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Characterization of two-phase flow patterns in small diameter round and rectangular tubes

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Abstract

The present study investigates the effect of tube diameter and shape on flow regime transitions for two-phase flow in tubes with small hydraulic diameters. Flow patterns for co-current flow of air–water mixtures in horizontal round and rectangular tubes are determined by high-speed video analysis to develop flow regime maps and the transitions between these flow regimes. Gas and liquid superficial velocities range from 0.1 to 100 m s^{-1}, and 0.01 to 10.0 m s^{-1}, respectively. Bubble, dispersed, elongated bubble, slug, stratified, wavy, annular–wavy, and annular flow patterns are observed. The effect of tube diameter and shape on the flow patterns for hydraulic diameters ranging from 5.5 to 1.3 mm is documented and compared with the literature.

Nomenclature

A area
D diameter (round)
D_{h} hydraulic diameter
F modified Froude number
f friction factor
G total mass flux, based upon superficial area
g gravitational constant
h liquid or gas level height
K dimensionless parameter for wavy flow
Re Reynolds number
S perimeter over which shear stress acts
s Jeffrey's sheltering coefficient
T dimensionless parameter for dispersed flow
u velocity in the x-direction
X Martinelli parameter.

Greek symbols

α tube aspect ratio = height/width
θ angle of inclination
μ dynamic viscosity
ρ density
σ surface tension.

Subscripts and superscripts

˘ dimensionless variable
G gas
i interface
L liquid
s superficial, for single fluid flow.

1. Introduction

It has long been known that the pressure drop for two-phase flow is much greater than that of a single phase fluid. While the introduction of a second phase results in a reduction of the flow area of both phases, this alone cannot account for the dramatic increase in pressure drop. Boelter and Kepner [1] showed that the introduction of a small amount of liquid into the gas flow increased the pressure drop by 15%. This small amount of liquid is pushed either to the bottom or around the circumference of the pipe and ripples are formed by the gas pushing on the liquid. The result is a large loss of energy in the gas phase. Lockhart and Martinelli [2] conducted a series of experiments on tubes with sizes ranging from capillary to 25.40 mm diameter, and found an empirical relationship between the two-phase pressure drop and the superficial gas velocity. The experimentally measured pressure drops of Jenkins [3] and Bergelin and Gazley [4] showed large discrepancies when compared to

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the Lockhart–Martinelli [2] correlation. Alves [5] recognized several different flow patterns corresponding to different gas and liquid superficial velocities and suggested that it was necessary to take the flow pattern and regime into account while computing two-phase pressure drops.

The particular flow regime established by a given combination of liquid- and gas-phase velocities depends upon the interaction of gravity, shear (inertia) and surface tension forces. It is believed that flow mechanisms in small diameter round and rectangular tubes are different from those in larger diameter tubes primarily due to the different relative magnitudes of these forces. Recent attempts at understanding two-phase flow in small hydraulic diameter channels have primarily used isothermal air–water mixtures. The importance of tube diameter was recognized by Govier et al. [6] and Govier and Short [7] even though their work was limited to a relatively larger diameter range (16.00–63.50 mm). Wambsganss et al. [8] reported flow patterns and flow regime transitions in a single rectangular channel with aspect ratios of 6.0 and 0.167 and hydraulic diameter of 5.45 mm through flow visualization and dynamic pressure measurements. The two different aspect ratios were obtained by rotating the tube by 90°. Wambsganss et al. [9] extended this work to develop criteria for transition of two-phase slug flow based upon root-mean-square pressure changes.

1.1. Previous research on large diameter round tubes

The first flow pattern map was created by Baker [10], who defined flow pattern transitions based upon the superficial gas and liquid velocities. Flow patterns such as bubble, plug, stratified, wavy, slug, annular, and spray were observed in a total of 27 experiments using oil and gas. The pipe diameters in the experiments ranged from 102 to 258 mm. Superficial pressure drops were calculated using a modified Fanning equation and it was found that the pressure drops for the large pipes (200 mm and larger) were 40–60% less than those predicted by the Lockhart–Martinelli [2] correlation. This finding suggested that a significant change in flow mechanisms took place in large diameter tubes, and visual analysis showed that the onset of slug flow occurred at lower values of the Lockhart–Martinelli parameter, X, in the larger pipes. Thus, the influence of pipe diameter on flow patterns cannot be disregarded in pressure drop correlations.

These conclusions were investigated further by a number of researchers. White and Huntington [11] investigated the pressure drop in two-phase flow with three different liquids and two different gases in pipes ranging from 25.4 to 50.8 mm and proposed a new pressure drop correlation to better fit their data and the data of Jenkins [3]. Govier and Omer [12] investigated geometric and fluid property effects including pipe diameter, liquid and gas mass flow rates, liquid and gas densities, liquid viscosity, interfacial tension and gravity. Their pressure drop data were in good agreement with the correlation developed by Lockhart and Martinelli [2] when both phases are turbulent, and fair agreement when the liquid is turbulent and the gas is laminar. There was poor agreement with the Lockhart–Martinelli correlation when the liquid was in laminar flow.

Al-Sheikh et al. [13] conducted a review of the current experimental data and attempted to match the data with the available flow pattern transition correlations. It was found that no single correlation could predict to any significant or acceptable degree a flow regime transition. Instead of using a single and generic transition correlation, an attempt was made to enclose all of the data from several investigators belonging to a certain flow regime pattern into a common flow regime area. This approach did not provide direct transition correlations but was used to reduce the number of possible flow regimes for any given flow conditions to one or two. They compared the area of each flow regime from various maps and used the Reynolds, Froude, and Weber number of each phase, and the Mach number of the gas to define the flow pattern transitions. A series of correlations were developed for determining the flow patterns and it was found that this new approach was able to distinguish between different flow regimes reasonably well. In some cases, there was no overlap between the respective patterns, while in others, a maximum overlap of 60.3% was observed.

Mandhane et al. [14] also tested the available flow maps with data representing a wide range of flow conditions. Nearly 6000 data points were tested for various flow conditions for pipe diameters ranging from 12.7 to 165.1 mm. No distinction could be made between plug and slug flow, or between annular and annular mist flow. The most surprising results of this work were that certain property corrections proposed by other researchers actually reduced the reliability of the data, and that the maps were unable to predict dispersed flow. From the currently available flow regime maps, a 'best fit' map was developed along with physical property corrections for gas and liquid density, gas and liquid viscosity, and surface tension. They found that for pipe diameters of less than 50.8 mm, 71.6% of the data fit the new map. For diameters between 50.8 and 101.6 mm, the map correctly predicted 59.6% of the data, and for diameters greater than 101.6 mm, 60.8% of the data matched the map. They concluded that the effect of diameter was adequately taken into account by using the superficial velocity as the coordinate axis on a flow regime map, and that significant improvement in the flow pattern prediction has not been achieved through the incorporation of the effect of fluid properties.

Several investigators attempted a purely theoretical approach to predict flow regime transitions [15–17]. Govier and Aziz [15] provide a good summary of flow regime transitions as well as continuity and momentum balances for each flow regime. A theoretical model of slug flows in horizontal and near horizontal tubes was developed by Dukler and Hubbard [16]. Nicholson et al. [17] have extended the Dukler and Hubbard model to include the elongated bubble flows. The onset of elongated bubble flow was developed by Agrawal et al. [18] and was compared with data from a 26.0 mm tube with good agreement. Taitel and Dukler [19] devised a theoretical approach to flow regime mapping for air–water mixtures using a momentum balance on a purely stratified flow pattern. A set of four non-dimensional parameters was created to identify criteria for the transition from one regime to another. The theoretical model was compared with the experimentally developed flow map of Mandhane et al. [14] and good agreement was shown between the theory and experimental data.

The effects of fluid properties and pipe diameter on two-phase horizontal flow patterns were investigated extensively by Weisman et al. [20] for pipe diameters ranging from 11.5 to 127.0 mm. The effects of liquid viscosity were measured by varying the liquid viscosity and maintaining a constant surface tension. The surface tension was also varied by using a surfactant to decrease the surface tension while maintaining a constant liquid and gas density. The gas density was varied by using various gases in the two-phase flow test setup. Using data from other investigators as well as new experimental data, modifications to existing correlations were developed for the flow-regime transitions. It was concluded that for the range of diameters tested, the pipe diameters and fluid properties have only moderate influences on the lines of transition.

More recently, statistical approaches have been taken to better define the transitions between flow regimes that are more difficult to distinguish visually [21, 22]. These transitions include plug or bubble to slug flow and annular to annular mist flow. This approach utilizes fluctuations in the pressure/time signals, root mean square of pressure/time signals, frictional pressure gradients and chaos theory to provide an objective means to interpret flow pattern transitions. Annunziato and Girardi [23] used a differential pressure measurement and local void fraction probes to measure the temporal fluctuations in a 90 mm diameter tube. Wambsganss et al. [8] showed that the transition from plug or bubble to slug flow and the transition from slug to annular flow can be clearly identified by plotting the root mean square pressure signal vs the mass quality.

The previous work discussed thus far addressed tubes of relatively large diameters ranging from 11.5 to 258.0 mm, and showed that pipe diameter and fluid properties have only minor effects on the flow regime transitions for this range of pipe diameters. For diameters larger than 200 mm the Lockhart–Martinelli [2] correlation for pressure drop predicts a value that is 40–60% higher than the experimentally measured values. Also, flow map predictions of Mandhane et al. [14] and the correlations of Weisman et al. [20] may not be applicable as both of these works are based upon significantly smaller pipe diameters. For pipe diameters smaller than 11.5 mm, it is to be expected that the differences in the relative effects of gravitational, shear, and surface tension forces will cause the transitions between flow regimes to be different from those found in large tubes. The theoretical map of Mandhane et al. [14] and the transition lines proposed by Weisman et al. [20] may not be applicable to these smaller diameters. Thus, the behavior of the two-phase flow pattern transitions must be identified before pressure drop and heat transfer correlations can be developed.

1.2. Previous research on small diameter tubes

There has been relatively little work done on the development of two-phase flow regime maps for small diameter tubes. Suo and Griffith [24] investigated the elongated bubble flow pattern in capillary tubes with diameters ranging from 1.0 to 1.6 mm. They identified and attempted to correlate the transition lines from elongated bubble to annular and bubbly flow by using the average volumetric flows of the liquid and gas phases and the velocity of the bubbles. Barnea et al. [25] made visual observations of the two-phase flow patterns found in small horizontal tubes with diameters ranging from 4.0 to 12.0 mm and classified these flow patterns according to four major regimes (dispersed, annular, intermittent and stratified). They found that all transitions except the stratified to non-stratified transition were satisfactorily described by the Taitel–Dukler [19] model. More recently, Damianides and Westwater [26] developed individual flow regime maps for air–water mixtures for each diameter in the range 1.0–5.0 mm. Conflicting trends of the effect of diameter on flow regime transitions were observed. For example, the transition from a pseudo-slug pattern to an annular pattern occurs at a lower, higher, and then lower value of superficial gas velocity as the diameter is decreased. These investigators reported similar results for other lines of transition. Fukano et al. [27] investigated the flow patterns found in capillary tubes for air–water flow with diameters ranging from 1.0 to 4.9 mm and compared their small diameter flow maps with the Mandhane et al. [14] flow regime map. They identified the flow pattern for each data point but did not provide the flow pattern transition lines.

When comparing the data of Fukano et al. [27] with those of Damianides and Westwater [26], some difficulties arise in interpreting the position of flow transition lines. The general trends of how the transition lines are shifted as the diameter is decreased are unclear, because of the disagreements between the flow patterns reported by these two studies. However, these studies do point out that the flow regime map presented by Mandhane et al.

[14] cannot sufficiently predict the flow regime transitions in small diameter tubes. Also, it appears that the theoretical predictions of Taitel and Dukler [19] and the correlations presented by Weisman et al. [20] are not reliable for small diameters. The present work will therefore focus on developing flow regime maps as a function of diameter for small diameter tubes. The maps developed here will also be compared with the Taitel–Dukler predictions and the modified correlations presented by Weisman et al. [20].

1.3. Previous research on rectangular tubes

Most of the research on two-phase flow in small hydraulic diameter rectangular channels uses tubes of either small ($\alpha < 0.50$) or large ($\alpha > 2.0$) aspect ratios [28–31]. Hosler [28] investigated two-phase flow patterns in a vertical rectangular channel and found that pressure had a significant effect on the flow transitions. Richardson [32] studied rectangular tube flow patterns for aspect ratios ranging from 0.125 to 0.50 and hydraulic diameters ranging from 11.30 to 33.90 and provided flow pattern maps for each of the three channels tested. For each of the three channels tested, the width was held constant at 50.80 mm and the height was varied from 6.35 to 25.4 mm. The smaller aspect ratio suppressed the stratified and wavy flow regimes and promoted the onset of elongated bubble and slug flows due to the ability of the liquid to more readily rise to the top of the tube. Troniewski and Ulbrich [33] studied 10 different channels with $0.09 < \alpha < 10.10$ and $7.45 < D_h < 13.10$ mm with the smallest diameter tube having the largest aspect ratio. The liquid viscosity was varied using different concentrations of a sugar–water solution. They proposed flow regime maps for both horizontal and vertical rectangular tube flows and concluded that liquid viscosity has an insignificant effect on the flow pattern transition lines for the range of tube diameters and aspect ratios studied. Lowry and Kawaji [30] studied rectangular geometries with $D_h < 2.0$ mm and $40.0 < \alpha < 60.0$ in vertical upward flows. The flow pattern transitions were compared with the theoretical model presented by Taitel and Dukler [19]. They concluded the theoretical model was not valid for narrow channel flow and that the transition to annular flow was dependent upon the superficial liquid velocity. Wambsganss et al. [8] developed a flow pattern map for a 19.06 by 3.59 mm rectangular tube as well as a quantitative method for detecting the transition to slug flow. The transition was detected using the root-mean-square pressure fluctuations and plotting this value vs the mass quality of the mixture.

The above discussion shows that there are significant gaps in the understanding of two-phase flow regimes in small diameter round and rectangular tubes. Specifically, the effect of tube diameter and aspect ratio on flow pattern transitions is not well understood, with conflicting trends reported by different investigators. The variation of flow patterns with tube diameter and shape could reflect the varying influences of surface tension, shear, and gravity. The present study attempts to explain the effect of diameter on round-tube two-phase flow patterns, as well as the differences between flow patterns for round and rectangular tubes of similar hydraulic diameters. Thus, flow patterns in round tubes with diameters in the range $1.30 < D < 5.50$ mm were investigated and the effect of tube diameter documented. Furthermore, the specific effect of tube shape was investigated by comparing the flow patterns in a round tube with those in a rectangular tube of similar hydraulic diameter and aspect ratio close to 1.0. It is expected that a rectangular tube with sharp corners could allow the liquid to be drawn up and held more readily along the tube walls, thus allowing plug, slug and annular flows to be sustained at higher gas and liquid superficial velocities, while delaying stratified, wavy and dispersed flow regimes. The following sections describe the experimental techniques used to observe these phenomena and present comparisons with the literature described above.

2. Experimental setup

The experimental setup used in this study was designed for adiabatic co-current flow of air-water mixtures in either round or rectangular horizontal tubes. A schematic diagram of the test setup is shown in Fig. 1. Water and air were used to represent the liquid and gas phases, respectively. In a few cases, a blue dye (Formulabs STD Blue) was injected into the water stream to better delineate the two phases. Both the liquid and gas streams flowed separately through a bank of rotameters of the appropriate flow rate ranges before combining in a straight run of pipe. The mixture then flowed into a liquid–gas mixer before entering the test section. The uncertainties in the flow rate measurements are estimated to be $\pm 4\%$.

The test sections for the round tubes were made of Pyrex glass and the test section for the rectangular tube was made of transparent plastic. The two-phase mixture exited to a drain after flowing through the test section. The flow patterns were recorded at regular intervals of a range of liquid and gas flow rates ranging from 0.0126 to 8.33 l min^{-1} and from 0.002 to 1.18 m^3 s^{-1} respectively. The recording equipment used was a Canon ES5000 8 mm video camera with a zoom range of $40\times$ ($80\times$ digital). A shutter speed of 0.0001 s and a frame speed of 0.033 s were used. The video was recorded using a High-8 video recorder, and subsequently analyzed to determine the respective flow regimes.

3. Round tube results

One of the problems in studying and reporting two-phase flow patterns is the lack of uniformity in the ter-

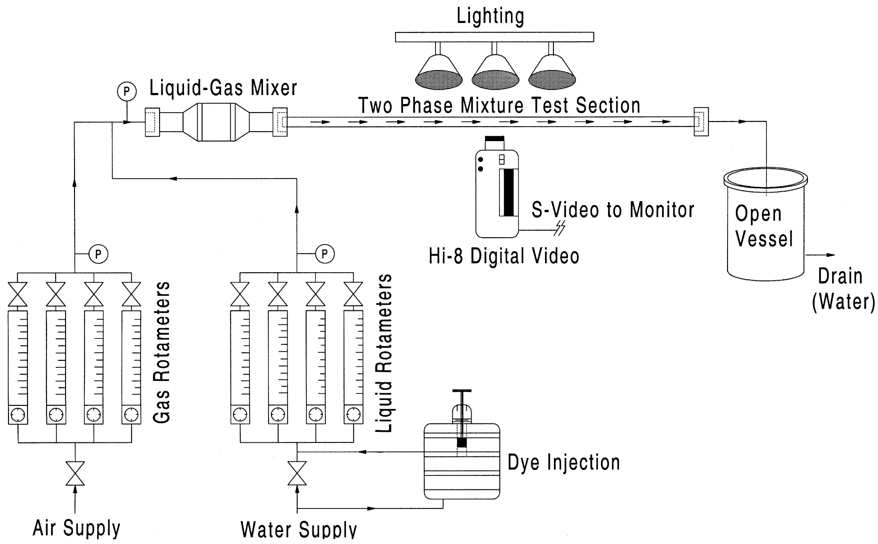

Fig. 1. Experimental apparatus.

minology used by the various investigators for the different flow regimes. In addition, some investigators have subdivided the flow regimes into as many as 16 distinguishable patterns [34]. It is important that specific definitions for these regimes be established and described before the flow regime maps are presented. For this work, four major flow regimes were identified, including stratified, intermittent, annular and dispersed flow (see Table 1). These flow regimes are further subdivided into flow patterns [35]. The stratified flow regime is divided into the stratified flow pattern and the wavy flow pattern. The intermittent flow regime is divided into the elongated bubble and slug flow patterns. Furthermore, the dispersed flow regime is divided into the bubble and dispersed flow patterns. Examples of these flow patterns are shown in Fig. 2 and consecutive frames of the video corresponding to $t = 0.0$, $t = 0.033$, and $t = 0.066$ s are shown in Fig. 3. These frames were obtained from the video for the 5.5 mm diameter tube; similar flow patterns were observed and recorded for the other tubes also. A brief description of each flow regime and flow pattern is provided.

Table 1
Flow regime classifications

Major flow regimes	Flow patterns
Stratified	Stratified smooth
	Stratified wavy
Intermittent	Elongated bubble (plug)
	Slug flow
Annular	Wavy annular
	Annular
Dispersed	Bubble
	Dispersed

3.1. Flow regime descriptions

3.1.1. Stratified flow regime

The stratified flow regime is characterized by a complete separation of the liquid and gas phases. When both of the liquid and gas flows are laminar and no fluctuations at the flow interface can be detected, the flow pattern is called stratified (stratified smooth). As the gas mass flow rate is increased, instabilities form at the liquid–gas interface due to the interfacial velocity differential (Kelvin–Helmholtz instability). This flow pattern is called wavy flow (stratified wavy) and is characterized by the formation of small interfacial waves. In larger diameter tubes, these waves can amplify and crest. The waves are easier to detect in large diameter tubes and the wave height can be large enough to allow the waves to break. In small diameter tubes, such as the ones used for this study, large breaking waves were typically not observed.

3.1.2. Intermittent flow regime

The intermittent flow regime is characterized by discontinuities in the liquid and gas flow. Elongated bubble flow (plug flow) is characterized by a continuous stream of vapor plugs flowing in the liquid. A thin film of liquid coats the tube wall and surrounds the vapor plug. Small disturbances may exist fore and aft of the bubbles, but as a whole the plugs remain intact and uniform. As the gas mass flow rate is increased, these disturbances amplify until the aft portion of the plug breaks apart into smaller bubbles. At this point, the flow pattern becomes slug

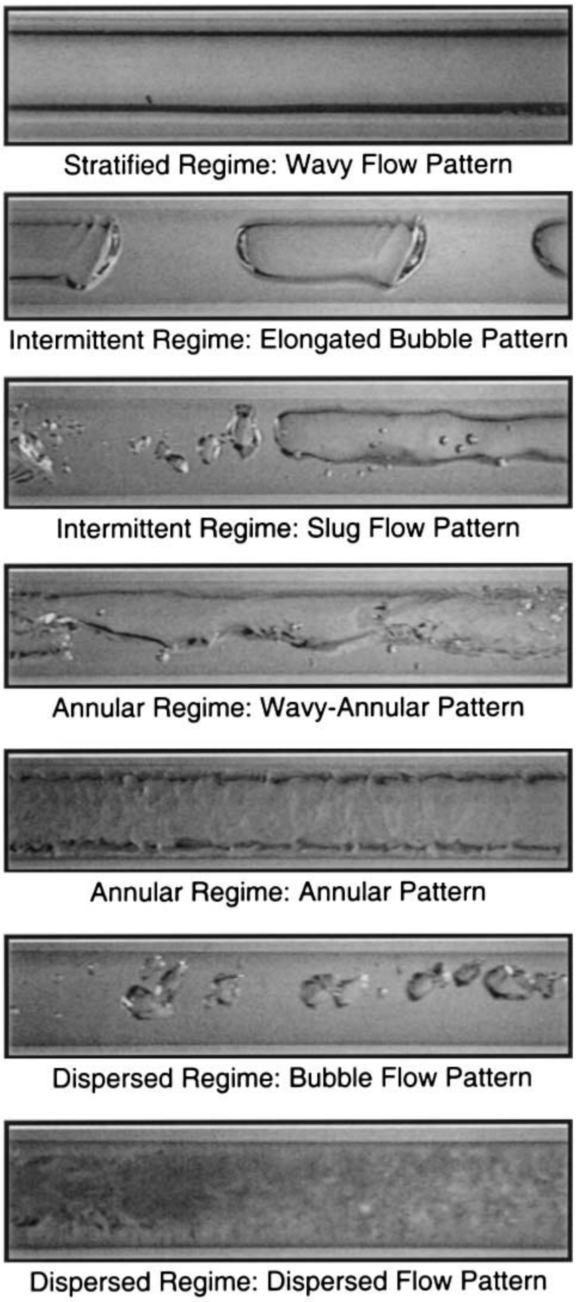

Fig. 2. Description of flow regimes and patterns.

flow. These smaller bubbles become trapped in the liquid flow and impact the front of the following slug causing disturbances in the front flow profile.

3.1.3. Annular flow regime

The annular flow regime consists of a nearly complete separation of the liquid and gas along the circumference of the tube wall. The first form of annular flow occurs when the surfaces of waves in wavy flow amplify to the extent that they touch the top of the tube wall. This flow pattern is known as wavy–annular flow (pseudo-slug flow). As the mass flow rate is increased, the liquid is pushed up around the circumference of the tube wall by the increase in the gas momentum and falls downward under gravity in the form of annular waves. When the liquid coats the tube wall completely (forming an annular ring of the liquid phase) and the gas flows through the core of the tube, the flow pattern is known as annular flow. In annular flow there could also be small droplets entrained in the gas core. This flow is also known as annular mist flow.

3.1.4. Dispersed flow regime

Dispersed flow occurs when the liquid flow is turbulent and the gas phase is in laminar or turbulent flow. When the gas flow is laminar, small bubbles are driven by buoyancy forces and flow primarily in the top half of the tube. This pattern is known as bubble flow. As the Reynolds number of the gas increases, keeping other variables constant, the bubble size decreases and the bubbles begin to disperse across the entire tube cross section. This flow pattern is known as dispersed bubble or dispersed flow.

3.2. Flow regime maps

The four round tubes analyzed in this study included 5.50, 2.60, 1.75 and 1.30 mm inner diameter tubes. Individual flow regime maps for each tube are shown in Fig. 4. The four flow regime maps were superimposed to identify trends as the tube diameter is decreased and this result is shown in Fig. 5. Over 690 data points were used to define the flow maps. The stratified smooth flow pattern was not observed for any of the tubes tested, and for tubes with an inner diameter less than 5.50 mm, the stratified–wavy flow pattern was not observed for the flow velocities tested. The resulting flow maps were compared (Fig. 6) with the theoretical results of Taitel and Dukler [19], experimental results of Damianides and Westwater [26] and the experimental results of Fukano et al. [27]. For example, in Fig. 6, as a baseline case, the results for the 5.50 mm round tube in the present study are presented with the results of Damianides and Westwater [26] for a 5.00 mm round tube. A comparison of the observed flow regime transitions with the transition correlations provided by Weisman et al. [20] is provided in Fig. 7.

Figure 5 clearly shows that the tube diameter has a significant effect on flow regime transitions. As the tube diameter is decreased, the transition from an intermittent (plug and slug) regime to a dispersed or bubbly regime occurs at progressively higher superficial liquid velocities, u_L^s. It is possible that as the diameter decreases, surface tension effects are more dominant and the liquid may

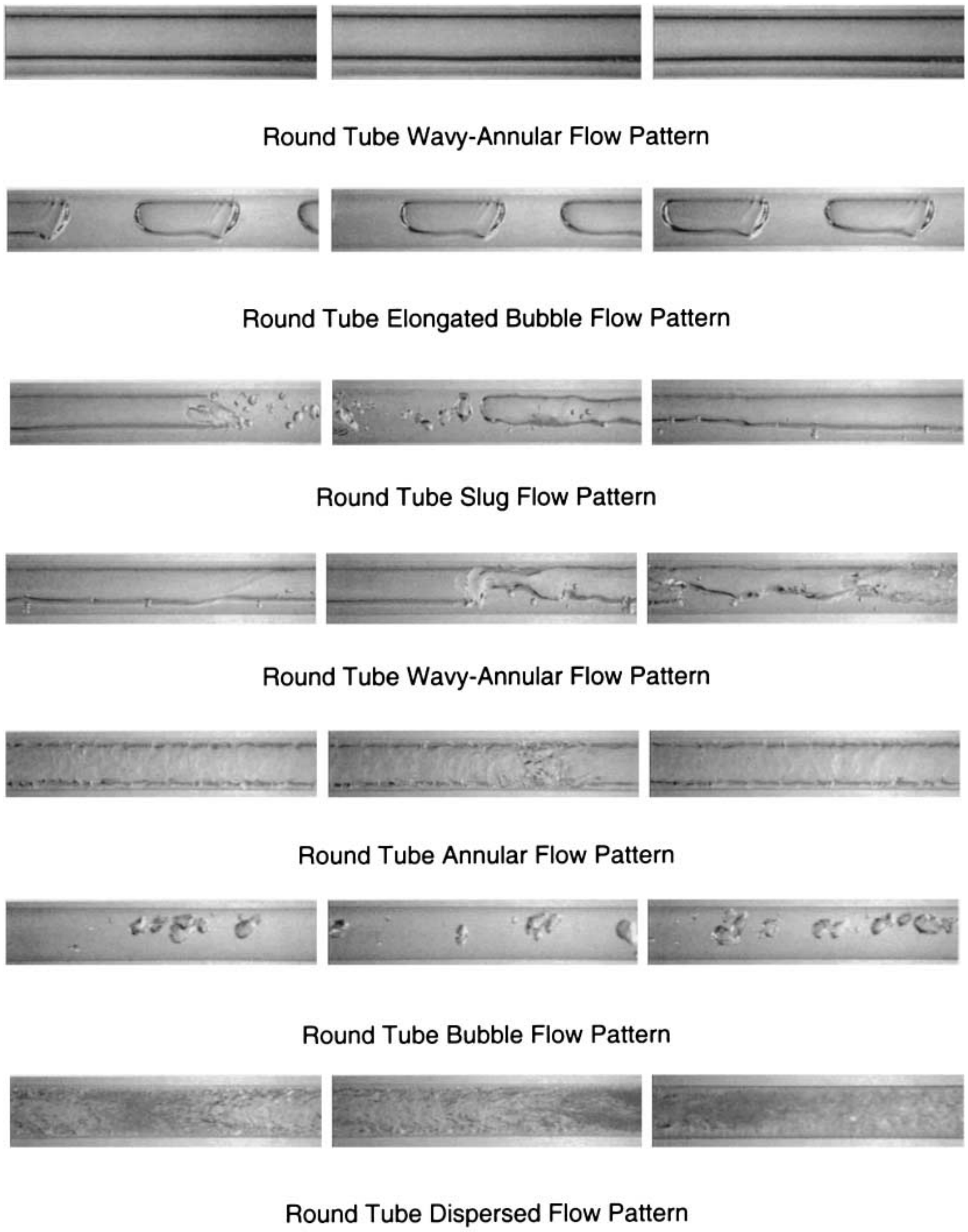

Fig. 3. Time lapse photographs for $t = 0.000$, 0.033 and 0.066 s.

readily coat the circumference of the tube. The result is that the elongated bubble and slug flow patterns are sustained at higher values of u_L^s.

The transition from the intermittent flows to the annular category of flow regimes (wavy–annular and annular flow) occurs at a higher value of u_G^s when the diameter is decreased below 5.50 mm, but remains nearly unchanged as the diameter is further reduced to 1.75 and 1.30 mm. With a smaller diameter, the intermittent regime is sustained to a higher value of u_G^s and u_L^s while the transition to the annular flow regime is delayed. Due to the increased ability of the liquid to coat the tube wall, the relative size of the wavy–annular regime is decreased with decreasing diameter. The transition from a wavy–annular flow pattern to a pure annular flow pattern occurs at a slightly higher and nearly constant value of u_G^s.

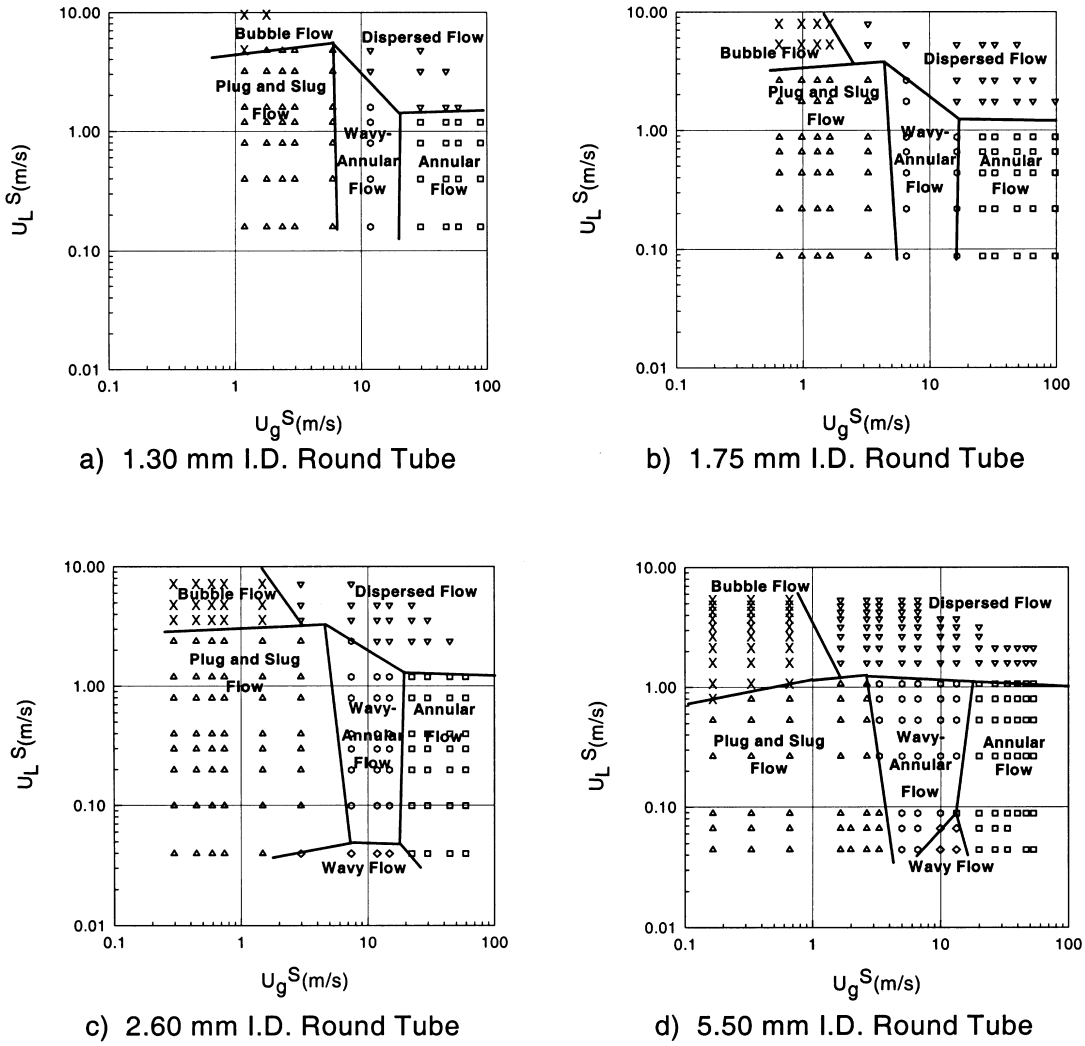

Fig. 4. Flow regime maps for tubes tested in this study.

3.3. Comparison with Taitel and Dukler [19] results

Taitel and Dukler [19] attempted to predict the flow regimes for concurrent gas–liquid flow in pipes using a momentum balance. The momentum balance was non-dimensionalized with respect to D for length, D^2 for area, and u_L^s and u_G^s for velocities. Each flow regime transition was defined by a separate transition criterion using a set of non-dimensional parameters X, F, T and K:

$$X = \left[\frac{(\mathrm{d}P/\mathrm{d}x)_L^s}{(\mathrm{d}P/\mathrm{d}x)_G^s}\right]^{1/2} \tag{1}$$

$$F = \sqrt{\frac{\rho_g}{(\rho_L - \rho_G)}}\,\frac{u_G^s}{\sqrt{Dg\cos\theta}} = \sqrt{\frac{\rho_G}{(\rho_L - \rho_G)}}\,Fr^{1/2} \tag{2}$$

$$K^2 = \left[\frac{\rho_G \rho_L u_G^{s2} u_L^s}{(\rho_L - \rho_G) g \mu_L \cos\theta}\right] \tag{3}$$

$$T = \left[\frac{(\mathrm{d}P/\mathrm{d}x)_L^s}{(\rho_L - \rho_G)\, g\cos\theta}\right]^{1/2} \tag{4}$$

For the transition from stratified flow to wavy flow, Taitel and Dukler used a condition for wave propagation of air on still water. In dimensionless form, this condition can be expressed as:

$$K \geqslant \frac{2}{\sqrt{\breve{u}_L \breve{u}_G}\sqrt{s}} \tag{5}$$

where s is the sheltering coefficient for the waves as proposed by Jeffreys [36]. For the transition between the

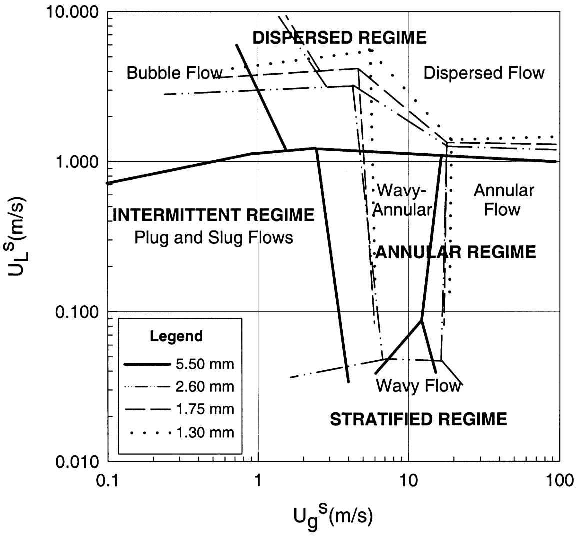

Fig. 5. Flow regime transitions for round tubes tested in this study.

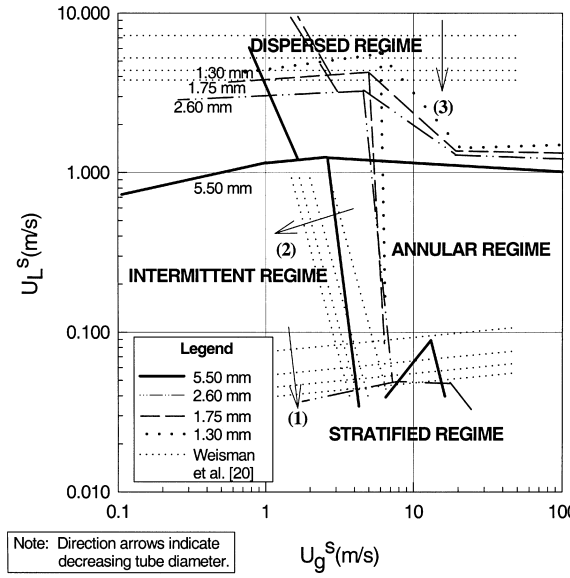

Fig. 7. Comparison with correlations by Weisman et al. [20].

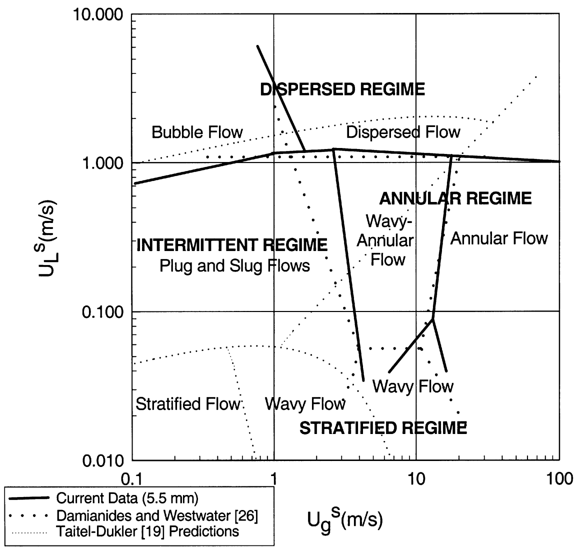

Fig. 6. Theoretical and baseline comparison (5.5 mm diameter round tube).

stratified regime and the intermittent regime, the Kelvin–Helmholtz theory was extended to a wave height equal to half of the tube inside diameter. This led to the following transition criterion:

$$F^2\left[\frac{\breve{u}_G(\mathrm{d}\breve{A}_L/\mathrm{d}\breve{A}_G)}{\breve{A}_G\left(1-\dfrac{h_L}{D}\right)^2}\right] \geqslant 1 \tag{6}$$

For the transition between intermittent flow and annular flow, a constant value of liquid height was used ($h_L/D = 0.5$). For a horizontal tube, this leads to a constant value of $X = 1.6$. The transition between intermittent and dispersed flow was assumed to occur when the turbulent forces overcome the buoyancy forces. This leads to the transition condition:

$$T^2 \geqslant \left(\frac{8\breve{A}_G}{\breve{S}_i\breve{u}_L^2(\breve{u}_L\breve{D}_L)^{-n}}\right) \tag{7}$$

Taitel and Dukler found good agreement between their transition predictions and data from Mandhane et al. [14] for a 25.0 mm diameter tube. For smaller tubes, large deviations from this theory have been reported by Damianides and Westwater [26]. A comparison between the Taitel–Dukler predictions, the data of Damianides and Westwater, and experimental results from the present work for the 5.50 mm round tube is presented in Fig. 6.

The reasons for the deviations seen in Fig. 6 can be explained on the basis of the transition criteria chosen by Taitel and Dukler. Their criterion for transition from the stratified smooth regime to the stratified wavy regime makes use of a wave sheltering coefficient as proposed by Jeffreys [36]. This coefficient is difficult to determine experimentally and the authors suggest the coefficient be adjusted to fit the data [19]. In small diameter tubes, however, only a limited stratified region may exist. It appears that surface tension forces will pull the liquid up around the tube wall and force the onset of intermittent or annular flow even though the Taitel–Dukler theory will predict a stratified flow pattern. These deviations have also been reported by Barnea et al. [25] for tube diameters ranging from 4.0 to 12.30 mm, who suggested a modification to the criterion for transition between stratified and non-stratified regimes to better account for the effects of surface tension. The transition to intermittent flows occurs when the equilibrium gas height is less than $\pi D_i/4$. It was found that this modification resulted in a better fit to the data for tubes larger than 4.00 mm.

The Taitel–Dukler correlation for the transition from intermittent to annular flow is based upon a non-dimensional liquid equilibrium height of 0.50 which leads to a constant value of $X = 1.60$. However, for most published data, the transition to annular flow more closely approximates a constant value of F, rather than a constant value of X [20]. This implies that the transition is a strong function of the superficial gas velocity, with a weak dependence upon the superficial liquid velocity. Barnea et al. [25] suggested that this transition should be assumed to occur at $h_L/D = 0.35$ rather than $h_L/D = 0.50$ to better fit the data for tube diameters larger than 5.00 mm. This modification will shift the transition to include more data points but will not change the slope to that of a nearly vertical line. Hence, this modification also does not completely explain the differences in the transition prediction and the experimental data.

3.4. *Comparison with Damianides and Westwater* [26] *and Fukano et al.* [27]

Several of the results from the present study are in very good agreement with the experimental work of Damianides and Westwater [26] on tubes ranging in diameter from 1.00 to 5.00 mm. As a baseline case, a comparison between their 5.00 mm tube data and the results of the present work for the 5.50 mm tube is shown in Fig. 6. This figure demonstrates the agreement between the present study and the work of Damianides and Westwater [26]; however, both these experimental studies show large deviations from the theoretical results of Taitel and Dukler. The transition to annular flow at a nearly constant value of the superficial gas velocity was observed by the present investigators, Damianides and Westwater [26], and Weisman et al. [20]. Stratified flow was not observed for the range of diameters investigated in the present study as well as in the work of Damianides and Westwater. Furthermore, the wavy flow pattern was observed at a higher gas velocity than that predicted by Taitel and Dukler [19]. The present study is also in agreement with the findings of Damianides and Westwater [26] that show a decrease in the size of the wavy-annular flow regime and an increase in size of the intermittent flow regime as the tube diameter decreases. The most striking difference between these two experimental studies, however, is the transition from the intermittent regime to the dispersed regime. Damianides and Westwater [26] show this transition occurring at a lower value of u_L^s, whereas the present study shows this transition to occur at a higher value of u_L^s as diameter decreases. This finding of the present study is substantiated by Fukano et al. [27], who presented results for tubes with diameters of 1.00, 2.40 and 4.90 mm. Although no flow pattern maps were provided by Fukano et al. [27], the data provided clearly show the transition to dispersed flow occurring at a higher value of u_L^s as the diameter decreases.

3.5. *Flow regime transition correlations*

Weisman et al. [20] proposed property and diameter corrections to an overall flow map and presented several new transition correlations. These correlations are based upon a compilation of data from other investigators and also extensive amounts of new data. While general conclusions can be drawn about the effect of diameter on flow patterns, it should be noted that all tube diameters used in developing these correlations were substantially larger than those analyzed in the present work.

The transition from stratified flow to intermittent flow is given by

$$\frac{u_G^s}{(gD)^{1/2}} = 0.25\left(\frac{u_G^s}{u_L^s}\right)^{1.1} \tag{8}$$

This correlation appears to imply that liquid density, liquid viscosity, and surface tension have no effect on this transition line. The transition to annular flow is given by

$$1.9\left(\frac{u_G^s}{u_L^s}\right)^{1/8} = \left(\frac{u_G^s \rho_G^{1/2}}{[g(\rho_L-\rho_G)\sigma]^{1/4}}\right)^{0.2}\left(\frac{u_G^{s2}}{(gD)}\right)^{0.18} \tag{9}$$

This correlation appears to imply that liquid viscosity has no effect and liquid density and surface tension have only minor effects on this transition line. The transition to dispersed flow is given by

$$\left[\frac{(\mathrm{d}P/\mathrm{d}x)_L^s}{(\rho_L-\rho_G)g}\right]^{1/2}\left[\frac{\sigma}{(\rho_L-\rho_G)Dg^2}\right]^{-0.25} = 9.7 \tag{10}$$

where

$$(\mathrm{d}P/\mathrm{d}x)_L^s = \frac{f}{2}\frac{G_L^2}{g\rho_L D} \tag{11}$$

Transitions observed in the present study are compared with the transitions predicted by the above equations developed by Weisman et al. [20] in Fig. 7. Weisman et al. [20] predict a transition between stratified flows and other regimes at decreasing liquid velocities as the tube diameter decreases as shown by trend (1) in Fig. 7. While this trend was observed in the present study, Weisman et al. [20] predict the transition occurring at a nearly constant value of u_L^s, whereas the present work shows peaks in these transition lines. This departure from transition at a constant value of u_l^s is in fact consistent with the data of Damianides and Westwater [26] and Fukano et al. [27], as shown in Fig. 6. This implies that the correlation by Weisman et al. [20] for this transition does not adequately account for the effects of decreasing tube diameter and surface tension.

For a given tube diameter, Weisman et al. [20] predict the transition between intermittent and annular flows to occur at a nearly constant value of u_G^s, as shown by trend (2) on Fig. 7. This is in agreement with the current data. However, as the tube diameter decreases, they predict a shift in the transition line to a lower value of u_G^s, whereas the present data show the transition line to shift to an increasing value of u_G^s. Similarly, their correlation for transition to dispersed flows (shown by (3) on Fig. 7) predicts this transition to occur at a high and constant value of u_L^s for a given diameter. However, the present data show that there is a definite change in slope for this transition line, and the effect of decreasing tube diameter is to move the transition line to a higher value of u_L^s, which contradicts the results of Weisman et al. [20]. Thus, it appears that while there is some agreement in transition predictions between the present work and the correlations by Weisman et al. [20], especially at the larger diameter, their correlations may not be suitable for the prediction of the effect of tube diameter on the shifts in transition. This is understandable because their work was based on larger diameter tubes than those investigated in the present study and may not adequately account for the effects of tube diameter, surface tension and liquid viscosity.

4. Rectangular tube results

Rectangular heat exchanger tubes result in significantly more compact heat exchangers than the conventional round tube geometries [37]. These tubes are routinely used in automotive heat exchangers for single-phase (radiators) as well as two-phase (condensers and evaporators) heat transfer. Current condenser tubes have rectangular cross-sections with internal strengthening webs. Thus, refrigerant flow passages in condensers can be viewed as several small hydraulic diameter rectangular tubes with aspect ratios close to 1.0 in parallel. However, little research has been done on flow-regime maps for small hydraulic diameter rectangular tubes and the effect of decreasing hydraulic diameter is currently unknown. For these tube geometries, there is an added complication of the effect of aspect ratio on the specific flow regimes and transitions between them.

In rectangular tubes, the effects of surface tension are expected to be more important as the liquid is more readily pulled up into the corners of the tube and held against gravity. To investigate the effects of surface tension in small diameter tubes, a rectangular tube of hydraulic diameter 5.36 mm with an aspect ratio of 0.725

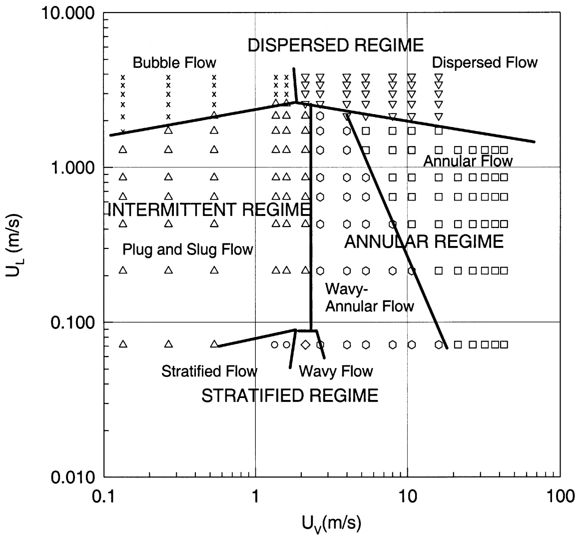

Fig. 8. Flow regime map for rectangular tube ($D_h = 5.36$ mm, $\alpha = 0.725$).

was chosen and the results were compared with those for the 5.50 mm round tube. The flow regime map for the rectangular tube is shown in Fig. 8, and a comparison between the round and rectangular tube flow patterns is shown in Fig. 9. The principal difference between the rectangular and round-tube flow patterns appears to be the transition to the dispersed flow regime at a higher value of u_L^s. It can also be seen that in this rectangular tube, the transition to the annular regime (wavy–annular and annular flow) occurs at a nearly constant value of

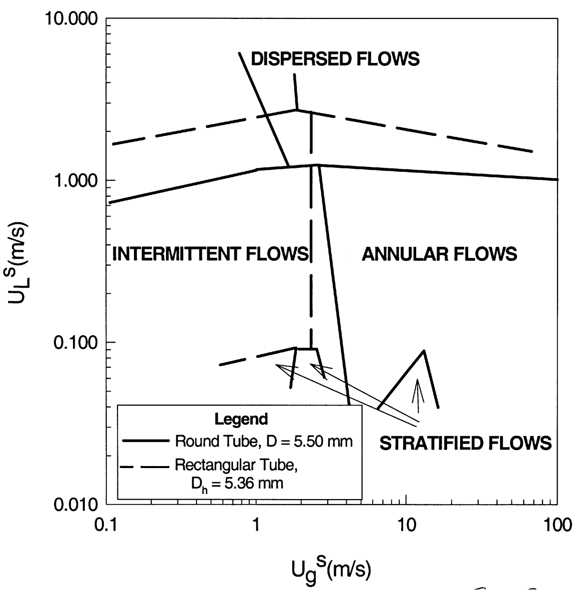

Fig. 9. Comparison of round and rectangular tube flow maps.

u_G^s. Both the round and rectangular geometries show stratified flows; however, the stratified flow regime occurs at a lower gas velocity in the rectangular tube. Further investigations to understand the influence of tube shape on the flow patterns are underway. Investigations on smaller hydraulic diameter rectangular tubes, similar to those reported here for round tubes are also underway. In addition, the present authors are currently investigating flow regime maps during condensation of refrigerants in such channels. This ongoing work will help identify any potential differences between air–water flow regime maps and the corresponding maps obtained during phase change.

5. Conclusions

Flow regime maps for two-phase flow in round and rectangular tubes of small hydraulic diameters were presented in this study. (The study was limited to adiabatic flow of air–water mixtures, therefore, results obtained here might not be directly applicable to phase-change situations.) Several previous investigators have concluded that the effects of pipe diameter and surface tension are negligible [14, 20] in determining the specific flow regime at a particular combination of liquid and gas flow velocities. The results of present study seem to imply that this may be true for pipe diameters on the order of 10 mm or larger; however, in the case of tubes with diameters smaller than these, the present study shows that diameter and surface tension effects play an important role in determining the flow patterns and transitions between them. Therefore, flow regime maps such as those developed by Mandhane et al. [14] based upon data from larger tubes may not be applicable for a smaller tube diameter range. It was also shown that the theoretical results of Taitel and Dukler [19] and the inherent assumptions in these analyses may not be valid for small diameter tubes. Similarly, transition correlations, such as those presented by Weisman et al. [20], also based upon data from large diameter tubes, were demonstrated to be inapplicable to the small diameter round or rectangular tubes considered in this study.

From the flow regime maps presented here for round and rectangular tubes, it can be concluded that as the tube diameter decreases, transitions between these flow regimes occur at different combinations of superficial gas and liquid velocities. Decreasing the tube diameter shifts the transition to a dispersed flow regime to a higher value of u_L^s due to the combined effects of surface tension and tube diameter. The transition to purely annular flow occurs at a nearly constant value of u_G^s and approaches a limiting value as the tube diameter decreases. Another effect of surface tension and tube diameter is to suppress the stratified regime in small diameter tubes and to increase the size of the intermittent regime. These effects are expected to be compounded in small hydraulic diameter rectangular tubes. The aspect ratio, hydraulic diameter and surface tension will be important factors in determining the locations of flow regime transitions.

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