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Determination of Void Fraction in Separated Two-Phase Flows Using Optical Techniques

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ABSTRACT

Experimental determination of void fraction in two-phase flows can be achieved in a number of different ways, including: the quick closing of valves at each end of a test section, impedance measurement techniques, gamma or x-ray absorption, and analysis of visualization results. This paper presents a method of determining void fraction in separated, two-phase refrigerant flows through analysis of images obtained through high-speed visualization. A statistical technique known as Change Point Analysis was used to automate the determination of the location of the liquid/vapor interface in stratified and intermittent type flows. This determination allows for a calculation of the void fraction in these separated flows that can be examined as a function both of time (different images) and length (location within the image). The developed technique was applied to visualization results of separated R134a flows in transparent tubes with diameters of 7.2mm, 8.7mm, and 15.3mm.

1. INTRODUCTION

Like fully developed two-phase flow mapping, the study and modeling of void fraction in two-phase flow is made up of a very mature body of literature. Thom (1964) studied and developed a model for predicting the total pressure drop in a two-phase mixture of boiling water and steam. The model accounted for three causes of pressure drop: acceleration, friction, and gravity. Zivi (1963) presented a method for the prediction of void fraction in steady-state steam flows through the utilization of the assumption that the void fraction is such that it minimizes the entropy production in the stream. Kroeger and Zuber (1968) studied the effect of four parameters on the prediction of void fraction under subcooled boiling conditions. Rouhani and Axelsson (1970) studied the calculation of volumetric void fraction in the subcooled region and the quality region of flow boiling. In the quality region, the calculation of void fraction in steam flow followed closely a derivation proposed by Zuber and Findlay (1965). Butterworth’s (1975) work was aimed at showing the similarity amongst several different and well accepted void fraction correlations in the literature. The correlations compared are the ones developed by Zivi (1963), Turner and Wallace (1965), Lockhart and Martinelli (1949), Thom (1964), Baroczy (1963). Most importantly, Butterworth noted that all of these correlations, because they have the same form, lack the ability to capture any effect that the flow rate may have on the void fraction.

Seeing a need for further visual investigation into developing and developed two-phase refrigerant flows as well as a means of quantifying their characteristics, the authors have undertaken a study of these very issues through flow visualization of developing adiabatic two-phase R134a flow directly after an expansion device. However, such flow visualization studies frequently rely heavily on the visual analysis of the images by the eye of the experimentalist, causing these studies to be both highly subjective and time intensive. For this reason, it would be valuable to have a way to cut down on the subjectivity of such studies as well as reduce the time intensity through means of statistical analysis and automation. The authors believe that the implementation of an established simple statistical tool called Change Point Analysis offers a solution to this problem. Implementing a Change Point Analysis of the images offers a more objective manner in which to determine important characteristics of developing two-phase flows, namely the liquid/vapor interface location and separation distance, which can be easily determined.
2. EXPERIMENTAL FACILITIES

The facility used for the study of developing and developed adiabatic two-phase flow is presented schematically in Figure 1. This facility was designed to allow oil free two-phase R134a flow to be generated. A liquid pump was used instead of a compressor. A variable frequency drive speed controller was used in conjunction with the pump to allow a variety of mass flow rates to be studied. The total mass flow rate of refrigerant was measured using a Micro Motion CMF025 Coriolis type mass flow meter, with a manufacturer listed accuracy of +/- 0.10% of flow rate. Inlet quality was also a parameter of this study. In order to maintain quality after the expansion process, an electric heater was used in order to heat the flow to an appropriate condition prior to entering the expansion valve. To ensure that the flow was adiabatic, it was expanded to room temperature (~25°C) through a manually controlled needle valve. The flow then entered the test section, an approximately 1.2m long transparent PVC tube. The visualized portion of the test section was 700mm; however the test section was made longer in order to ensure that the exit from the test section had little effect on the flow being visualized upstream. After passing through the test section, the two-phase refrigerant entered the 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, depending upon the mass flow rate and quality being tested. High side pressure was measured using a Sensotec TJE pressure transducer with a range of 0MPa to 3.45MPa (gauge) and an accuracy of +/- 0.10% (with a listed temperature effect of +/- 0.0025% full scale/°F). The low side pressure of the system was limited to the saturation pressure of R134a at room temperature, approximately 620kPa. This pressure was also measured with a Sensotec TJE transducer, however, the range on this transducer was 0MPa to 1.38Mpa (gauge), with the same listed accuracy as the high side transducer.

![Figure 1: Developing Two-Phase Flow System Schematic](image)

The two key flow parameters varied were quality and mass flow rate (mass flux). To study the effects of each, both were controlled independently. Quality was determined by knowing the pressure and temperature before the expansion and then saturation pressure after the expansion combined with the assumption that the expansion process was isenthalpic. The inlet qualities in this study were varied from 0.05 to 0.35, in increments of 0.05. 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 diameters of 7.2mm, 8.7mm, and 15.3mm, yield a mass flux range of 54kg/m²s to 860kg/m²s. The valve used was a Swagelok (SS4MG2) needle valve. In order to ensure that changes caused by differences in needle valve openings did not affect the results of the experiments, the needle valve was at the same setting for all test conditions.

3. VOID FRACTION DETERMINATION

3.1 Determination of Liquid Vapor Interface

The first step in an image processing scheme is to break down the images obtained from the experiments into pixel values. Pixel values are a description of the brightness of the pixel. In the case of the camera used for this study, the pixel depth was 8 bit, meaning that the pixel values ranged from 0 to 255, with 0 representing a black, or full dark
pixel, and 255 representing a white, or fully saturated pixel. Over saturated pixels were also given grayness value of 255. Pixels with grayness between black and white were assigned a value between 0 and 255 directly proportional to the light intensity. Once the image has been converted to a matrix of pixel values, line profiles in the “y” direction at each “x” value were created. Figure 2 is an example image of flow in the 15.3mm tube from which the image analysis technique will be outlined. It can be seen from Figure 2 that at the 100th column there is a sharp change in the darkness of the pixels at approximately the 190th row. This corresponds to the location of the top of the liquid/vapor interface, at this particular x value.

The left graph in Figure 3 shows a line profile of pixel values produced at the 100th column of the image in Figure 2. There are several points at which the pixel values seem to shift dramatically their values from light to dark, or vice versa. Of interest is the dramatic change slightly before and after the 200th row. This seems to correspond to both the “top” and “bottom” of the liquid vapor interface seen in Figure 2. The other dramatic shifts are easily explained by the change in the light the camera sees caused by the top and bottom of the tube. In Figure 2, the darker region caused by the top of the tube occurs between the 115th and 130th row, approximately. This corresponds well to the dramatic drop and then rise in pixel values seen in the line profile shown in Figure 3. Similar remarks could be made about the shift in pixel values caused by the bottom of the tube. Because any statistical method employed to determine where the liquid/vapor interface is located relies on these shifts in pixel values to determine where the shifts occur, it is prudent in such an analysis to remove any such shifts that are not of relevance. In this case, only the region of the image within the tube need be analyzed to avoid detecting changes in pixel trends that are known not to be caused by flow structure.

With the above in mind, the right side of Figure 3 shows a gray scale line profile for only the points observed to be within the tube wall. (It should be noted that the locations of the tube wall were determined by the experimentalist’s visual inspection of the image, and thus introduces a degree of subjectivity). From Figure 3, it is again evident that there is a dramatic shift in the pixel values beginning near the 190th row. Just as important, however, is that now only pixels within the tube are being examined. This shift, correspondent with the liquid/vapor interface, seems to be the only major shift in pixel values.

While comparison of the line profile to the image from which it was obtained offers insight into the location of the interface, locating this change in the data is nearly as subjective as filtering through each image and marking the
interface location. If a representation of how sharply a pixel value changed with respect to those pixels nearest it
could be produced, it might offer a better means of locating the interface. This was attempted through the
production of a moving standard deviation ($\sigma$) within the line profile. The moving standard deviation was made
using five pixels within a column. In other words, the standard deviation for point $i$ is determined by finding the
standard deviation of the set $i-2$ through $i+2$. Producing a moving standard deviation of the pixel values in the line
profile yields the graph shown in Figure 4. Again, there seems to be a sharp change in the behavior of the data at
approximately the 190th row. The location of the liquid/vapor interface could possibly be characterized as the point
at which the standard deviation exceeds a previously determined value. This would introduce another degree of
subjectivity, in addition to the assumption that a moving five point standard deviation is a good metric for
comparing how individual pixels change in comparison to their neighbors.

![Figure 4: Moving 5 Point Standard Deviation at the 100th Column of Image in Figure 2](image)

While analyzing the data through the method outlined has drawbacks, the data represented by Figure 4 can be
statistically evaluated through the use of change point analysis to determine where the interface location lies in a
more objective manner. Change Point Analysis is a method often employed to predict when a change occurs in a
time dependent set of data. While the data being generated in this project is time dependent, the independent
variable that will be examined using a change point analysis is not time, but the spatial variable of distance. This
method of regression analysis relies on the construction of cumulative sum charts to determine where the sharpest
change in trend occurred. Taylor (2000) offered a step by step method of employing a Change Point Analysis, much
of which is based on Hinkley’s (1971) work in the area. The method outlined by Taylor, while followed closely in
the analysis of images in this study, is simplified slightly.

Taylor refers to the metric which finds the sharpest change in data as the cumulative sums estimator. For this study,
the cumulative sums estimator was used to determine the location of the liquid/vapor interface. The first step in
determining this estimator is to create a cumulative sum (CUSUM) chart of the data in question. To create such a
chart, the average of the data must first be calculated. The data in this case is represented by the moving five point
standard deviations of the pixels within the tube. The average of these values is then determined. In order to create
the CUSUM chart, the first cumulative sum (in this case at the 100th row) is set to zero and the other cumulative
sums are calculated by adding the difference between the value of the current five point standard deviation ($\sigma_{5P,i}$),
and the average five point standard deviation to the value of the previous sum, as expressed in Equation 1.

Performing the above described calculations on the moving standard deviation data shown in Figure 4 and plotting
the absolute value yields the CUSUM chart shown in Figure 5. There are several inflection points in this graph.
Taylor argues that the inflection point with the largest absolute value represents the strongest change in trend of the
data in question. Taylor refers to this largest inflection point as the CUSUM estimator which corresponds in this
analysis to the liquid/vapor interface location.

$$\text{CUSUM}_i = \text{CUSUM}_{i-1} + (\sigma_{5P,i} - \bar{\sigma}_{5P})$$

(1)
Using the change point analysis process for determining the liquid/vapor interface location outlined above, the 100th column of the image in Figure 2 was analyzed. Figure 6 shows the results of the liquid/vapor determination method in the form of a red dot superimposed over the image at the determined interface for the 100th column only on the left. The point determined by the change point analysis corresponds well to the top of the liquid/vapor interface at this particular x location. Moving one step further, the change point analysis can be applied to each column of the image to determine the liquid/vapor interface over a whole section of tube. An example using the same image is shown on the right side of Figure 6, with the interface presented as a curve overlaid onto the image analyzed. This example shows that the change point analysis offers a good method of tracking the liquid/vapor interface in a separated two-phase flow.

Figure 7 contains four examples of the interface determination method applied to four distinctly different flow types, one in which flow separation is incomplete and three in which the two phases are separated but in different regimes, Stratified, Intermittent, and Annular. The image on the top right of Figure 7 shows that the image analysis technique tracks the interface very well, when the flow is completely separated and the interface is distinct. The image on the top left side, however, shows that prior to the formation of a sharp interface it is very difficult for the analysis technique to determine locate the interface. This fact can be taken advantage of in determining the distance required
to separate the two phases. The images on the bottom left and right of Figure 7 are a result of the image analysis technique being applied to intermittent and annular flow, respectively. The bottom images show that, while the determination of the interfaces in these two non-stratified regimes is not perfect, the application of this technique is suitable to flow regimes beyond stratified. For Annular flow, the two interfaces were found by splitting the tube into a top and bottom half and the Change Point Analysis was applied to each half.

3.2 Determination of Void Fraction from Liquid Vapor Interface

Because the interface of the flow can be readily determined through the method outlined above, it is possible to estimate the void fraction based upon this calculation. Wojtan et al. (2005) developed a method for determining the void fraction based on the location of the interface in a cross section of a tube. Here, the approach taken was slightly different since a length of the tube, not a cross section, is visualized. This requires some assumptions to be made but also allows for easy examination of the void fraction as a function of length. The first assumption is that, at any given point along the length of the tube, the interface value is constant across the depth of the tube. This is not necessarily true, but the two dimensional images of the flow offer little information on how liquid depth varies through this dimension of the tube. The second assumption is that the interface sharply divides the liquid from the vapor. When the flow has distinct separation, this is a very good assumption. However, in flows where the two phases are not entirely separated, if there is a small amount of vapor intruding into the liquid flow field in the form of small bubbles riding on the top of the liquid flow, this assumption becomes weaker.

Presented in Figure 8 is a schematic of the tube and the flow fields of the two phases, the liquid being the hatched field on the bottom of the tube and the vapor, the white section above. The distance \( h_{lv} \) is the distance from interface location to the top of the tube. Equation 2 through Equation 6 describes how the void fraction can be calculated taking into account the assumptions mentioned above. The angle \( \beta \), determined by Equation 2, is the chord angle, in degrees, defined by the liquid/vapor interface. Knowing the chord angle, the liquid area \( A_L \) can be calculated by Equation 3. With the area occupied by the liquid having been determined and the total tube area \( A_T \) easily calculated from Equation 4, calculating the void fraction \( \alpha \), is a simple matter of finding the ratio of area occupied by vapor to total area, Equation 6. The results of this are shown graphically in Figure 9, for the entire width of the image in Figure 2.

\[
\beta = 2 \cos^{-1} \left( 1 - \frac{D - h_{lv}}{D/2} \right) \tag{2}
\]

\[
A_L = \frac{D^2}{8} \left( \frac{\pi}{180} \beta \sin \beta \right) \tag{3}
\]

\[
A_T = \frac{\pi D^2}{4} \tag{4}
\]

\[
A_v = A_T - A_L \tag{5}
\]

\[
\alpha = \frac{A_v}{A_T} \tag{6}
\]
Figure 10 contains results of both the interface tracking method and the void fraction determination based upon this analysis for example images of Intermittent, Stratified-Smooth, and Stratified-Wavy flows. For the void fraction results, both the local void fraction, at each column, and the average void fraction over the entire image are presented. In the Intermittent regime, the void fraction is nearly 0.8 for the cross sections of the tube with vapor present. In the portion of the tube filled with liquid, the void fraction goes to zero, as expected. In the case of the Stratified-Smooth example, the interface is smooth; this is mirrored in the smoothness of the calculated void fraction. The example of Stratified-Wavy flow serves to show the difference between Stratified-Smooth and Stratified-Wavy flow. Namely, the “choppy” liquid/vapor interface translates to large and frequent variations in the determined local void fraction. It is also interesting to note that while the liquid/vapor interface is very different in the Stratified-Smooth and Stratified-Wavy regimes, the average void fraction over these individual images is very similar. This method in combination with a library of high speed images allows for different kinds of void fraction determinations, instantaneous local, instantaneous spatial averaged, time averaged local, and combined temporal and spatial averaged values.

Figure 10: Examples of Determined Interface Location as Well as Local and Average Void Fraction in Three Flow Regimes

4. VOID FRACTION IN SEPARATED FLOWS AT LOW QUALITIES

The image analysis technique described above, allowing for the determination of the void fraction based upon the location of the liquid/vapor interface, was applied to the developed region of each tube diameter investigated. The results of the analysis are time averaged over 900 images for each condition (3 movies of 300 images each). This allows for the changes in void fraction caused by waves or intermittent flow to be averaged. The results of this determination are presented graphically for all tube sizes and all flow conditions in Figure 11. These results show that at the same mass flow rate and quality, the void fraction in the developed region increases as the diameter of the tube decreases. In order to show the effect of mass flow rate on quality, the void fraction in the developed region increases as the diameter of the tube decreases. In order to show the effect of mass flow rate in each tube diameter, a plot of void fraction as a function of quality and mass flow rate for each tube diameter was created. These are presented in Figure 12, which are the same results shown in Figure 11 arranged in a slightly different manner. These results show that while there is some dependence on mass flow rate, the effect of tube diameter on void fraction tends to be much stronger.
5. CONCLUSIONS

A unique method of determining the location of the liquid/vapor interface in separated two-phase refrigerant flow was developed. This involved the implementation of a change point analysis of the images. With this method a determination of local void fraction in both Stratified and Intermittent flows was shown to be possible. Void fraction determination in Annular flow could also be achieved through minor modifications of this analysis. In conjunction with the high speed video, the void fraction determination method developed here allows for both instantaneous and time averaged void fraction results. Of course there are limitations associated with this particular method as well. It requires transparency in the tube being investigated which on top of limited practicality can cause safety complications when working with higher pressure fluids than the R134a used for the current study.
NOMENCLATURE

<table>
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<tr>
<th>A</th>
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<td>Diameter (mm)</td>
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<td>h</td>
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<td>Void Fraction (–)</td>
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<td>Chord Angle (°)</td>
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<td>σ</td>
<td>Standard Deviation (–)</td>
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Subscripts

| L | liquid |
| lv | liquid/vapor |
| T | total |
| v | vapor |
| 5P | five point |

REFERENCES

Hinkley, D.V., 1971, Inference about the change-point from cumulative sum tests, *Biometrika*, 58, 509-523

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