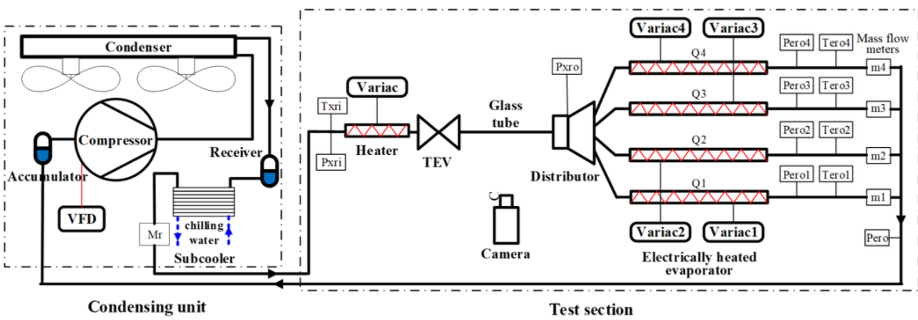


**Figure 1:** Schematic of the facility

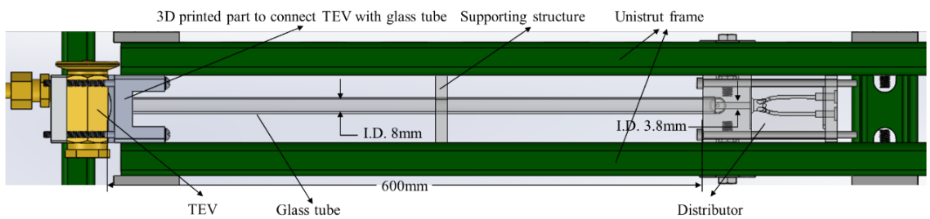


**Figure 2:** TEV and distributor assembly

Table 1 lists the operating conditions for all the experiments in this paper. Because of the large pressure drop of vapor flow through mass flow meters, it is difficult to keep a constant pressure inside the glass tube as the operating condition changes. Generally, the saturation pressure will increase 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% POE 32 | L=600, D=8 | 100 - 480 | 0.002 - 0.50 | Horizontal | 410-680 |

## 3. RESULT AND DISCUSSION

Based on the observations in our experiments, the two-phase flow patterns after the thermostatic expansion valve can be divided into four regions: well-mixed, separating, separated but developing, and fully developed flow. The same conclusion was drawn by Bowers and Hrnjak (2009) in their research with pure R134a two-phase flow. In the well-mixed region, the liquid and vapor phases are mixed thoroughly. This region is characterized by plenty of bubbles or droplets (sometimes ligaments) dispersed uniformly in the continuous phase. As the two-phase flow moves along the tube, the liquid and vapor phases are separating from each other. This is called the separating region. The end of the separating region is defined when there is a clear interface between the liquid and vapor. However, a clear interface does not necessarily mean a stable flow structure. Therefore, the separated but developing region is defined between the separating and fully developed flow. In this region, the flow characteristics, such as void fraction or flow velocity are still changing. Finally, after a long enough distance, the flow will get steady and fully developed. The detailed description for each region will be discussed further in the following parts.

### 3.1 Well-mixed Region

The two-phase flow right after the throttle of the expansion device is usually well-mixed. This is because of the sudden expansion inside the TEV. Flash evaporation can generate several possible phenomena, such as bubble generation, bubble breakup, ligament or droplet formation, droplet breakup, etc. In this region, the bubbles or droplets are distributed uniformly in the continuous phase, resulting in a flow pattern similar to the homogeneous flow in nature.

Fei and Hrnjak (2004) and Bowers and Hrnjak (2009) concluded that the bubble flow usually happens at low quality while it is droplet flow at high quality. When the vapor quality is relatively low, the bubbles generated from flash evaporation are packed tightly together in the liquid phase. As the quality increases, the bubble size, or the volume occupied by the vapor phase also increases. At the same time, the volume of liquid ligaments, filled among the gaps of bubbles, becomes smaller and smaller. Finally, the bubbles merge, break, and form a continuous vapor phase, while the liquid ligaments break into droplets and disperse in the continuous vapor phase. The well-mixed bubble or droplet flow can keep the homogenous-like structure for some distance after the throttle. This distance is determined by several factors, including the working condition, tube geometry, and the valve inner structure. In this paper, only the effect of the working condition is discussed, while the impact of tube geometry and valve structure will be examined in another paper.

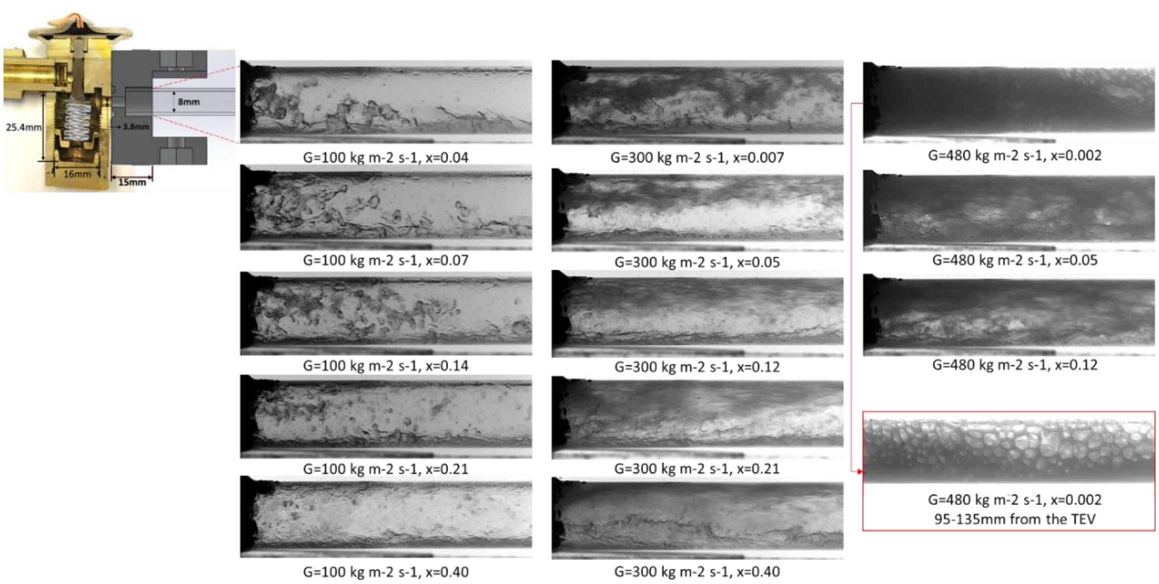


**Figure 3:** Flow patterns at the TEV exit (15-55 mm from the TEV)

Figure 3 presents the two-phase flow regimes right after the TEV at different mass fluxes and qualities. In addition to the effect of quality as mentioned above, the flow regime also changes with mass flux. When the mass flux is 100 kg m-2 s-1, there is no homogeneous bubble or droplet flow at the TEV exit. This is because when the bubbles are created right after the throttle, the relative space for each individual bubble is large at low mass flow rates. This spacious room, presumably filled with the vapor phase, makes it easier for the bubbles to break up. This process is similar in nature to spraying pressurized liquid into the air. At low mass flux and low quality (G=100 kg m-2 s-1, x=0.04), a short liquid jet is observed at the TEV exit. The liquid jet cannot keep its integrity for a long distance due to the relatively low velocity. When the vapor quality increases, the liquid jet has a severe deformation and finally disintegrates into tiny droplets by the high-velocity vapor flow. As the mass flux increases to 300 kg m-2 s-1, the liquid jets are stronger and keep an intact structure for a longer distance. This is logical because the velocity of the liquid jet is increased as the mass flux gets higher. The change in flow pattern is much more obvious as the mass flux increase to 480 kg m-2 s-1. The images look darker but more uniform in brightness. The darkness indicates that there are many interfaces between the liquid and vapor phases. This conclusion is supported by the image inside the red rectangle in Figure 3, which is taken at a longer distance after the TEV. As the distance from the TEV increases, the size of the bubbles also increases and multiple smaller bubbles merge into larger ones. At this location, it is much clearer that plenty of bubbles are packed together tightly at the upper part and a thin layer of liquid is accumulated at the bottom of the tube. Based on the flow patterns shown in Figure 3, the well-mixed region is observed at the TEV exit (15mm) when the mass flux is relatively high (for this specific expansion valve). For the low mass flux conditions, the liquid and vapor are separating from each other. In this case, it is possible that the well-mixed flow only exists inside the TEV or at the beginning of the tube before visualization.

### 3.2 Separating Region

Well-mixed flow is the first region after the sudden expansion in TEV. But it is not observed at low mass flux conditions even the distance from TEV is only 15 mm. For these cases, the flow patterns are in the separating region. It is speculated that the bubbles due to flash evaporation have merged and become a continuous vapor phase inside the TEV (in the big chamber with the spring in the center, as shown in Figure 3) or in the non-transparent 15 mm of the tube at the very beginning. As the mass flux gets higher, the well-mixed region appears and can maintain for a certain length. However, this homogeneous-like flow cannot keep its structure indefinitely. It will evolve into the separating region since the small particles (bubbles, droplets, or liquid ligaments) are affected more and more by gravity and buoyancy force. In the separating region, the bubbles are moving towards the upper part of the tube, and droplets or liquid ligaments are going downward. Thus, the liquid layer at the bottom of the tube is getting thicker.

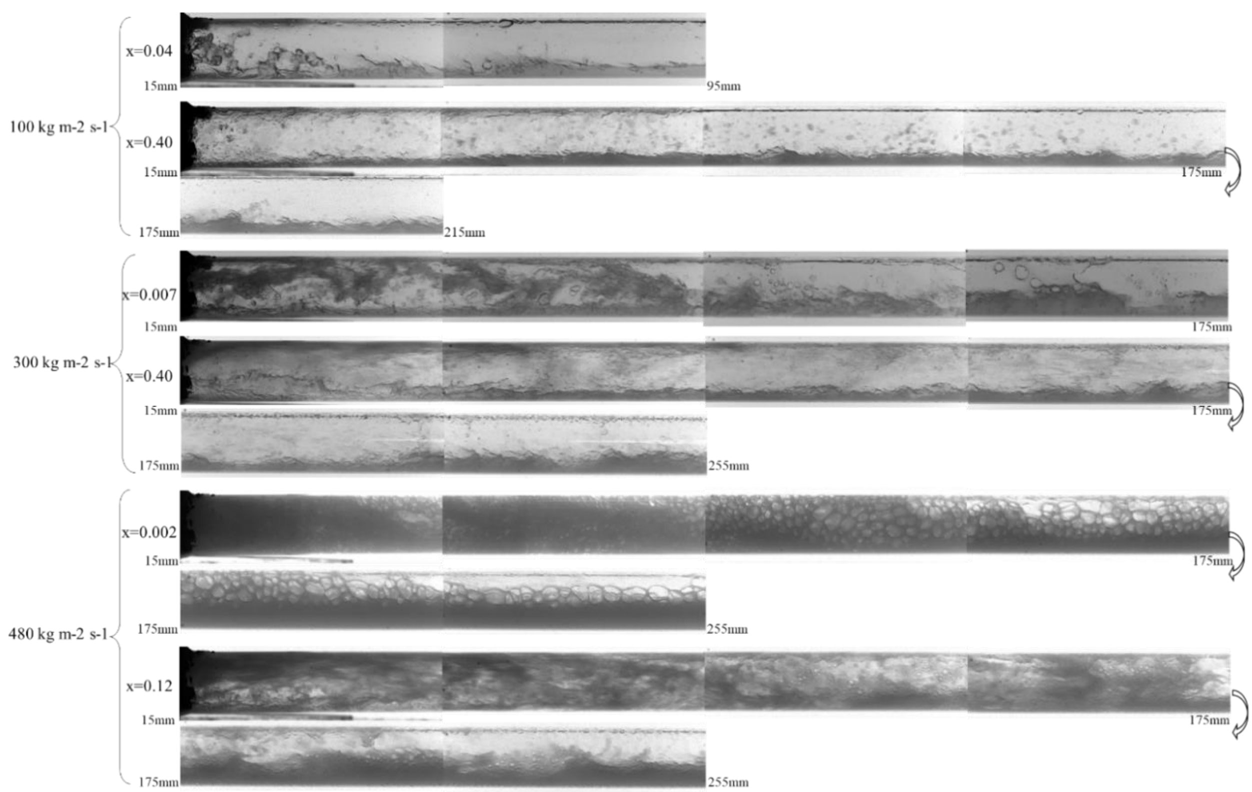


**Figure 4:** Separation of two-phase flow at different mass flux and quality

Figure 4 presents several separation processes under different working conditions, covering the mass flux and vapor quality from low to high. For low mass flux and low-quality cases (G=100 kg m-2 s-1, x=0.04), the liquid jet only lasts for about 10 mm before it is disintegrated and falls to the bottom of the tube. After the phase separation, the flow pattern changes to a stratified wavy flow. Keeping the same mass flux but increasing the quality to 0.4, there are many tiny droplets and liquid ligaments at the TEV exit. As the two-phase flow moves forward, these small particles are settling at the bottom of the tube. As a result, the liquid level at the bottom increases, leaving nearly any droplet in the vapor phase after 175 mm from the expansion valve.

As the mass flux increases to 300 kg m-2 s-1, the liquid jet shoots to a longer distance when quality equals 0.007. There are no droplets in the vapor phase after 135 mm from the expansion valve. As the vapor quality increases to 0.4, more liquid droplets and ligaments (the black clouds at the upper part of the tube) are carried by the main vapor flow compared to the low mass flux case. The liquid particles can survive for a longer distance due to the higher velocity of the vapor flow.

When we have homogeneous bubble flow in the well-mixed region (G=480 kg m-2 s-1, x=0.002), the phase separation happens in such a way: first bubble growth, then coalescing, deforming, and bursting. Figure 5 shows one of the examples. The bubbles are migrating to the top of the tube. At the same time, the liquid between the bubble gaps is falling to the bottom and forms a liquid layer with increasing thickness. At high mass flux and high-quality conditions (G=480 kg m-2 s-1, x=0.12), the separation process is similar in principle to low mass flux cases at the similar quality.

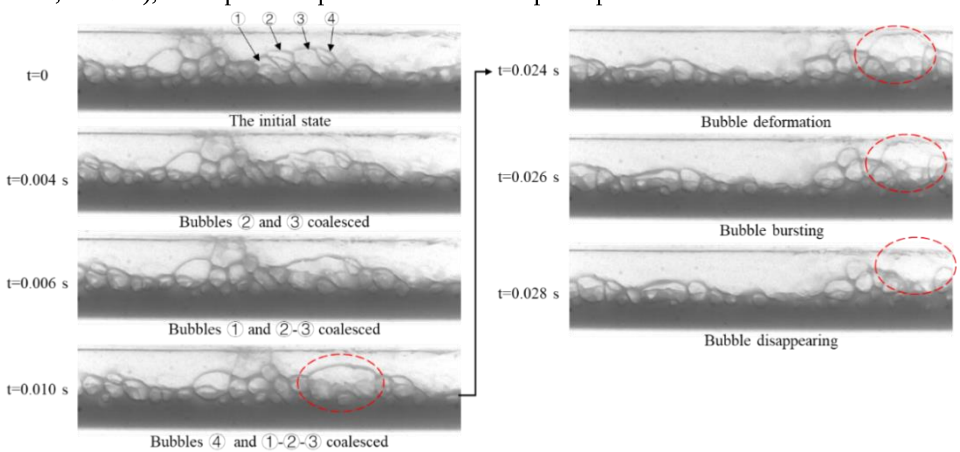


**Figure 5:** Bubble coalescing, deforming, bursting, and disappearing (G=480 kg m-2 s-1, x=0.002, 215-255 mm from the TEV exit)

### 3.3 Separated but Developing Region

The end of the separating region is marked by a clear liquid-vapor interface, with most of the bubbles or droplets merging into the continuous phase. When the phase separation is completed, the flow characteristics, such as void fraction, flow velocity, or flow regimes, continue to change gradually. Figure 6 depicts some examples of the flow regime transformation in the separated but developing region.

When both the mass flux and quality are relatively low (G=100 kg m-2 s-1, x=0.04), the separation of the two phases is achieved within a short distance (~40mm after the TEV), where the liquid layer at the bottom of the tube is thin. As the separated two-phase flow travels further along the tube, the liquid layer at the bottom of the tube thickens, and the liquid waves get more turbulent. Finally, the waves are high enough to reach the top of the tube, forming an intermittent flow. The waves in a stratified flow will grow when the velocity difference between the liquid and vapor phase exceeds a certain threshold to trigger the Kelvin–Helmholtz instability. When the two-phase flow is generated from flash evaporation through the expansion device, the two phases are well mixed and have the same velocity right after the throttle inside the TEV. However, as the flow progresses along the tube, the slip ratio increases due to different properties of liquid and vapor phases (density and viscosity) and the no-slip condition on the tube wall. Assuming homogeneous flow at the beginning and fully developed flow at the end, the flow velocity and void fraction will change along the length of the tube, as illustrated in Figure 7. The vapor velocity increases while the liquid velocity decreases. This explains why the waves at the downstream location have a bigger amplitude in the first case of Figure 6 (G=100 kg m-2 s-1, x=0.04). Figure 7 also reveals a decrease in void fraction, indicating an increase in the liquid level. In our experiments, the developing two-phase flow is visualized from 15mm after the TEV. The observed developing two-phase flow may or may not start from a homogenous state and end in the fully developed flow. But the change in flow velocity and void fraction should follow a similar pattern as illustrated in Figure 7.

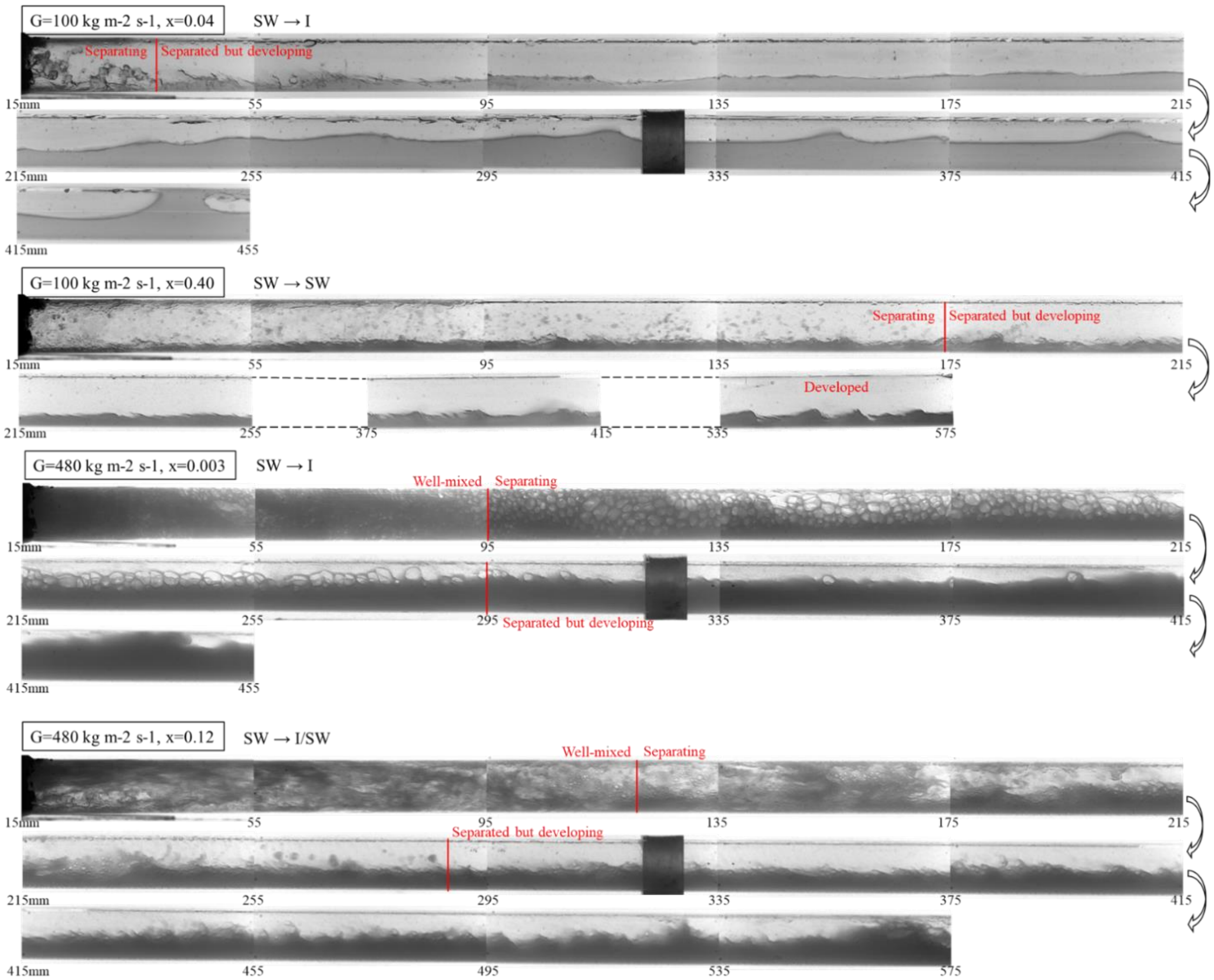


**Figure 6:** Examples of flow pattern development in separated but developing region

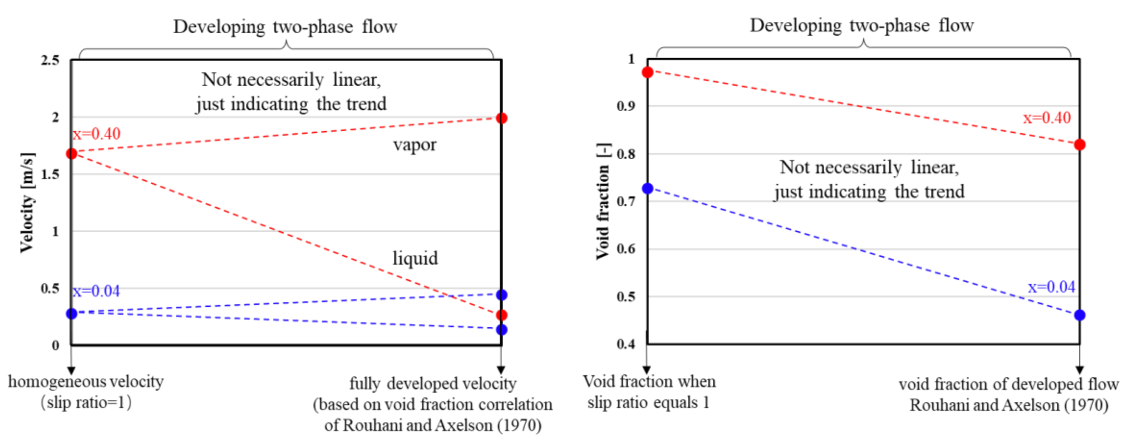


**Figure 7:** Flow velocity and void fraction: homogeneous flow vs. fully developed flow (d=8mm, m=5 g s-1)

As the vapor quality increases to 0.40 (G=100 kg m-2 s-1), the change in flow regime along the length of the tube is not that remarkable. The stratified-wavy flow maintains until the flow is fully developed. The liquid level is nearly unchanged with a slight rise. Figure 7 also indicates that the change in the void fraction is smaller as the quality increases.

The separating region is substantially longer in the low quality but high mass flux case (G=480 kg m-2 s-1, x=0.003) than in the situation with a low mass flux case and similar quality. During this long separating process, the liquid level has already reached a certain height. Then, in the separated but developing region, the stratified-wavy flow develops further into the intermittent flow. A similar phenomenon can be seen as the quality increases to 0.12 (G=480 kg m-2 s-1). But in this case, the stratified-wavy flow develops into intermittent/wavy flow. It is different from the intermittent flow in that only part of the waves with high amplitude can reach the top of the tube.

### 3.4 Developed Region

The fully developed two-phase flow is achieved when the flow structure does not change anymore. The majority of studies in open literature regarding flow patterns are focused on this region. Figure 8 demonstrates all the flow patterns at 600 mm after the expansion valve. In most cases, the flow patterns do not change further at the end of the tube. Only for four conditions at low mass flux and low quality, the flow patterns are still changing slightly. But the void fraction estimated from the videos is pretty close to the void fraction of the fully developed flow calculated from Rouhani and Axelsson (1970)'s correlation, which have been proved to have good accuracy (Qian & Hrnjak, 2020, 2021b, 2021c). For now, we check if the flow is fully developed mainly based on visualization. More rigorous criteria will be developed in future work.

With a few exceptions, the flow pattern map in Figure 8 can be regarded as a developed map for R134a with 1.3% POE 32. At vapor qualities below 0.1, only intermittent flow is observed for all mass fluxes. As the quality increases, the void fraction also increases, leading to a decrease in the liquid level. As a result, only part of the waves can touch the upper wall of the tube. This type of flow pattern is named intermittent/wavy flow. When the quality increases further, the liquid level continues to decrease. None of the waves can totally block the tube area. On the other hand, the vapor velocity is insufficient to sustain the liquid film around the upper wall of the tube. Hence, there is a region of stratified wavy flow between the annular flow and intermittent/wavy flow. However, the "stratified-wavy" flow at mass fluxes greater than 200 kg m-2 s-1 is slightly different from the typical stratified-wavy flow at low mass flux.

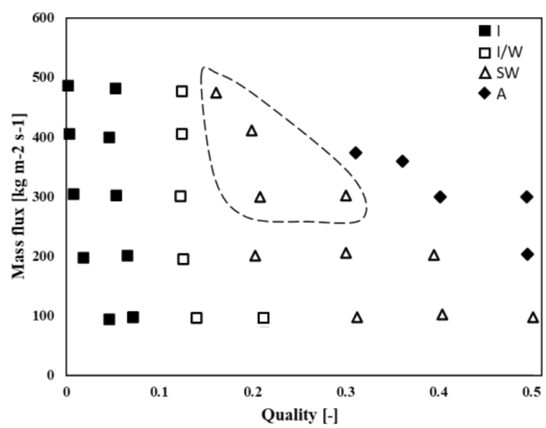


**Figure 8:** Flow patterns at 600 mm after the TEV with R134a and 1.3% POE 32 (developed flow for mast cases)

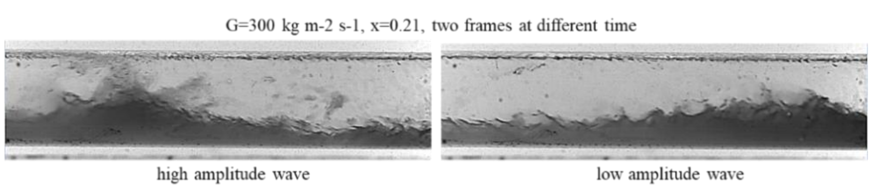


**Figure 9:** "Stratified-wavy" flow at high mass flux condition

Figure 9 illustrates the visualized flow structure of such an example at the mass flux of 300 kg m-2 s-1 and quality of 0.21. The high wave (Figure 9 left) almost reaches the top of the tube, but it appears that the wave does not entirely block the tube area. The tip of the wave is not as dark as the liquid layer at the bottom. On the other hand, although the liquid phase wets the top of the tube wall, the liquid film is pretty thin and may not be continuous (Figure 9 right). Therefore, the "stratified-wavy" flow at higher mass flux also resembles annular flow and intermittent flow. It's not surprising, given that this region (shown as a dashed-line triangle in Figure 8) lies at the intersection of the three flow regimes (I/W, SW, and A). A comparison of the developed flow regime map with refrigerant and oil mixture in this paper with the existing flow pattern map in the open literature and the effect of the oil will be discussed in another paper.

### 3.5 3D Flow Pattern Map for Adiabatic Two-Phase Flow

From sections 3.1 to 3.4, the developing adiabatic two-phase flow from the exit of the expansion valve along a 600mm-long straight tube is discussed. The two-phase flow pattern is shown to be influenced not only by mass flux and quality but also by the distance from the expansion valve. Based on this situation, the traditional 2D developed flow pattern map is extended to a 3D version of developing two-phase flow map.

As the two-phase flow enters the straight tube from the exit of the TEV, bubbles, droplets, liquid ligaments, and liquid jets are usually observed due to flash evaporation. This brings more complexity to the developing two-phase flow patterns compared to the traditional developed flow. For example, we may get a stratified-wavy flow with some bubbles at the upper part of the tube, which is defined as bubble/stratified-wavy flow in this paper. Figure 10 shows the definitions for all the possible flow patterns for developing two-phase flow. For simplicity purposes, only three types of flow patterns are named in the well-mixed region: bubble flow, droplet flow, and bubble/droplet flow. The droplet flow covers the flow pattern with small liquid particles in the form of droplets, liquid ligaments, and liquid jets. The flow patterns in the separating region are a combination of bubbles or droplets with the basic flow patterns usually observed in developed flow. Therefore, we use two symbols to indicate each flow pattern in this region: one for bubbles or droplets, the other for the basic flow pattern. In separated but developing region, all the types of flow patterns are similar to developed flow, but flow structure or void fraction is still changing. With all these definitions in Figure 10, we can propose a 3D developing flow pattern map in Figure 11.

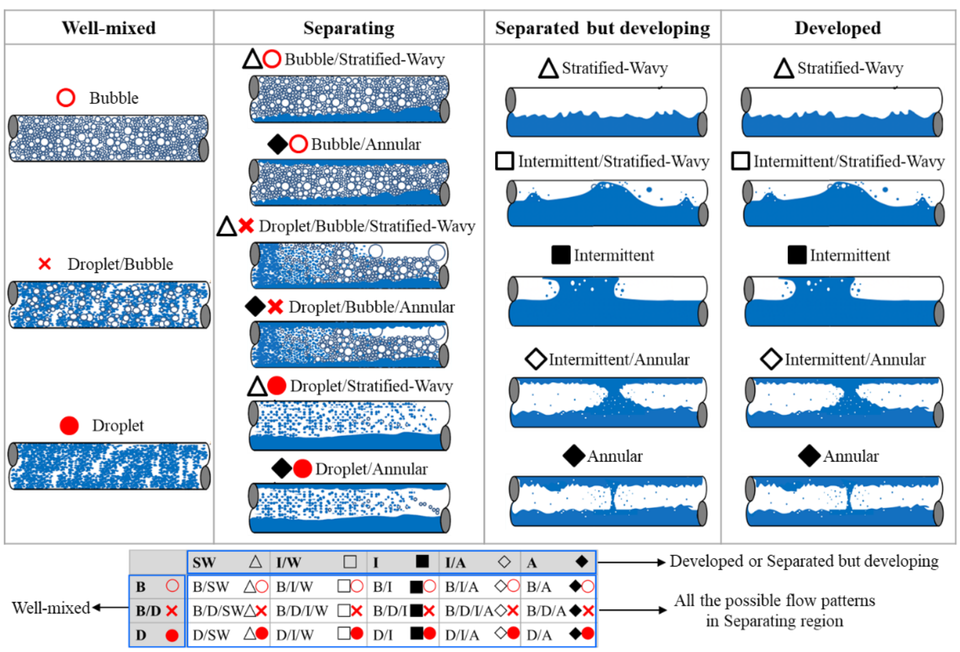


**Figure 10:** Definition of flow regimes in 3D flow pattern map

In Figure 11, bubbles or droplets are observed at the beginning of the tube for all the tested working conditions. The distance they can survive is determined by both mass flux and vapor quality. As the mass flux increases, the length for bubbles/droplets growing, coalescing, bursting, and finally disappearing is longer. It is also worth noting that the bubbles are more common at low qualities while the droplets are at higher qualities.

To analyze the 3D flow pattern map from a different perspective, we will ignore the bubbles and droplets for the time being and concentrate solely on the development of the basic flow patterns, as shown in Figure 12. At the beginning of the tube (right after the TEV), there are only two types of flow patterns: stratified-wavy and annular. As the two-phase flow progresses along the tube, the annular flow covers a wider range first and then shrinks. This can be explained by the schematic drawing in Figure 12. The flow patterns near the TEV exit are usually well-mixed bubbles or droplets with a thin layer of liquid at the bottom of the tube. Then, most of the droplets are falling to the bottom, but part of them may attach to the top of the tube and form a continuous liquid film at the top as annular flow. When the quality is not high enough, this type of annular flow is temporary and will transform back to stratified-wavy flow. For high quality, the annular flow can maintain its structure stably. As the mass flux decreases, the separation of liquid and vapor starts at a shorter distance. The observed flow patterns at the TEV exit begin from annular flow (G=200 kg m-2 s-1). As mass flux decreases further (G=100 kg m-2 s-1), the flow velocity is pretty low and only a few bubbles or droplets exist at the exit of the TEV. The flow regime is always stratified-wavy flow along the tube.

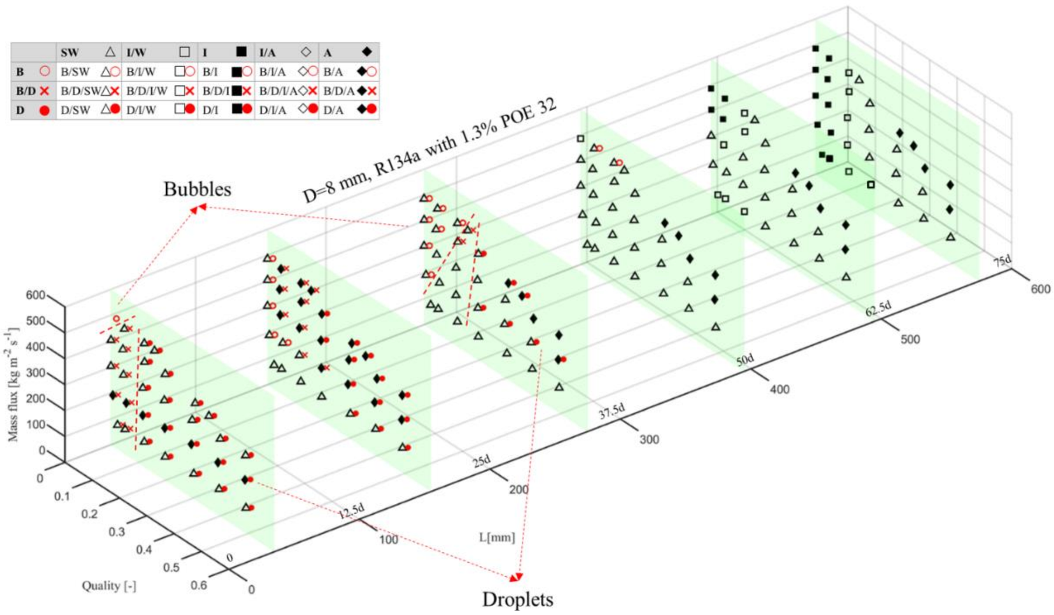


**Figure 11:** 3D flow pattern map of adiabatic two-phase flow in a horizontal tube

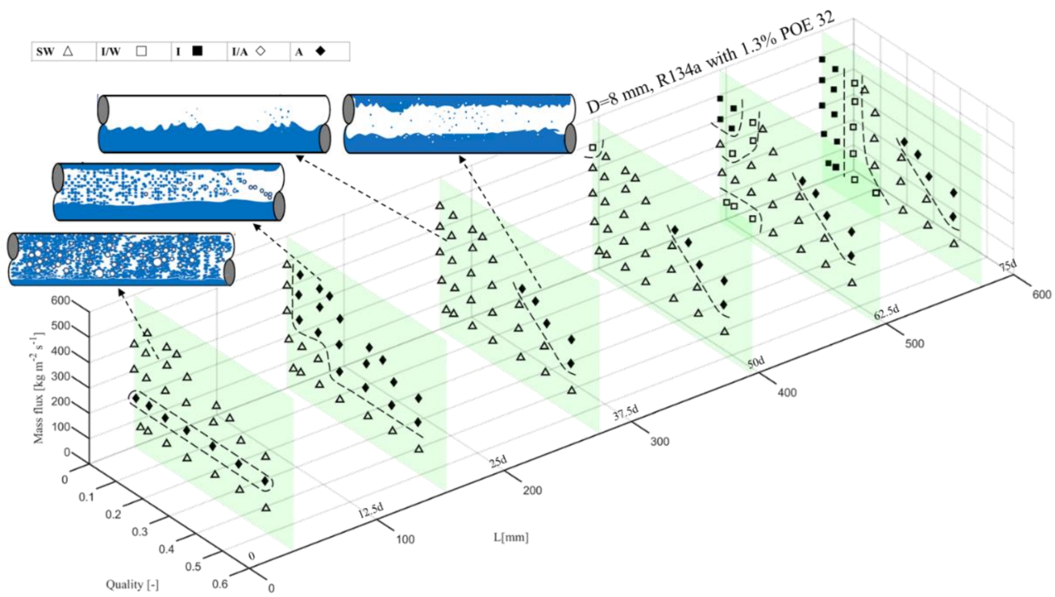


**Figure 12:** 3D flow pattern map of adiabatic two-phase flow in a horizontal tube: basic flow pattern neglecting the bubbles and droplets

From roughly 300 mm after the expansion device, the annular flow is only observed at higher mass flux and higher quality. This region of annular flow maintains its structure until the end of the tube (near 600mm). A longer distance (500-600mm) is needed to get an intermittent or intermittent/wavy flow. Both evolved from the stratified-wavy flow at relatively low vapor qualities.

## 4. SUMMARY AND CONCLUSIONS

The developing adiabatic two-phase flow after a thermostatic expansion valve with refrigerant and oil mixture is discussed in this paper. The developing flow patterns along a 600mm-long straight tube are divided into four regions: well mixed, separating, separated but developing, and fully developed flow. The flow patterns near the expansion valve may belong to the well-mixed or separating region, depending on the mass flux. In general, it is more likely to get a well-mixed flow for higher mass fluxes. The transition from well-mixed to separating flow occurs because of the gravity/buoyancy force. As the two-phase flow moves downstream along the tube, the gravity/buoyancy force takes precedence over inertia and surface tension due to the decrease in liquid velocity and growth of bubbles, resulting in the separation of liquid and vapor phases. The end of the separating region is marked by a clear interface between the liquid and vapor phases. However, the flow structure may still change slightly before it is fully developed.

This paper also proposes a 3D developing flow pattern map by adding the distance from the expansion device as the third dimension. The bubbles and droplets are common near the expansion device, and they last a longer distance at higher mass flux, owing to a stronger effect of inertia over gravity/buoyancy force. The length to get a fully developed intermittent flow is longer than the annular flow. In both cases, the thickness of the liquid layer at the bottom is similar in the well-mixed region (Figure 3). But this thin layer of liquid can increase to a high level at low vapor quality when it is transformed to intermittent flow in the fully developed region (Figure 6). But the variation in liquid level is indistinctive for annular flow.

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