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ABSTRACT

Two-phase flow distribution in evaporators has been shown to be directly affected by the development of the flow between the expansion device and the heat exchanger, namely, the separation characteristics of the two phases. For this reason the development of adiabatic two-phase R134a in an 8.7mm transparent PVC tube directly after an expansion valve was studied. This paper presents a mapping of this developing adiabatic two-phase R134a flow until the flow is "fully developed". This mapping was obtained through the use of a high speed video camera traversing a 700mm long tube and recording the various flow regimes seen by the fluid.

1. INTRODUCTION

Previous experimental studies have shown that the way in which two-phase refrigerant flow develops before and as it enters the header of parallel flow evaporators greatly influences refrigerant distribution within the heat exchanger, which in turn, influences the thermal performance. Bowers et al. (2006) reported, for R134a flow in microchannel heat exchanger manifolds, that expansions occurring closer to the manifold yielded better distribution of the liquid phase due to the fact that the flow did not have time to fully develop and separate. Elbel and Hrnjak (2004) noted that the separation of the two phases in the inlet header of an evaporator led to maldistribution and in return could reduce the thermal performance of a heat exchanger. Vist and Pettersen (2004) noted that a "disturbed chaotic" flow as well as a shorter inlet pipe before a manifold feeding a bank of tubes yielded better distribution. They also concluded that characteristics of the flow entering the manifold were of great importance. From their studies, Fei et al. (2002) were able to conclude that homogenous type flow, specifically very small droplets dispersed in a vapor stream yielded very good distribution in the header of a plate evaporator. Kulkarni et al. (2004) noted that the absence of correlations for developing two-phase flow in evaporator inlet headers limits ability to accurately analyze header designs and their influence on refrigerant distribution. Poggi *et al.* (2007) mentioned that two-phase flow distribution was significantly affected by the inlet quality of the flow, which in turn significantly affected the flow regime entering the manifold. Flow pattern changes caused by variations in flow conditions changed the distribution of an air/water manifold, as reported by Marchitto *et al.* (2007). Lee and Lee (2005) noted that the distribution pattern in a header is strongly influenced by the configuration of the two-phase flow in the header. All of these works serve to underscore the need for further study in the area of developing two-phase flows; specifically, the flow between the expansion valve and the evaporator inlet in air-conditioning applications.

There is a well established body of literature dealing with the mapping of fully developed two-phase flows; including, but not limited to, work done by Baker (1954), Taitel and Dukler (1976), Weisman *et al.* (1978), and Mandhane *et al.* (1974). Some of the more recent work, like that done by Kattan *et al.* (1998) and Wojtan *et al.* (2005) have included diabatic effects on the flow regimes of two-phase refrigerants such as R134a. R402A, R404A, and R410A. Jassim *et al.* (2006) used a probabilistic approach to two-phase flow mapping, taking into account that the transition from one regime to another is not sharp.

While the above are very important advancements in the field of two-phase flow, little work has been done in the developing of region of such flows. Several of the existing studies focus on the interaction of dispersed two phase developing flows with very low void fractions or qualities in a vertical orientation, specifically air/water flows. These flows tend to be significantly different from the developing flows seen in air conditioning applications; namely, the flow observed directly after an expansion at the entrance to an evaporator. There has however, been very limited study conducted on these specific kinds of developing flows. One of the few studies done in this arena, by Fei and Hrnjak (2004), established three specific regions of development in the flow and a specific set of criteria for distinguishing these regions. The three regions of the flow Fei and Hrnjak identified were the expansion region, developing region, and fully developed region. The criterion for transition between the expansion region of the flow and the developing region was the separation of the two phases. This point is referred to as the separation distance.

While the criterion for transition to the fully developed regime from the developing regime was that no further changes in the general characteristics of the flow were observed.
Seeing an area that needs further investigation and has relevance to important engineering applications, the authors have undertaken a study of developing two-phase refrigerant flows through flow visualization of developing adiabatic two-phase R134a flow directly after an expansion device. While the authors have conducted studies of the same nature in different tube sizes, this paper presents qualitative results of the ongoing study in an 8.7mm tube.

2. EXPERIMENTAL APPROACH

2.1 Experimental Facilities

The facility used for the current study is presented schematically in Figure 1. This facility was designed in such a manner as to allow oil free two-phase R134a flow to be generated. For this reason a liquid pump was used instead of a compressor. A speed controller was used in conjunction with the pump to allow for a variety of mass flow rates to be studied. The total mass flow rate of refrigerant was measured using a coriolis type mass flow meter (MFM). Varying inlet quality was also a parameter of this study. In order to maintain these various qualities after the expansion process an electrical pre-heater was used in order to heat the flow to an appropriate value prior to entering the expansion valve. To ensure that the flow was adiabatic in nature it was expanded to room temperature (~23°C) through a manually controlled needle valve. The flow then enters the test section, an approximately 1.2m long transparent PVC tube. The visualized portion of the test section was only 700mm, however the test section was made so much longer in order to ensure that the exit from the test section had no effect on the flow upstream. After passing through the test section, the two-phase refrigerant entered a condenser where the vapor phase was condensed into liquid. Before the flow entered the pump to be recycled back into the loop it entered a reservoir to ensure that only liquid refrigerant was fed to the pump. To measure system temperatures and pressures, thermocouples and pressure transducers were placed before and after the test section. The high side pressure (before the expansion valve) in the system varied from 1MPa to 3MPa (145psi to 450psi), depending upon the mass flow rate and quality being tested. The low side pressure of the system was limited to the saturation pressure of R134a at room temperature, approximately 620kPa (90psi).

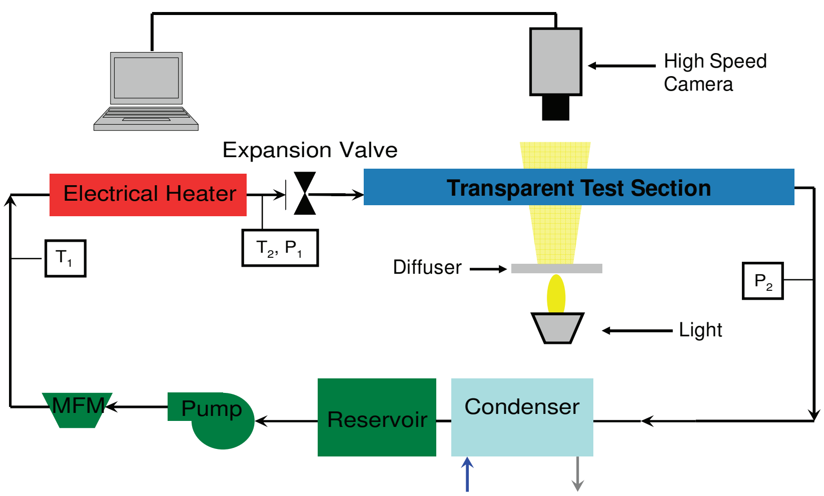
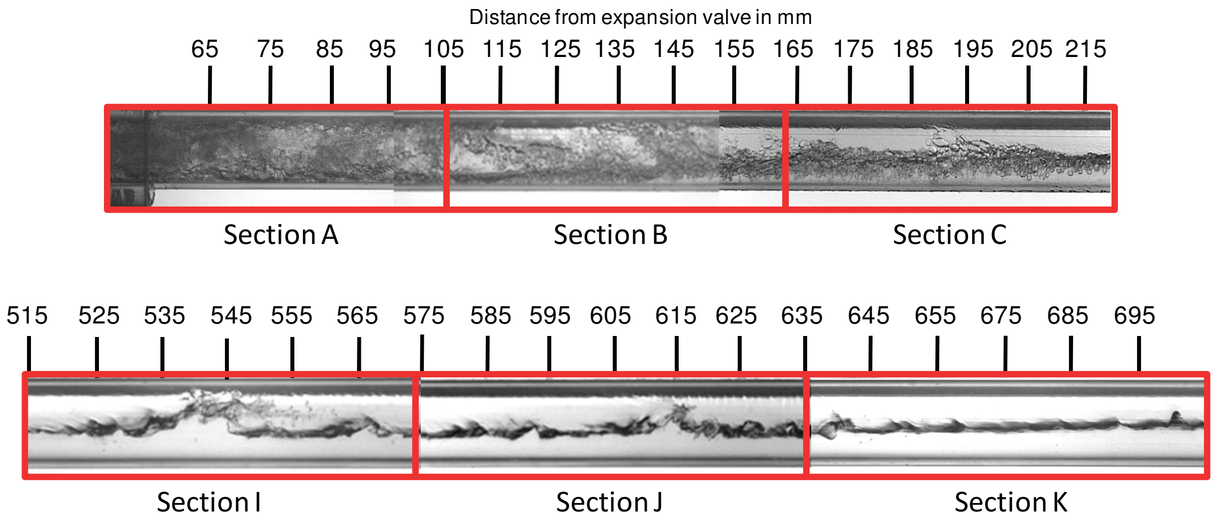


Figure 1: Schematic of Experimental Facilities

As mentioned earlier, the two key flow parameters varied were quality and mass flow rate (mass flux). To study the effects of each, both were controlled independently of the other. The inlet qualities in this study were varied from 0.05 to 0.35. These values were chosen as representative values of qualities typically seen at the inlet of automotive type evaporators. The mass flow rates in the test section were varied from 10g/s to 35g/s in increments of 5g/s. Coupling the flow rates with the tube diameter of 8.7mm used in this study yielded a mass flux range of 168kg/m^{2}s to 588kg/m^{2}s.

2.1 Flow Visualization

To study the flows being generated in the above described manner, a high speed camera was used to visualize the flow in the transparent test section. A high speed camera was used to avoid "blurring" and the subsequent loss of information that frequently occurs using traditional video recording devices in applications that have short time scales. The camera used in this study was a black and white Vision Research SR-CMOS camera capable of operating at frame rates of up to 90,000 frames per second and exposure times of 2μs. While the cameras maximum resolution was 512x512, the resolution used for this study was 512x256 with framing rates of 1000fps and 1500fps and an exposure time of 15μs. The flow in the test section was backlit by a studio light passed through a frosted glass diffuser as shown in Figure1. Due to the large aspect ratio (L/D) of the length of pipe being studied, it was necessary to break the visualized tube into 11 distinct sections, labeled A through K. Several example images of the two-phase R134a flow in 6 of these sections are presented in Figure 2. These images were all taken under the same flow condition of a mass flux of 336 kg/m^{2}s (20g/s) and a quality of 0.15.



Flow Conditions: ID = 8.7mm, mass flux = 336 kg/m^{2}s, quality = 15%

Figure 2: Example Images of Developing Two-Phase R-134a Flow

Several key characteristics of developing flow can be seen through a simple examination of these example images. In Section A, the flow nearest the expansion is very well mixed with small droplets and some bubbles dispersed in the upper part of the tube while a thin liquid film seems to be forming near the bottom of the tube. As the flow progresses into Section B, the liquid falls to bottom of the tube and distinct liquid and vapor flows begin to establish themselves. In Section C, the two phases stratify themselves further, with only a thin layer of a two-phase mixture existing between each. As the flow progresses further down the tube this layer thins until it vanishes completely. Once the flow reaches Sections I, J, and K, the structure of the flow has changed considerably from what it was near the expansion valve. Under these flow conditions, a stratified wavy flow is setup with the wave height occasionally being such that it nearly wets the top wall of the tube.

3. Developing Flow

3.1 Regions of Flow Development

The flow seen in this study can be classified into several regions as it progresses through the length of the tube. These regions are defined by the characteristics of the flow in that region. The first region of the flow is the Well Mixed region. This region is characterized by the phases being very well mixed together, very similar in nature to a homogenous type flow. Both bubbles and droplets are seen in this region, as will be discussed in the following section. As the flow progresses down the length of the tube the phases begin to separate themselves from one another. This region of the flow is referred to as the Separating region. It is characterized by two distinct features of the flow appearing, a liquid film on the bottom of the tube and a vapor region at the top of the tube. The end of the Separation region, and thus the beginning of the next, is marked by the point at which an interface between the vapor phase at the top and liquid phase becomes traceable. This next section is for all intensive purposes separated but still developing. It is still developing because there is still a thin layer between the two pure phases that has both liquid. Even after that layer disappears the flow is still considered to be developing because the characteristics of the flow changes as it progresses down the length of the tube. The final region of the flow is the Fully Developed region. This region is characterized by flow that while dynamic in nature no longer changes its overall characteristics. Example images of the four regions discussed above are shown in Figure 3 for flow under the same mass flow and quality conditions. All of the characteristics described above are present in these images. Further discussion of these different regions and their characteristics as a function of flow conditions will be discussed in the following sections.

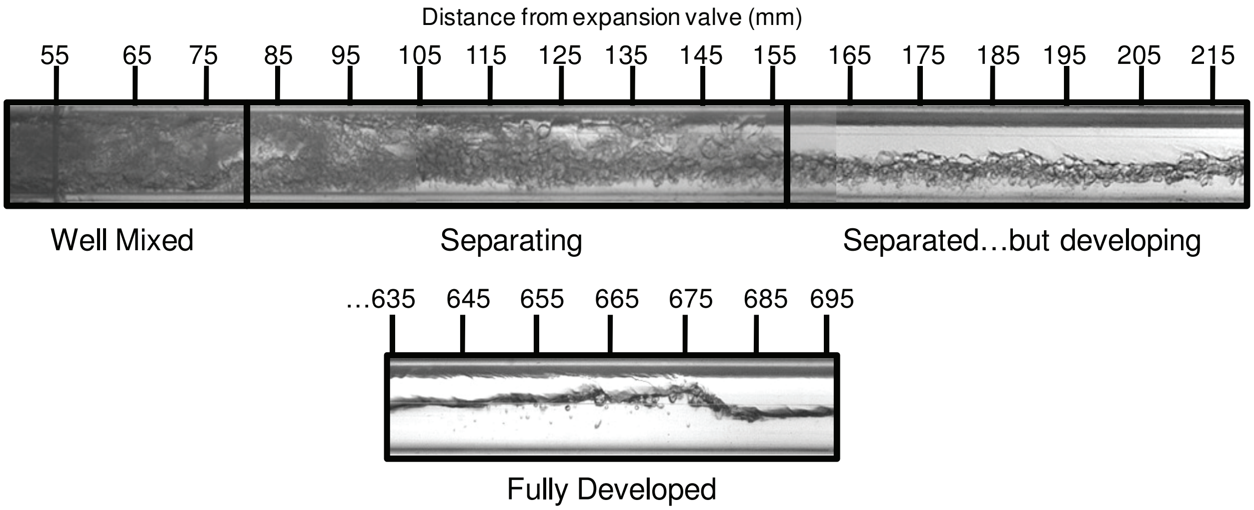


Figure 3: Regions of Flow Development

3.2 Flow Types in the Well Mixed Region

In the well mixed region of the flow there are three flow types that were observed. Example images of the flow types observed are presented in Figure 4. These have been designated at Droplet, Bubbles and Droplets, and Bubble type flows. In the Droplet type flow, small droplets are dispersed in a continuous vapor phase. Much of the time a very thin liquid film is seen at the bottom of the tube. In Bubble type flow, the tube is filled completely with a large amount of small bubbles and a few larger ones. The Bubble and Droplet type flow is a mixture of the two, with both droplets and bubbles present.

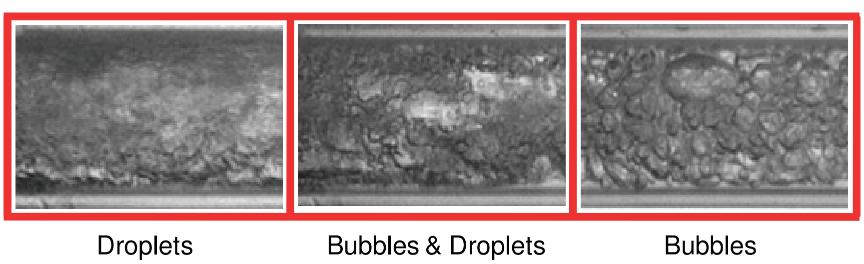


Figure 4: Flow Types in the Well Mixed Region

With these definitions established a mapping of the flow types as a function of the flow conditions studied was made and is presented in Figure 5. This map was made through visual inspection of the videos of the earliest sections of the tube before separation occurred. From Figure 5 it can be seen that Bubble flow only occurs at the lowest qualities (5% and 10%). It can also be seen that as the quality increases, the flow transitions from Bubbles, to Droplets and Bubbles, and finally into Droplets. This trend agrees well with the theory that Fei (2004) proposed, namely that bubble breakup and consequent ligament and droplet formation is caused by the increase in void fraction that occurs with an increase in quality. It could also be surmised that the reason a transition from Droplets and Bubbles type flow to Bubbles flow occurs with an increase in mass flux is that at the lower mass flux values there simply is not enough refrigerant to fill the tube with bubbles. A drawing of the possible transition from bubbly flow to droplet flow, as first proposed by Fei, is also presented in Figure 5.

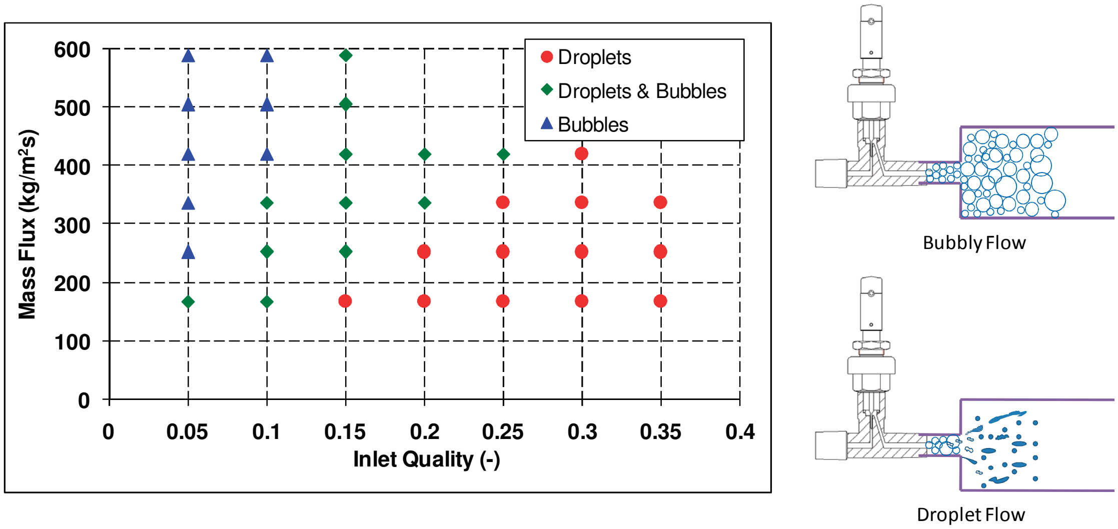


Figure 5: Distribution of Flow Types in the Well Mixed Region as a Function of Flow Conditions & Hypothetical Transition from Bubbly Flow at Inlet to Droplet Flow

3.3 Flow Characteristics in the Different Regions of the Flow

Many evaporators, for packaging reasons, have a significant distance between the expansion valve and the inlet to the evaporator. In order to understand how the flow changes along this distance and with the varying flow conditions seen by most evaporators, maps of the different regimes were made as function of distance and flow conditions (inlet quality and mass flux). In order to better present these results, example images of several of the flow regimes seen are presented in Figure 6. In all these images the flow is from left to right. The five regimes on the left side of Figure 6; stratified-smooth, stratified-wavy, intermittent, stratified/intermittent, and stratified/annular, are representative of flows commonly seen in both developing and developed flows. Stratified-smooth flow is characterized by distinct separation of the two phases with the liquid on the bottom and the vapor on the top; there is little to no turbulence at the interface. Stratified-wavy flow is very similar to stratified-smooth flow except that the interface has very "choppy" turbulent waves. Intermittent, in this case is characterized by bubbles passing through periodically, while the rest of the time the tube is full of liquid. Stratified/Intermittent flow is a transitional regime in that it is neither fully stratified nor fully intermittent; however it is not transitional in that it is a regime that stays established in the fully developed region of the flow. It is characterized by long regions of stratified flow with periodic cresting waves that do not quite form intermittent flow. The last regime presented on the left side of Figure 6, Stratified/Annular is again transitional in that it is neither fully stratified nor fully annular; however, like Stratified/Intermittent flow it stays established in the fully developed region of the tube.

The example images on the right side of Figure 6 are different in that they are representative of purely transient regimes. That is, these regimes are only experienced in the developing section of the flow. Both the Bubbly regime and the Bubbly/Droplet regime, along with the Droplet regime, were discussed and characterized in the section above. The example of Droplet/Annular flow shown on the right side of Figure 6 shows that this regime is actually something in between both droplet flow, as described above, and the classical definition of annular flow, the droplets in the flow are distinct in the left side of the image; however as the flow progresses it begins to appear more annular with liquid on both the upper and lower walls. This flow regime is not seen in the fully developed region of the tube. In a very similar manner, the Bubbly/Stratified flow is more of a combination of two different regimes, Bubbly and Stratified. Again, this regime is not seen in the fully developed region of the tube. Other regimes similar to Droplet/Annular and Bubbly Stratified could be imagined as transitions from one regime to another are realized over a short section of tube. This is in fact the case, as will be shown in following figures and discussion.

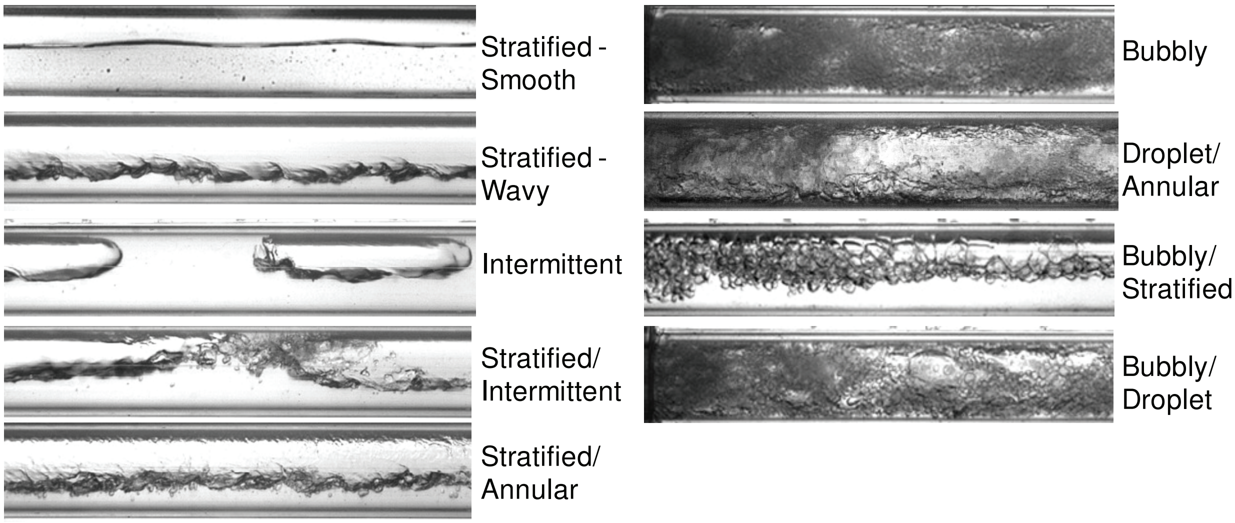


Figure 6: Examples of Observed Flow Regimes

Figure 7 is a mapping of the flow regimes as determined through visual inspection in the first section (A) of the transparent PVC located after the expansion valve. This section of the tube spans from 55mm to 105mm from the center of the expansion valve body. Most of the regimes reported in Figure 7 are actually the transitional regimes that do not exist in fully developed flow as described above. Generally, this could be considered to cover two of the regions described above, namely, the well-mixed and separating regions. The flow regimes experienced at the lowest quality (5%), generally start out as bubbly flow but begin to transition to stratified flow early on in this first section of tube. As the quality increases, the regime becomes a mix of droplet and bubbles transitioning into stratified flow. As the inlet quality is increased further, the flow regimes seen are droplet type flows transitioning

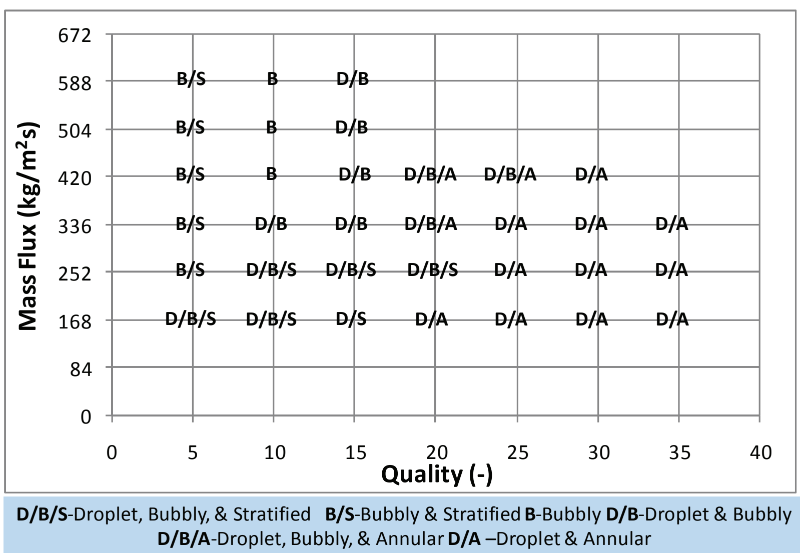


Figure 7: Flow Regimes Observed in Section A (55-105mm) as a Function of Flow Conditions

into an annular flow. While changes in quality change the type of flow regime experienced, an increase in mass flux seems to prolong the length that a given regime occurs over, as well as change the flow regime. This can be seen by looking at varying mass flux at a constant inlet quality of 10%. At the lowest mass flux (168kg/m^{2}s) the regime is a transitional one between droplets and bubbles to stratified. As the mass flux is increased to 336kg/m^{2}s it becomes a regime of droplet and bubbly mixture, without the transition to stratified. When the mass flow is increased further, the regime is changed to only bubbly flow, again without a transition to stratified flow present.

It should be noted that there is a correlation between Figure 5 and Figure 7. Figure 5 reports the flow types in only the well mixed region of the tube; however, Figure 7 reports the overall flow regime in Section A of the tube. These two figures do not directly match up because the well mixed region of the flow does not always exist through the entire length of Section A due to separation of the two phases. It should be noted that the separation of the two phases in this matter occurs mostly in the first section, but occasionally as late as Section B (105mm-155mm from valve). A method for determining this separation length as well as the location of the liquid/vapor interface based upon statistical analysis of the high speed images was developed by Bowers and Hrnjak (2007) and has been applied to a tube with a 15.3mm diameter, Bowers & Hrnjak (2008), and will soon be applied to the current results.

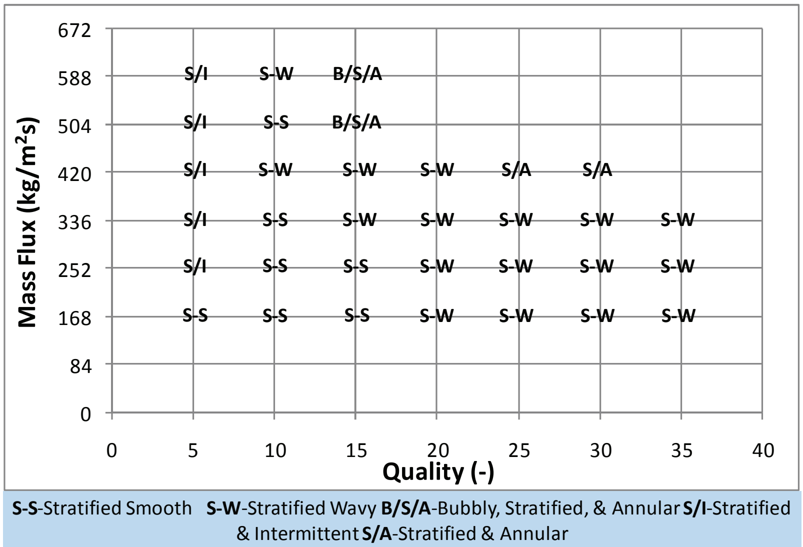


Figure 8: Flow Regimes Observed in Section F (335-395mm) as a Function of Flow Conditions

Figure 8 is a mapping of the flow regimes seen in Section F of the test section which spans 335mm to 395mm from the center of the expansion valve body. It can be seen from this figure that the structure of the flow has changed considerably from what it was in the earliest part of the test section, for the same qualities and mass fluxes. This flow is in the third region discussed earlier, namely, the separated but still developing region. At an inlet quality of 5% all the mass fluxes, except the lowest, experience a flow regime that is the Stratified/Intermittent regime described earlier. Much of the flow conditions produce a stratified flow (both wavy and smooth) in this area of the test section. It should be noted that there are two flow conditions that are still in the process of transitioning from the bubbly type flow experienced early on in the tube; these are seen at an inlet quality of 15% and mass fluxes of 504kg/m^{2}s and 588kg/m^{2}s.

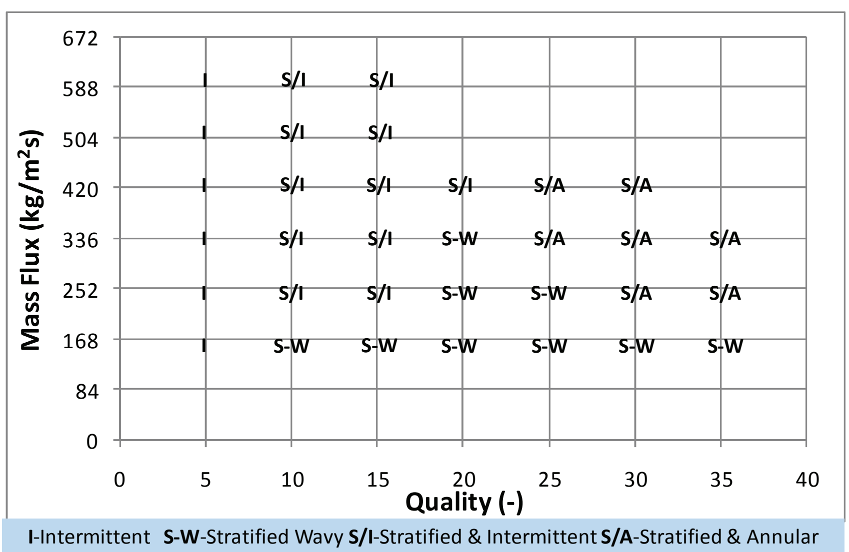


Figure 9: Flow Regimes Observed in Section K (635-695mm) as a Function of Flow Conditions

Figure 9 shows the flow regimes for the different conditions at the final visualization section (K) of the test section. Section K spans from 635mm to 695mm away from the center of the expansion valve body. Here the flows are considered to be fully developed. The only flow regime realized at the lowest quality (5%) was the intermittent regime. As the quality was increased to 10% and 15%, the flow regime was Stratified-wavy at the lowest mass flux. However, at all the other mass fluxes tested the flow was consistently in the transitional Stratified/Intermittent regime. As the quality was increased further to 20%, the mass flux range over which the Stratified-wavy flow occurred was increased from 168kg/m^{2}s to 336kg/m^{2}s. At this quality, Stratified/Intermittent flow was only experienced at a mass flux of 420kg/m^{2}s. Increasing the quality to the highest values (25%-35%), reduced the mass flux range in which the Stratified-Wavy regime was observed. Instead of realizing the Stratified/Intermittent regime at the higher mass fluxes, the regime that was observed was the Stratified/Annular regime.

6. CONCLUSIONS

The characteristics and development of two-phase flow between the expansion valve and the inlet of the evaporator plays an important role in the distribution of refrigerant in microchannel evaporators. For this reason a study of the development of two-phase R-134a along a length of 700mm after an expansion valve was undertaken through use of a high speed camera. Several distinct regions of the flow were observed and defined. These regions were described as the well-mixed region in which the two-phases are well mixed, the separating region in which the two phases begin to separate from one another, the separated but developing region in which the two phase are distinctly separated but the flow regimes are not fully developed, and the fully developed region in which there is little to no change in the flow structure. Example images of both the fully developed regimes and the transitional ones seen early in the length of the tube were provided. Mapping of these regimes as a function of flow conditions (mass flux and quality) were provided at three sections of the tube, Section A (55mm-105mm from the valve), Section F (335mm-395mm), and Section K (635mm-695mm). These maps showed that there is a significant change in the structure of the flow as it progresses down the length of the tube; however significant separation of the phase was almost always experienced within the first 155mm after the expansion valve. Further statistical analysis of the images obtained, similar to those presented by Bowers & Hrnjak (2008) in a different tube size, is currently underway and will serve to add quantitative results to the qualitative ones presented here.

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