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ABSTRACT

An experimental investigation of adiabatic void fraction was conducted using 6-port and 14-port microchannels with hydraulic diameters of 1.54 mm and 1.02 mm, respectively. Two-phase fluid flow conditions include mass fluxes from 50 to 300 kg/s.m^2, qualities between 0 and 1, and saturation temperatures for working fluids carbon dioxide at 15ºC and ammonia at 35ºC. Experiments indicate that void fraction is dependent upon hydraulic diameter, mass flux, quality, and flow regime, which can be related to the vapor density of the refrigerant. In general, models exist to predict the experimental two-phase flow pressure drop and void fraction satisfactorily for specific conditions, but no comprehensive model has been formulated that encompasses the physical properties defining two-phase flow.

1. INTRODUCTION

Popularity of microchannel heat exchangers using extruded aluminum, multi-port tubes has grown recently due to their potential for increased performance and cost reduction. As industries attempt to reduce size and increase efficiency of heat exchangers, microchannels are becoming a common solution in automotive condensers and increasingly in evaporators designed for air conditioning applications. Aluminum microchannel tubes are flat, having several small diameter channels, or ports, with hydraulic diameters typically ranging from 0.5 mm to 2 mm in size. Although called microchannels, implying diameters on order of 1 μm, microchannel port diameters are actually much larger, making the name somewhat misleading. Despite the misnomer, the term microchannel will be used, as commonly accepted in industry, in this particular application as micro refers to the small size of the channels when compared with conventional refrigeration tubing.

The purpose of this article is to increase the basic understanding of void fraction by presenting the experimental results of an investigation using aluminum microchannels with carbon dioxide and ammonia. Refrigerants in this study were chosen because they represent extremes of liquid and vapor densities that are commonly found in refrigeration systems; carbon dioxide has low liquid and high vapor density while ammonia has low liquid and vapor density. While a myriad of correlations predicting void fraction are already available, these formulas generally apply only to the specific conditions under which they were developed. The results of this study are valuable

because they will potentially help achieve a fundamental understanding of void fraction that will contribute to the future development of a generalized physical model of this phenomenon.

2. LITERATURE REVIEW

Numerous void fraction correlations have been developed that are formulated using either a slip ratio (S) or a dependence on the Lockhart-Martinelli parameter (X_{tt}). Void faction (α) is related to the slip ratio by the following equation

$$\alpha = \frac{1}{1+\frac{1-x}{x}\left(\frac{\rho_v}{\rho_l}\right)S} \qquad \text{where } S = \frac{V_v}{V_l} \tag{1}$$

where x is the quality of the fluid, ρ represents density, V represents fluid velocity, and the subscripts v and l indicate vapor and liquid properties, respectively. Equation (1) can be used to represent homogeneous flows when the slip ratio is one, or separated flows when the slip ratio is greater than one.

Many models exist to predict void fraction of separated flow; however, Niño (2002) determines these models unsatisfactory at predicting void fraction in microchannels proposing instead the following relation to correlate annular flows in microchannels

$$\alpha_{Annular} = \left[1+\left(X_{tt}+\frac{1}{We^{1.3}}\right)\left(\frac{\rho_l}{\rho_v}\right)^{0.9}\right]^{-0.06} \tag{2}$$

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.875}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.125} \tag{3}$$

$$We = \frac{x^2 G^2 D_h}{\rho_v \sigma} \tag{4}$$

where μ is the viscosity of the fluid, We is the Weber number, G is the mass flux, D_h is the hydraulic diameter, and σ is the surface tension.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental test section consists of a microchannel and two transition sections that connect the flat microchannel to round 8.9 mm (3/8") tubes common in refrigeration systems. Transition sections also serve as locations for the measurement of system pressure and the evacuation of refrigerant to the void fraction tank. Two multi-port, rectangular aluminum microchannels were used for conducting void fraction experiments. Both carbon dioxide and ammonia were studied using adiabatic conditions in 14-port, rectangular microchannel tubes with a hydraulic diameter and cross-sectional area of 1.02±0.01 mm and 15.0±0.01 mm^2, respectively. Ammonia was also studied in a 6-port tube with a hydraulic diameter of 1.54±0.02 mm and a cross-sectional area of 16.7±0.1 mm^2. Carbon dioxide was not studied in the 6-port tube due to concerns about high pressures. Dimensions of the microchannels were measured using digital image processing. This method analyses a digital image of the polished cross-section of a microchannel and essentially counts pixels to determine the area of each channel.

Transition sections, which are machined from aluminum and sealed using O-rings, connect the circular tubes of the flow facility to the flat microchannel tube, allow pressure measurement, and facilitate evacuation of refrigerant to the void fraction tank. Details of transition section design can be found in Payne (2000). A void fraction tank with a known volume is connected to the transition section via a ball valve so that refrigerant trapped in the microchannel test section can be expanded into the vapor phase. Flow facilities used for experimentation allow mass flux, quality, and saturation temperature of the refrigerants to be controlled precisely. Details relating to the design and construction of these facilities can be found in Payne (2000) and Vollrath (2003) for carbon dioxide and ammonia, respectively. In general, each facility is equipped with identical instrumentation and the corresponding accuracies will apply. Mass flow meters are used to measure liquid and vapor flow with an accuracy of ±0.10% and ±0.50%,

respectively. Pressures were measured using transducers with an accuracy of ±0.25% of full scale. Temperature measurements were obtained using type T thermocouples with an accuracy of ±0.25ºC. Liquid and vapor densities of a refrigerant are calculated using computer programs in which thermodynamic properties are calculated using a function call in terms of temperature and pressure. The precision of quality is found with error propagation analysis. It was found that the error decreases as quality increases. Error propagation analysis gives the precision for quality to be $x = 0.003x^{-1.193}$, allowing qualities above 0.4 to be determined with an error less than 1%. Pressure measurements in the void fraction tank have an accuracy of 10 kPa, which corresponds to errors of 5% to 11% and 1% to 5% for void fraction measurements of carbon dioxide and ammonia, respectively. Propagation analysis found low quality conditions to have a greater amount of error than high quality conditions.

Void fraction data was collected for mass fluxes ranging from 50 to 300 kg/s.m^2 and qualities from 0 to 1. To measure void fraction, steady-state conditions are achieved and the valves to the differential pressure transducer are quickly closed, followed by the valves on each side of the test section. It is imperative that the valves be closed very quickly so that additional refrigerant cannot enter or exit the test section, skewing the void fraction results. This technique was practiced until near simultaneous closing of the valves was achieved. Once the test section is isolated, a valve leading to the evacuated void fraction tank is opened, causing the expansion of the refrigerant into the vacuumed tank, which vaporizes all of the liquid phase in the test section. At this point the pressure and temperature in the void fraction tank are measured and the density of the vapor phase refrigerant in the tank (ρ_{tank}) is determined using property look-up tables. Since the volume of the test section (V_{TS}) and void fraction tank are known, the mass of trapped refrigerant ($m_{trapped}$) can be determined.

$$m_{trapped} = \rho_{\tan k} V_{TS} \tag{5}$$

Void fraction was measured in three separate lengths of microchannel tubing, 1.0668 m (42”), 0.6096 m (24”), and 0.0762 m (3”) to ensure consistency of data and to extrapolate entrance and exit effects. Mass trapped in the shortest transition sections was subtracted from either of the longer sections, allowing refrigerant mass in a 0.9906 m (39”) or 0.5334 m (21”) microchannel to be determined. The test section quality (x_{ts}), which is different than the inlet flow rate quality (x), is solved using

$$x_{ts} = \frac{\rho_v \rho_l V_{microchannel} - \rho_v m_{microchannel}}{m_{microchannel}\left(\rho_l - \rho_v\right)} \tag{6}$$

where $V_{microchannel}$ is the volume of the microchannel alone, $m_{microchannel}$ is the mass trapped in the microchannel alone, and ρ_l and ρ_v are the liquid and vapor densities of the refrigerant, respectively. Finally, the void fraction (α) in the microchannel is determined by using the following relation.

$$\alpha = \frac{1}{1 + \frac{1 - x_{ts}}{x_{ts}}\left(\frac{\rho_v}{\rho_l}\right)} \tag{7}$$

This relation is similar to the homogeneous void fraction, with the difference being that the test section quality (x_{ts}) will only be equal to the inlet quality (x) when the flow is purely homogeneous. For separated flow, or even flow that is not strictly homogeneous, the test section quality will be less than the inlet quality.

4. RESULTS AND DISCUSSION

4.1 Entrance and Exit Holdup Effects

To calculate void fraction in a microchannel, the amount of refrigerant mass held-up, or contained, in the transition sections must be determined. The mass can be measured by connecting the two transition sections with a short, 0.0762 m (3”), microchannel section. For each refrigerant and mass flux combination, a correlation of mass trapped must be developed for the complete range of quality from 0 to 1, which can be closely approximated as a third order polynomial function of quality. Establishing an accurate correlation for entrance and exit hold up is of paramount importance because, on average, 64% of the ammonia mass and 40% of the carbon dioxide mass is held up in the transition sections during experiments. Quality and mass flux do not have a definite observed impact on mass holdup. However, intermittent flows using carbon dioxide causes less mass to be located in the transition sections than annular flows using ammonia. This is likely because the quickly flowing vapor core of annular flow moves rapidly through the transition section while the liquid phase fills the sides of the transition sections. In intermittent flows, the vapor and liquid phases are mixed, leading to less liquid, and thus less mass, in the transition sections.

While it appears that flow regime is the contributing factor to transition section holdup, this effect has not been studied enough for any definite conclusions to be established. Ultimately, void fraction data was obtained in 1.0668 m (42") and 0.6096 m (24") microchannels with transition sections, the mass trapped due to entrance and exit effects, measured in the short 0.0762 m (3") section, was subtracted, and the resulting void fraction was calculated for a 0.9906 m (39") and 0.5334 m (21") microchannel tube.

4.2 Carbon Dioxide Results, Analysis, and Correlations

Displayed in Figure 1, the carbon dioxide void fraction data follows some definite trends. Most noticeably, void fraction increases with increasing quality. As mass flux increases, void fraction can be seen to increase, with the exception of the data at 300 kg/s.m^2. Additionally, carbon dioxide data closely follows the line depicting homogeneous flow and a vast majority of the data falls within ±15% of the homogeneous model prediction. Void fraction values are calculated for the homogeneous model using Equation (1) with a slip ratio of one. For low qualities, the homogeneous model under-predicts the void fraction. At high qualities, the homogeneous model slightly over-predicts the experimental void fraction data although values fall within ±15% of homogeneous flow.

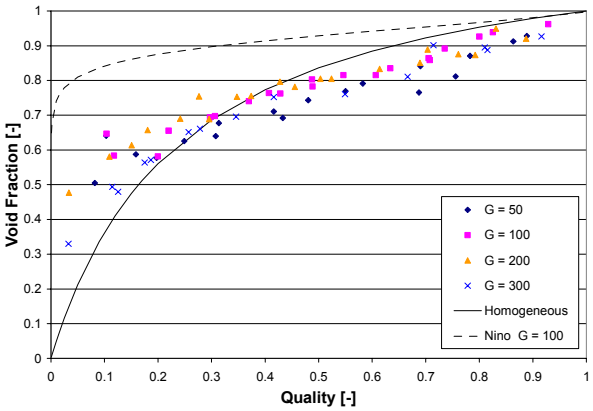

Figure 1: Void fraction of carbon dioxide in a 14-port microchannel.

This trend is more easily understood by examining the slip ratio, which is the ratio of the vapor velocity to the liquid velocity. For homogeneous flows, the slip ratio is equal to one by definition because the liquid and vapor phases are perfectly mixed. Separated flows have slip ratios greater than one because the vapor and liquid phases are separate and the vapor possesses a greater velocity than the liquid. Figure 2 presents the slip ratio of carbon dioxide in a 14-port microchannel. Slip ratio is seen to increase with quality, which is an expected result, signifying that the vapor phase is accelerating with increasing quality. Additionally, the slope of the slip ratio is nearly constant until a quality of 0.7 where it becomes steeper. While the slip ratio is greater than one for qualities greater than 0.3, the slip ratio remains, until a quality of 0.7 is reached, below a value of two. This indicates that the flow is most likely intermittent until this quality where it may obtain more annular characteristics. However, the flow may also remain intermittent, with bubbles or slugs moving more quickly than the thinning outer liquid ring.

An unexpected result uncovered by the examining void fraction is that the slip ratio has a value less than one at low qualities, which should be physically impossible. A potential answer to this conundrum is that the microchannels in this study have multiple ports and the flow may not be the same in each of these. In his research, Niño (2002) used flow visualization to determine flow regime and found that for low qualities and mass flux, the flow regime may be entirely different in separate ports. At low mass flow rates and qualities, Niño (2002) found the outer ports of the microchannel to contain a greater amount of vapor than the center ports, meaning that they contain fluid of a higher quality and thus a greater pressure drop if all channels flow at the same speed. However, pressure drop across the length of the microchannel must be the same for all ports since the flows are connected at each end. This leads to the possibility that the ports containing a lower quality mixture must have faster flow to equalize the pressure drop. In this scenario, the bulk of the liquid phase could actually travel faster than the vapor phase, allowing a slip ratio less than unity to exist in multi-port microchannels. As quality and mass flux increase, the distribution of flow in each of the microchannel ports equilibrates and the slip ratio increases toward one.

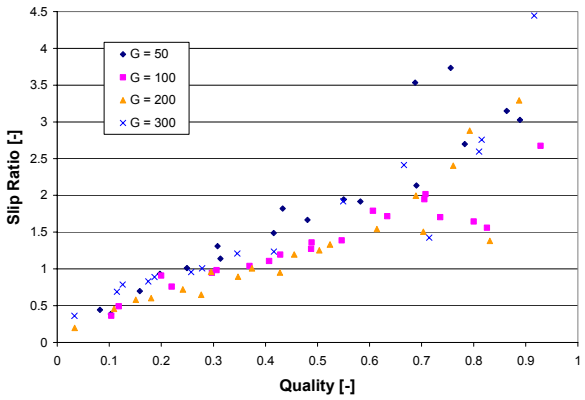

Figure 2: Slip ratio of carbon dioxide in a 14-port microchannel

4.3 Ammonia Results, Analysis, and Correlations

Ammonia void fraction data is presented for 6-port and 14-port microchannels in Figure 3. Again, void fraction increases with quality and with mass flux, although the mass flux dependency in the 6-port microchannel is not as distinctive as the dependency in the 14-port microchannel. The separated flow void fraction model devised by Niño (2002) is plotted against the experimental void fraction in Figure 3 for 6 and 14-port microchannels with ammonia. This void fraction model shows very good agreement with experimental data; nearly all of the data falls within 10% of the predicted values.

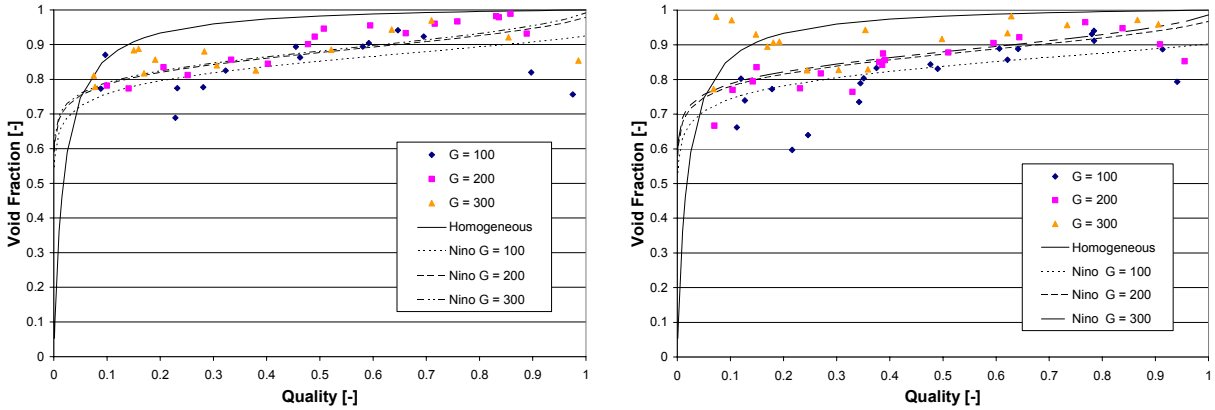

Figure 3: Void fraction of ammonia in (left) a 6-port microchannel and (right) a 14-port microchannel.

Figure 4 presents the slip ratio of ammonia in 6 and 14-port microchannels. Slip ratios in the 6-port microchannel start near one at the lowest qualities, increase to around three at a quality of 0.3, and tend to remain between three and eight until quality reaches approximately 0.8. At high qualities, slip ratios increase towards infinity as the annular liquid film around the tube thins. The data with highest quality is not shown in Figure 4 because the extremely high slip ratios, over 100, stretch the graph so that important trends cannot be observed. Slip ratio values increase towards infinity for annular flows because the no-slip condition at the wall keeps the thin liquid phase nearly stationary while the vapor flows more freely through the core of the tube. Ammonia in the 14-port microchannel produces a slip ratio that tends to increase nearly linearly with quality until high qualities are reached. Additionally, slip ratios between five and fifteen are most common in the 14-port tube, nearly twice as high as its 6-port counterpart. Again, the high slip ratios observed tend to indicate that the flow is annular.

Theoretical slip ratio lines shown in Figure 4 are created using void fraction values generated by the separated flow model developed by Niño (2002). For the 6-port microchannel there is reasonable agreement between theoretical and actual values until a quality of 0.5 is reached. Higher qualities show an over-prediction of slip ratio by the separated flow model. Agreement between the model and experimental data in the 14-port microchannel is also

acceptable for low qualities, but the model tends to over-predict the slip ratio at higher qualities and generally over-predicts all values for the highest mass flux.

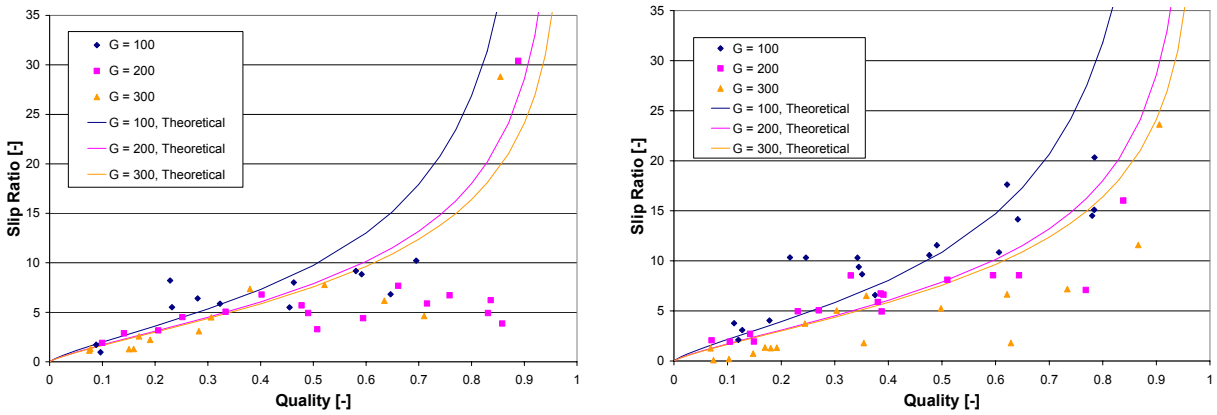

Figure 4: Slip ratio of ammonia in (left) a 6-port microchannel and (right) a 14-port microchannel

5. CONCLUSIONS

Void fraction data was presented and analyzed for two rectangular port microchannel tubes, showing a dependence on hydraulic diameter, mass flux, quality, vapor phase density, and flow regime. Entrance and exit holdup effects were examined and third order polynomials were formulated to relate quality to the mass of refrigerant trapped in the transition sections. Two correlations, the homogeneous and the separated flow models, were used to describe void fraction in the intermittent and annular regions and were tested for validity using carbon dioxide and ammonia in this investigation. Carbon dioxide, with a high vapor density, generally correlates within 15% of the homogeneous flow model. Additionally, carbon dioxide may flow homogeneously because the surface tension is very small as data was collected with a saturation temperature of 15ºC, near the critical temperature of 32.2ºC. For ammonia, possessing a low vapor density, the void fraction is predicted within 10% of the separated flow model proposed by Niño (2002). Despite the separated flow model's excellent agreement with ammonia void fraction data, the correlation fails when used with carbon dioxide, as shown in Figure 1. For carbon dioxide, the separated flow model predicts a higher void fraction than the homogeneous model, which indicates a violation of mass continuity and the failure of the model for those flow conditions. While this model appears to be useful for refrigerants with low vapor densities, it clearly is not a universally viable model.

For carbon dioxide in a 14-port microchannel, the slip ratio increases linearly for most of the quality range and remains below two, indicating intermittent flow. At the highest qualities the flow may become annular, but cannot be confirmed without flow visualization. Slip ratios of ammonia were calculated and tended to fall between three and eight for the 6-port microchannel and between five and fifteen for the 14-port microchannel. Since these slip ratios are much greater than one, they imply that the ammonia flow conditions studied are in the annular regime.

Based upon the knowledge gained through these experiments, a model that predicts slip ratio could be useful because the parameter allows the direct determination of void fraction and gives insight into the flow regime. Additional data must be collected using diverse refrigerants, conditions, and hydraulic diameters to develop a universally viable model for void fraction.

NOMENCLATURE

D_h	hydraulic diameter	(m)	**Subscripts**	
G	mass flux	(kg s^{-1} m^{-2})	l	liquid
m	mass	(kg)	ts	test section
S	slip ratio	(-)	v	vapor
V	velocity or volume	(m s^{-1}) or (m^3)		
We	Weber number	(-)		
x	quality	(-)		
X_{tt}	Lockhart-Martinelli Parameter	(-)		
α	void fraction	(-)		
μ	viscosity	(N s m^{-2})		
ρ	density	(kg m^{-3})		
σ	surface tension	(N m^{-1})		

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