SURFACE TENSION AND TUBE DIAMETER EFFECT ON HORIZONTAL TWO-PHASE FLOW IN SMALL DIAMETER CONDUITS

BY

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DEDICATION

This thesis is dedicated to my parents for all of their strength and support.
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I would like to thank my advisor, Dr. J. W. Westwater for his advice and guidance in directing me through this research.
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CHAPTER 1

INTRODUCTION

When a liquid and a gas flow through the same pipe, the gas usually flows faster than the liquid. The liquid accumulates in the pipe and reduces the cross-sectional area available for gas flow, resulting in a large pressure drop of the fluids flowing through the pipe. When the gas and liquid phase flow through the pipe the two phases will mix together to form certain flow patterns. The fluids pressure drop, the heat and mass transfer for a certain flow condition will be dependent on the resulting flow pattern. Therefore, it is important that we know which flow pattern exist under a given set of conditions.

Several flow patterns have been recognized for gas/liquid two-phase flow. In order to establish a basic criteria for each identified flow pattern, the flow patterns are identified as follow:

(a) Bubble flow: Bubbles of gas move along the upper part of the tube at approximately the same velocity as the liquid.

(b) Plug flow: Plugs of gas (bullet-shaped bubbles) move
along the upper part of the tube.

(c) **Stratified flow:** Liquid flows along the bottom of the tube and the gas flows along the top. The gas/liquid interface is smooth.

(d) **Wavy flow:** Liquid flows along the bottom of the tube and the gas flows along the top. The gas/liquid interface is wavy.

(e) **Slug flow:** The liquid flowing along the bottom of the tube forms a wave which is picked up by the more rapidly moving gas and ultimately touches the top of the tube. This forms a slug which moves at a velocity much greater than the average liquid velocity.

(f) **Pseudoslug flow:** Slug flow with a thin film of liquid flowing along the inside wall of the tube.

(g) **Annular flow:** The liquid flows in a film around the inside wall of the tube and the gas flows through the center. Liquid particle are entrained in the gas.

(h) **Dispersed flow:** Most or all of the liquid is entrained by the gas resulting in an intimately mixed
Figure 1: Flow patterns considered in this study.
homogeneous flow.
(The flow patterns are illustrated in figure 1.)

Many authors of earlier work grouped similar flow patterns together under one name. The flow patterns described above can be grouped as follow:

2. Intermittent flow: bubble, plug, and slug flow.
3. Annular flow: annular and pseudoslug flow.

There are many parameters for which two-phase flow patterns depend upon. The respective gas and liquid flow rates, the system conditions, and the properties of the fluids are a few of the major factors. By varying the gas and/or the liquid flow rates we can observe a change in the flow patterns. Most researchers present these flow patterns in the form of a flow map. A flow map is a plot of gas flow rate versus liquid flow rate showing the region where each flow pattern exists. Flow maps are also presented in this thesis.

It is expected that the fluid physical properties, especially surface tension, have an effect on the developed flow pattern for a set of flow conditions. Therefore the resulting flow pattern should vary depending on the fluid used.

This study used an air/water system and an air/acetic acid system. The water has a surface tension of about 70 dynes/cm.
while acetic acids is approximately 28 dynes/cm. The viscosity and density of the two liquids are very similar. By comparing flow maps of the air/water systems with the flow maps of the air/acetic acid system it was possible to determine the effect of the fluids surface tension on two-phase flow in small diameter conduits. Flow maps for different tube diameters were also compared to check the tube diameter effect on two phase-flow.
CHAPTER 2

LITERATURE SURVEY

Much of the early work on two-phase pressure drop was published by workers at the University of California starting in 1939 [3]. In 1944, one of the first studies of two-phase flow patterns and pressure drop through conduits was conducted by Martinelli et al. [1]. They were also the first to use photographic observations in determining the two-phase flow patterns. These studies resulted in a pressure drop correlation presented by Lockhart and Martinelli in 1949 [3]. In their calculations they defined a parameter $X$ as follows:

The two phase pressure drop is given by the equation:

$$\Delta P_r = \Delta P_e \phi_e^2$$
$$\Delta P_l = \Delta P_l \phi_l^2$$

Where $P_r$, $P_l$ are the pressure drops calculated above and the multiplier $\phi_e$ & $\phi_l$ are functions of $X$.

Lockhart and Martinelli presented their correlation for four different flow patterns. These were identified as follows:

(1) turbulent flow of both the liquid and the gas,
(2) laminar liquid flow and turbulent gas flow,
(3) turbulent liquid flow and laminar gas flow, and
(4) laminar flow of both the liquid and the gas.

Later in 1949, Gazley and Bergelin [4, 6] at the University of Delaware presented data on stratified flow and wave flow in a 2-in. pipe. Their results suggested that the Lockhart and Martinelli correlation was not valid for stratified flow or that 2-in. pipe had different relationship between $\phi_e$ and $X$.

In 1954, Aves [4] collected data on two-phase flow for a 1-in. pipe. He observed flow patterns for air/water and air/oil systems. Considering that there is a significant difference in viscosity and surface tension between the oil and water mixtures, it was very interesting to find that his data for the air/water and the air/oil systems were the same. A flow map of his results is shown in figure 2.

In 1954, Baker [8] presented a generalized plot of flow pattern regions which he had prepared from the data of Jenkin [2], Gazley [4], Alves [7], and Kosterin [5]. The flow map is shown in figure 3. The combined data were from observation of air/water systems for pipe diameters of 1 to 4-in. Baker also included dimensionless correction factors to account for the effect of the fluids physical properties. Holmes had earlier suggested of using the correction factors $\psi$ and $\lambda$ for correlating the flooding point of wetted-wall distillation columns. Figure 3 shows that the gas mass velocity is divided by:

$$\lambda = \left[ \left( \frac{\rho_g}{0.075} \right) \left( \frac{\rho_L}{62.3} \right) \right]^{1/2}$$
Figure 2: Flow map of Alves [7].

Figure 3: Baker Chart [8].
and the L/G ratio is multiplied by $\lambda\Psi$ where:

$$\Psi = \left(\frac{73}{\sigma}\right)\left[\left(\frac{92.3}{\rho_l}\right)^2 \mu_l\right]^{1/3}$$

- $\rho_g$ is the gas density in lb./ft. ,
- $\rho_l$ is the liquid density in lb./ft. ,
- $\mu_l$ is the liquid viscosity in cp. ,
- $\sigma$ is the liquid surface tension in dynes/cm. ,
- $G$ is the gas mass velocity in lb./hr.ft. ,
- $L$ is the liquid mass velocity in lb./hr.ft. , and
- the subscript G and L refers to the gas and the liquid phase respectively.

In 1959, Hoogendoorn [9] did further studies of the liquid effects in two-phase flows. He investigated the flow of air/water and air/oil mixtures through horizontally smooth and rough pipes. The smooth pipes inner diameter range from 24mm. to 140mm., and the rough pipe had an inner diameter of 50mm. In this study Hoogendoorn identified six flow patterns: stratified, wavy, plug, slug, annular, and dispersed flow. A flow map for air and oil is shown in figure 4. The flow map coordinates are based on $R_g$, the gas volumetric flow ratio, and $U_m$, the mixture velocity. The coordinates are defined as follows:

$$U_m = \frac{4(Q_g + Q_l)}{\pi D^2} \quad R_g = \frac{Q_G}{Q_G + Q_L}$$

where,
- $Q_g$ is the gas volumetric flowrate,
- $Q_l$ is the liquid volumetric flowrate, and
- $D$ is the tube diameter.
Table 1: Fluid physical properties of oil mixtures used by Hoogendoorn [9].

<table>
<thead>
<tr>
<th>Oil Type</th>
<th>Viscosity (m²/sec.)</th>
<th>Density (kg./m³)</th>
<th>Surface Tension (N./m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas oil</td>
<td>$2.9 \times 10^{-6}$</td>
<td>815</td>
<td>$27 \times 10^{-3}$</td>
</tr>
<tr>
<td>Spindle oil</td>
<td>$23. \times 10^{-6}$</td>
<td>905</td>
<td>$30 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Figure 4: Flow map of Hoogendoorn [9].
Hoogendoorn concluded from his data that fluid viscosity and pipe diameter has a small influence on flow pattern transitions. Physical properties of the oil are given in table 1. Hoogendoorn also stated that a 60 diameter calming length was sufficient to take out any effect by the mixing device.

In 1960, Vohr [10] did a literature survey on two-phase flow through conduits. He found that the investigators were not producing the same results in their experiments. He then emphasized that no standard method of classification had been established, and that no-one had used high-speed motion pictures to help in identifying the high-flowrate pattern transitions. He criticize Baker for using parameters which were not verified by Baker or anyone else at the time, to correlate his flow regimes. He also mentioned that very little information was available on the effect of fluid properties, and duct dimensions on flow pattern transitions.

In 1963, Scott [12], following Vohr's lead, modified Baker's flow map to account for the finding of Hoogendoorn [9] and Govier and Omer [11]. The modified flow map is shown figure 5. Scott claimed that the modified correlations were valid for all pipe sizes larger than 1-in. He stated that for pipes having a diameter of less than 1-in., the extent of the areas shown will tend to change rapidly as the diameters decrease.

In 1964, Suo and Griffith [13] explored two phase flow in a 1.018mm. I.D. capillary tube with water or heptane as the liquid, and air, helium, or nitrogen as the gas. They concentrated mainly on the flow pattern they identified as
Figure 5: Modification of Baker Chart by Scott [12].

Figure 6: Flow map of Mandhane et al. [15].
capillary slug flow (similar to plug flow). Observing that since capillary slug flow existed in horizontal as well as vertical tubes, the surface tension force must predominate over gravity force. From their study Suo and Griffith predicted transition lines from capillary slug flow to annular flow and bubbly slug flow (slug flow); however, their results did not agree well with experimental results.

In 1966, Hubbard and Dukler [14] used pressure transducers to sense fluctuating wall pressures. They found that the spectral distribution of the wall pressure fluctuation provided a suitable parameter for flow pattern identification. The normalized power spectral density distribution was calculated by statistical means, and used to classify flow patterns as either separated, dispersed, or intermittent flow.

In 1974 Mandhane et al. [15] collected data from earlier studies to correlate a new and improved flow map. They obtained a copy of the AGA-API Two-Phase Flow Data Bank which contained about 10000 data points, from studies prior to 1962, on two-phase flow pattern in horizontal and inclined pipes. The authors also added 4000 more updated points. They then choose 5395 points from the horizontal two-phase flow data. The flow map was then developed for air and water system, and is shown in figure 6. The flow condition used are given in table 2. Correction factors B and Z were proposed to account for differences in fluid physical properties. They are defined as follow:

\[
B = \left( \frac{\rho_g}{0.0808} \right)^{0.2} \left( \frac{\rho_l}{62.4} \frac{72.4}{\sigma} \right)^{0.25} \left( \frac{\mu_l}{0.018} \right)^{0.2}
\]

\[
Z = \left( \frac{\mu_l}{1.0} \right)^{0.2} \left( \frac{\mu_l}{62.4} \frac{72.4}{\sigma} \right)^{0.25}
\]
Table 2: Range of parameter values for data used by Mandhane et al. [15].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside pipe diameter</td>
<td>0.5 - 6.5 in.</td>
</tr>
<tr>
<td>Liquid phase density</td>
<td>44.0 - 63.0 lb./ft.³</td>
</tr>
<tr>
<td>Gas phase density</td>
<td>0.05 - 3.15 lb./ft.³</td>
</tr>
<tr>
<td>Liquid phase viscosity</td>
<td>0.3 - 90.0 centipoise</td>
</tr>
<tr>
<td>Gas phase viscosity</td>
<td>0.01 - 0.022 centipoise</td>
</tr>
<tr>
<td>Surface tension</td>
<td>24.0 - 103.0 dynes/cm.</td>
</tr>
<tr>
<td>Superficial liquid velocity</td>
<td>0.003 - 24.0 ft./sec.</td>
</tr>
<tr>
<td>Superficial gas velocity</td>
<td>0.84 - 560 ft./sec.</td>
</tr>
</tbody>
</table>

Table 3: Physical property correction factors proposed by Mandhane et al. [15].

<table>
<thead>
<tr>
<th>Transition Boundary</th>
<th>Physical Property correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statified to bubble</td>
<td>1.0/Z</td>
</tr>
<tr>
<td>Wave to slug</td>
<td>Z</td>
</tr>
<tr>
<td>Bubble to slug and dispersed</td>
<td>Z</td>
</tr>
<tr>
<td>Stratified and bubble to wave and slug</td>
<td>B</td>
</tr>
<tr>
<td>Wave and slug to annular</td>
<td>B</td>
</tr>
<tr>
<td>Dispersed to annular</td>
<td>B</td>
</tr>
</tbody>
</table>
Where \( \rho_g, \rho_l, \mu_g, \mu_l, \sigma \) have the same meaning used by Baker [8]. The correction factors are applied by multiplying the transition line equations by \( B \) or a function of \( Z \) as shown in table 3.

Mandhane et al. found that their map agreed well with those of Baker [8], Hoogendoorn [9], and Govier and Gomer [14]. They then concluded that the effect of pipe diameter can be accounted for by using superficial gas and liquid velocities as the axes. They also stated that the effect of physical properties was negligible compared to the error in determining the flow transition lines.

In 1976, Taitel and Dukler [16] developed the first theoretical model which predicted flow pattern transition lines given the following parameters: gas and liquid flowrates, properties of the fluids, pipe diameter, and angle of inclination to the horizontal. The flow pattern studied were intermittent (plug and slug), stratified, wavy, dispersed, and annular. The transition conditions for each flow regimes were analyzed individually. From this data they proposed a mechanism for the transition lines and the resulting flow patterns. Each mechanism was based on purely physical concepts, in that no experimental data were used in their development. From their analysis the authors derived the following dimensionless group:

\[
F = \left( \frac{\rho_0}{\rho_l - \rho_0} \right)^{1/2} \frac{U_{os}}{\left( Dg \cos \beta \right)^{1/2}}
\]

\[
E = \left[ \frac{|dP/dx|_l}{|dP/dx|_0} \right]^{1/2}
\]

\[
K = F \left[ \frac{D U_{ls}}{v_l} \right]^{1/2}
\]
\[ T = \left( \frac{\frac{dP}{dx}}{(A - A_g)g \cos \beta} \right)^\frac{1}{2} \] \quad \[ \gamma = \frac{(A - A_g)g \sin \beta}{\frac{dP}{dx}} \]

where,

\( \beta \) is the angle of inclination from the horizontal, and

\( \gamma \) is the kinematic viscosity of the liquid.

the authors also presented a flow map demonstrating their theory. Flow map is shown in figure 7. Their flow map agreed well with that of Mandhane et al. [15]. Their theory predicted a shift in the transition lines when the physical properties of the fluids were changed, but did not take into account fluid viscosity or surface tension.

In 1978, Choe et al. [17] observed two-phase flow of air/water system in 0.45-in., 1-in., and 2-in. I.D. glass pipes. The authors used visual observations and pressure-trace measurements to identify flow pattern transitions. They then proposed correlations for each transition boundary and presented a flow map based on these correlations. Instead of using the superficial velocities they used the superficial gas and liquid mass fluxes as coordinates. The pipe diameter and \( \omega \) were used as parameters, where \( \omega \) is given as:

\[ \omega = \left( \frac{\rho_g}{\rho_l} \right) S \]

and \( S \) is the slip ratio. See flow map in figure 8.

The authors reported that the flow pattern for the 0.45-in. I.D. pipe differed from the larger pipe sizes. They found that the transition from wavy to slug flow occurred at a higher liquid flowrate in the smaller pipe, and stratified flow did not occurred at the low gas velocities.

IN 1979, Weisman et al. [18] studied the effects of pipe
Figure 7: Theoretical flow map of Taitel and Dukler [16].

Figure 8: Flow map of Choe et al. [17].
diameters and fluid properties on two phase flow patterns. They obtained their data by visual observations, and pressure-drop readings. They studied pipe diameters of 11.4, 26.4 and 50.8 mm. Their study showed that tube diameter only has a small effect (much less than one order of magnitude) on the air/water system. They found that the transition to intermittent and dispersed flow occurred at higher liquid flowrates, and annular flow occurred at higher gas flowrates when the pipe diameter was increased.

The authors then added Aliquat 221, a surface active agent, to water and reduced the liquid surface tension from about 70 to 38 dynes/cm. The only significant finding was that stratified/wavy flow transition occurred at significantly higher gas flowrates for each diameter considered. The authors also studied the effect of changes in viscosity, liquid density, and vapour density.

Like Mandhane, Weisman et al. concluded from their data that the major factor in determining the flow pattern was the relative volumetric flowrates of the liquid and gas, and that the liquid properties and tube diameters only had a small effect on the flow patterns. The authors presented an overall flow map with physical property correction factors $\phi_l$ and $\phi_g$. The flow map is shown in Figure 9, and the correlation for $\phi_l$ and $\phi_g$ are listed in Table 4.

In 1983, Barnea et al. [21] presented two-phase flow pattern maps for air/water system through horizontal tubes with diameters of 4, 6, 8, 15, 9.85, and 12.3 mm, and vertical tubes
Figure 9: Overall flow map of Weisman et al. [18]

Table 4: Physical property and tube diameter correction factors proposed by Weisman et al. [18].

<table>
<thead>
<tr>
<th>Transition to dispersed flow</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>$\left(\frac{\rho}{\mu} \right)^{0.4} \left(\frac{D^2}{L} \right)^{0.08} \left(\frac{\mu_d}{\mu}\right)^{0.4} \left(\frac{\sigma}{\tau}\right)^{0.6}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transition to annular flow</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>$\left(\frac{D}{L}\right)^{0.16}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intermittent-separated transition</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>$\left(\frac{D}{L}\right)^{0.16}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wavy-stratified transition</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>$\left(\frac{D}{L}\right)^{0.16} \left(\frac{\rho}{\mu} \right)^{0.4} \left(\frac{D^2}{L} \right)^{0.08} \left(\frac{\mu_d}{\mu}\right)^{0.4} \left(\frac{\sigma}{\tau}\right)^{0.6}$</td>
</tr>
</tbody>
</table>

**Notes:**
- "s" denotes standard conditions
- $D = 1.8$ in. = 4.57 cm
- $\mu_d = 1$ centipoise
- $\rho_d = 0.0013$ kg/l.
- $\sigma = 70$ dynes/cm
- $\rho = 1$ kg/l.
with diameters of 4 and 12.3 mm. Their data showed somewhat
good agreement with Taitel and Dukler's theory [16]. From their
results Barnea et al. modified the Taitel-Dukler theory to take
into account the effect of fluid surface tension in
separated/intermittent flow transition. The modified theory
agreed well with their experimental results.

In 1984, Charlambos Damianides [22] at the University of
Illinois presented in his master's thesis results of two-phase
flow of air/water system in 5mm. and 15.9mm. I.D. tubes. Using
still pictures and high speed films of the flow field, he
constructed flow maps for each tube diameter, shown in figure 10
and 11. (The flow maps in figure 10 is a revised version of the
one in his master's thesis.

Damianides results showed that a decrease in tube diameter,
from 15.8mm. down to 5mm., causes large shifts in the flow
transition boundaries.

In 1984, Chisolm [23] proposed equations for predicting flow
pattern transition boundaries for two-phase flow in horizontal
tubes. The equations gave transition boundary lines for
separated, intermittent, annular, and dispersed flow regimes.
Chisolm modified Taitel and Dukler's theory so that it took the
following into account:

(1) the inclusion of terms for the relative motion of phases
    when applying the Kelvin-Helmholtz criterion,
(2) a revised equation for the wave blockage,
(3) the use of the hypothesis that the transition between
    intermittent and dispersed bubble flow is a consequence
Figure 10: Flow map of Damianides [22] for a 5 mm. I. D. tube system.

Figure 11: Flow map of Damianides [22] for a 15.8 mm. I. D. tube
of the Kelvin-Helmholz instabilities, and
(4) the use of assumption based on empirical evidence.

Chisolm used data obtained from Weisman [18], Pearse [19], and Hashizume [20] to demonstrate agreement between theory and experiment. The developed correlation did not include the effect of surface tension.

In 1984, Persen [24] developed analytical equations for the normal liquid depth and pressure gradient for steady, stratified two-phase flow in circular pipes. He assumed incompressible flow in both phases, and that the head losses could be introduced as if one had ordinary pipe flow. The following dimensionless quantities were introduced in his solution:

\[ p_1 = \frac{Q_g}{Q_l} \quad \left[ h_{cr1} \right]^3 = \frac{2Q_l}{\varrho g^3} \]
\[ p_2 = \frac{\delta_0}{\delta_l} \quad \left[ h_o \right]^3 = \frac{f Q_l^2}{g 4 r^3 \sin \beta} \]
\[ p_4 = \frac{f_i}{f} \]

where

- \( Q_l \) is the volumetric discharge of the liquid,
- \( Q_g \) is the volumetric discharge of the gas,
- \( f \) is the friction coefficient,
- \( f_i \) is the friction coefficient at the interface,
- \( \delta_l \) is the specific weight of the liquid,
- \( \delta_g \) is the specific weight of the gas,
- \( \beta \) is the inclination angle of the pipe, and
- \( r \) is the pipe radius.

Persen concluded from his study that the normal liquid depth seems to be mainly determined by the gas/liquid flow ratio, the
In 1987, Michael Graska [25] at the University of Illinois presented, in his master's thesis, the results of the air/acetic acid horizontal two-phase flow in 5mm., 12.6mm., and 16.5mm. diameter tubes. The flow maps are presented in figure 12, 13, 14. (Figure 12 contains a revised version of the 5mm. flow map he presented in his thesis. It was revised to show the stratified and wavy flow regimes.) Graska found that surface tension only had a moderate effect in the 12.6 and 16.5mm. tubes; however, there is a greater effect in the 5mm. diameter size tube. The entire 5mm. flow map is shifted to the right, indicating that a higher air flow rate is required to achieve the same flow regimes as in the air/water system. He also found that the stratified flow regime diminishes greatly as the tube diameter decreases. A study of the effect of tube inclination was also reported. Graska found that a slight inclination (upward 0.3 degrees) had a very large effect on the stratified flow transition line. Figure 15 illustrates the inclination effect.

Tube-diameter air/acetic-acid system.
Figure 13: Flow map for 12.7 mm. tube-diameter air/acetic-acid system.

Figure 14: Flow map for 16.5 mm. tube-diameter air/acetic-acid system.
Figure 23: Flow map for 12.7 mm inclined-tube air/water system (angle = 0.3 degree up).
CHAPTER 3

EXPERIMENTAL APPARATUS AND PROCEDURE

3.1 Description of Experimental apparatus

A schematic diagram for the air/acetic acid flow loop is shown in figure 15, and a photograph of the system is in figure 16. The flow loop is made out of stainless-steel and teflon to prevent corrosion from the acetic acid. A 1/3 horsepower stainless-steel gear pump with teflon packing was used to displace the acetic acid. The pump is placed inside a small recycle loop within the system. A specially fabricated filter was inserted into the loop to prevent particles from going through the pump. A valve is placed in the recycle loop to prevent particles from going through the pump. To guard against high pressure damaging the system, a pressure release valve was placed downstream from the pump.

The air flow system is made out of stainless-steel and brass tubings. An air filter was placed at the air entrance region to remove any suspended particles, and a stainless-steel check valve was placed in the air line before the mixing section to prevent the acid from corroding the air line.

Both the air and acetic acid flow rates were regulated by calibrated rotameters located upstream from the mixing section.
Figure 15: Schematic diagram of air/acetic-acid flow loop.
The rotameters were calibrated for water, except for the acetic acid. The water rotameters were calibrated immediately before the system. The rotameters were calibrated using a bellows type meter. The acetic acid rotameters were calibrated using a precision glass tubing test section of 3 mm. I.D. and 50 cm. length. A schematic diagram of the air/water system is shown in Figure 18. The air/water system was also employed to obtain data for a glass tubing of 16.5 mm. I.D. and 2.1 meter length. A test section's diameter is the smallest diameter in the flow system. The test section's diameter is the smallest diameter downstream from the test section's entrance. The test section is a precision glass tubing test section of 3 mm. I.D. and 50 cm. length. The viewing region was needed. The viewing region was 120 diameter upstram from the test section.

The mixing section was made up of a 1/2 inch pipe tee and located immediately to a 1/2 inch pipe tee pipe connected vertically, and the acetic acid was pumped in horizontally. Vertically, the acetic acid was pumped in horizontally from the building main compressor entered the mixing section collected per unit time. Air at 65 psig and room temperature rotameters were calibrated by measuring the liquid volume. The liquid rotameters were calibrated using a bellows type meter. The air rotameters were calibrated from a separating tank to the building drain. The rotameters were calibrated for water, except for the acetic acid. The water rotameters were calibrated immediately before the system.
Figure 18: Schematic diagram of air/water flow loop.
3.2 Experimental procedure

3.2.1 System Set Up

The flow system was previously assembled by Michael Graska for his master's thesis research. The system; however, had many leaks which presented an acid vapour problem for lab personnel. All pipe fittings were tightened and tested for leaks before the 3mm test section was placed into the system. A smaller liquid rotameter was also added into the system to achieve the lower flow rates required for stratified flow.

After a few test runs were performed on the system, a small amount of the used acetic acid was removed from the system for surface tension testing. A Cenco Tensiometer 70545 was used to determine the acetic acid's surface tension. Toluene, hexane, and water surface tension were also calculated to calibrate the tensiometer. The used acetic acid had a surface tension of 27.25 dyne/cm., and the new acetic acid had a surface tension of 27.30 dyne/cm. It was concluded that the flow system effect on the acid surface tension could be ignored. See appendix B for other surface tension measurement values.

When all data from the size E liquid rotameter was recorded, it was removed and replaced with the size A liquid rotameter. The size A rotameter was added to achieve a low enough flow rate to obtain stratified flow.

3.2.2 Flow Map Determination

The flow patterns, for the air/acetic system, were
determined over a wide range of gas and liquid flow rates. The air flow ranged from 0.10 to 30.0 m/s, and the acetic acid flow ranged from 1.0 x 10 to 3.0 m/s. Observations of the flow pattern were made through the 3 mm. glass tubing test section.

For the air/water system, the air superficial velocity ranged from 0.015 - 15.0 m/sec. and the water superficial velocity ranged from 0.007 - 0.30 m/sec. Observation were also made through the 16.5 mm. glass tubing test section.

High speed motion pictures of the flow patterns were used to help identify flow pattern transitions at high liquid and gas velocities. A total of 50, 20 foot rolls of high-speed films were shot and developed. Without these films it would have been very difficult to identify the high velocity flow pattern transitions.

3.2.3 Photographic Techniques

A WF3 Fastex 16mm. high-speed camera aided by a Goose power source, capable of taking high-speed motion pictures at 10000 frames per second, and a 2-in. f/2 Cine Velostigmat Wollensak lens was used.

Two DXB-RSP2 General Electric spot photo lamps, each having a 500 watt rating, were used for lighting. The lamps were positioned under the test viewing section, and pointed at a white cardboard matte at an angle of about 45 degrees from the horizontal. The result was a very bright and diffused background. A schematic diagram of the photographic system is shown in figure 19. A photograph of this set up is shown in
Figure 19: Schematic diagram of photographic arrangement.
Figure 20: Picture of photographic arrangement.
The exposure time for the high-speed motion pictures was approximately 4800 frames per second, and the f-stop was set at 4.0. The camera axis was horizontal and the camera lens was approximately 6.0cm. from the tube.
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Analysis of Film Results

Observation at high liquid flow rates (~ 2 m/s) found that the bubbles which developed during bubble flow were larger than the tube diameter. Therefore the bubble flow and plug flow patterns were indistinguishable from each other. It was concluded that for very small diameter tubes it was not necessary to distinguish between bubble and plug flow. It should be noted that the flow maps from the present study do make the distinction between bubble and plug flow.

The dispersed flow pattern which developed showed a constant pulsation which was present at all gas flow rates within the dispersed flow regime. The flow pattern can be described as a pulsating flow with most or all of the liquid entrained by the gas. The normally intimately mixed homogeneous flow is interrupted by an occasional slug shooting across the pipe. Damianides [26] reported that pulsation also was observed in the dispersed flow of air/water in the 3 mm diameter tube, but it was only an occasional occurrence. With the exception of Damianides, most authors who researched two-phase flow of air and water did not report of the pulsation in the dispersed flow pattern. The pulsation in the dispersed flow is most likely a
surface tension effect on the two-phase flow pattern.

Another interesting phenomena is that the mechanism for transition into annular flow seem to be the deposition of roll waves on the wall of the glass tubing, and not the atomization process observed for the larger diameter tubes. It seem that as the tube diameter gets smaller the more apparent the roll waves become. Graska [25] did not report of the roll waves mechanism from his study of air/acetic-acid two-phase flow in the 5 mm. I.D. tube. After a thorough analysis of his data, it is concluded that the roll waves were not present in the 5 mm. diameter tube. Damianides [26] reported that for his air/water system there was also no roll waves in the 5 mm. diameter tube. The roll waves were slightly detected in the 4 mm. tube, and was clearly observed in the 3 mm. diameter tube. Based on these data, the roll waves would have to be a tube diameter effect on two-phase flow. For further details of roll waves deposition mechanism refer to Damianides Ph.D. thesis [26].

4.2 Flow Map Presentation

A flow map of the air/acetic-acid system for the 3 mm. diameter tube and the air/water system for the 16.5 mm. diameter tube are shown in figure 21 and 22. The gas and liquid superficial velocities were used as coordinates for easy flow map comparison with earlier works. The data points shown as darkened circles represent specific transition points. Each point was obtained by holding one flow rate, either gas or
\[ U_{LS} \text{ [m/s]} \]

\[ U_{GS} \text{ [m/s]} \]

**Figure 21:** Flow map for 3mm. tube-diameter air/acetic-acid system.
Figure 22: Flow map for 16.5 mm tube-diameter air/acetic-acid system.
liquid, constant and varying the other flow rate until a transition zone was observed. A transition zone is in an area where one flow pattern is in the process of transforming into another flow pattern, and neither patterns can be clearly identified. Each transition point was plotted in the middle of the corresponding flow pattern transition zone. The boundary lines are best fit curves through the plotted points.

4.3 Flow Map Comparison

To establish the reproducability of the results obtained, a flow map from the present study was compared with a flow map obtained earlier by another researcher using the same system. Figure 23 shows the flow map for the 16.5 mm. tube-diameter air/water system from the present study in comparison with a flow map of Graska [25] for a 16.5 mm tube-diameter air/water system. The flow maps showed good agreement at all transition boundaries. The flow maps are not identical because each researcher has his own judgment on where each transition should be. One way of eliminating the discrepancies is to use static pressure traces as a basis in determining where each transition point should be located.

Since there is no other known data for air/acetic-acid two-phase flow in a 3 mm. diameter tube, the flow map for the 3 mm. tube-diameter air/acetic-acid system was compared with the flow map of Manhane et al. corrected for acetic acid properties. See flow maps comparison in figure 24. The present
Capital letter: Present classification
Lower-case letter: Graska's classification

Figure 23: Comparison of Graska's 16.5 mm. tube-diameter air/water system with 16.5 mm. tube diameter air/water system.
figure 24: Comparison of Manhane's flow map with 3 mm. tube-diameter alk/acetic-acid system.
study 3 mm. tube transition boundaries are occurring at much slower liquid flow rates than Manhane's finding. However, there is a very good transition boundary agreement with respect to the gas flow rates of the two studies. The plug-slug, slug-annular, stratified-wavy, and wavy-annular transition boundaries for both studies seem to occur at almost the same gas flow rates. The transition lines also seem to be shaped similarly.

The flow map for the 3 mm. tube-diameter air/acetic-acid system was also compared with Weisman et al. overall flow map. See map comparison in figure 25. The two flow maps had very little in common. The disagreement showed that Weisman's overall flow-pattern map was not valid or that the 3 mm. tube had a different relationship for the physical property correction factors.

4.4 Fluid Surface Tension Effect

With the exception of surface tension, most of the physical properties (density, viscosity, etc.) of the water and acetic acid are very similar. This makes the air/water system and the air/acetic-acid system ideal for the study of surface tension effect on two phase flow in small diameter conduits. Figure 26 shows the flow map comparison of the present study 3 mm. tube-diameter air/acetic-acid system with Dmianides [26] 3 mm. tube-diameter air/water system. The transition boundaries for the air/acetic system seem to be occurring at slightly lower liquid flow rates than the air/water system's transition
figure 25: Comparison of Weisman's flow map with flow map for 3 mm. tube-diameter air/acetic-acid system.
figure 26: Comparison of Damianides' flow map for 3 mm.
tube-diameter air/water system with flow map
for 3 mm. tube-diameter air/acetic acid system.
boundaries. The air/acetic-acid plug-slug transition line occurred at a slightly higher gas flow rate than the air/water system, while the slug-pseudoslug transition line for the air/water system occurred at a much higher gas flow rate than the air/acetic-acid system. Overall the flow transition zones for both systems appear to be covering the same relative areas. The strong agreement between the two flow maps showed that at the 3 mm. tube-diameter the surface tension effect does not yet play the dominant role. Further studies of the air/acetic-acid system for smaller diameter tubes are needed before the surface tension effect takes over as the dominant factor in two-phase flows.

4.5 Tube Diameter Effect

The 3 mm. tube-diameter air/acetic-acid system results were compared with Graska's results for the 5 mm. and 16.5 mm. tube diameter air/acetic-acid system. Figure 27 and 28 show the 3 - 5 mm. and 3 - 16.5 mm flow map comparisons. Both flow map comparisons showed a significant downward shift for the stratified flow transition as the tube diameter decreases. These results agree well with Taitel-Dukler and Weisman theory predicting a large down shift in separated flow transitions with decreasing tube diameter. The 3 - 5 mm. flow map comparison showed that the stratified-wavy flow transition line shifted to a higher gas flow rate for the 3 mm. tube-diameter system. This shift agree well with the findings of Weisman et
figure 27: Comparison of Graska's flow map for 5 mm. tube-diameter air/acetic-acid system with flow map for 3 mm. tube-diameter of the same system.
Capital letter: Present classification
Lower case letter: Graska's classification

figure 28: Comparison of Graska's 16.5 mm. tube-diameter air/acetic-acid system with 3 mm. tube-diameter for the same system.
This shift agree well with the findings of Weisman et al. [18]. However, the 3-16.5 mm. flow map comparison showed the opposite shift. The stratified-wavy flow transition line for the 3 mm. tube occurred at a lower gas flow rate than the 16.5 mm. tube-diameter system. Therefore it must be concluded that other parameters are needed in predicting the stratified-wavy flow transition boundary.

4.6 Photographic results

Still photographs of the flow patterns discussed are shown in figure 31-38.
figure 31: Stratified flow in 3mm. tube-diameter air/acetic-acid system
figure 32: Plug flow in 3mm. tube-diameter air/acetic-acid system
figure 34: Pseudoslug flow in 3mm. tube-diameter air/acetic-acid system
Figure 35: Wavy flow in 3mm. tube-diameter air/acetic-acid system
figure 36: Annular flow in 3mm. tube-diameter air/acetic-acid system
figure 37: Bubble flow in 3mm. tube-diameter air/acetic-acid system
figure 38: Dispersed flow in 3mm. tube diameter air/acetic-acid system
It is concluded from this study that surface tension is not an important factor in two-phase flow through tubes of 3mm. diameters. Flow map comparison of the present study 3 mm. tube-diameter air/acetic-acid system with Damianides [26] 3 mm. tube-diameter air/water system showed that surface tension does not seem to affect the flow patterns to any extent. Further data will be needed to determine how small of a tube diameter is needed for surface tension to be the dominating factor in two-phase flow through conduits.

Stratified and wavy flow transition boundaries are definitely affected by the tube diameter size. The tube diameter effect is illustrated in the air/acetic-acid system comparison of the 3 mm. with the 16.6 mm., and the 3 mm. with the 5 mm. tube diameters.

The flow map of Manhane et al. [15] agreed well with the present study 3mm. tube-diameter air/acetic-acid system. Weisman et al. [18] overall flow-pattern correlations did not agree with the present study results. Their correlation, as it is, is not valid for the 3 mm. tube-diameter air/acetic-acid system.

This study, as many other studies, showed that there are many discrepancies among each different author as to where the
flow pattern transition points should be located. It is concluded from this that quantitative methods are needed to establish a basis on how flow transition points should be determined. One such method is the static pressure trace process.
CHAPTER 6

RECOMMENDATIONS FOR FUTURE WORKS

Future works should concentrate on determining what size tube diameter is needed for the fluid surface tension to become an important factor for two-phase flow in small diameter tubes. It is proposed that experiments be conducted using air/acetic-acid and air/water systems for tube diameters of 2mm., 1 mm., and even smaller diameter tubes. Then compare the flow maps of the air/acetic-acid system with the air/water system to determine the effect of fluid surface tension on the different flow pattern regimes.

In order to establish more well defined flow-pattern transition boundaries, pressure trace measurements should be incorporated with visual data in determining transition boundaries.

Finally experimental research should concentrate on all the different flow regimes which exist in compact heat exchangers. Figure 35 illustrates the compact heat exchanger of special interest. Such a configuration can be built between two transparent parallel plates so that the flow patterns can be observed.
Figure 28: The lower sketch shows the general flow pattern in a plate-type, compact heat exchanger. The upper sketch shows the offset fins in each flow passage. Two-phase flow occurs in the uninterrupted flow passages.
REFERENCES


6. Holmes, "Flooding Velocities in Empty Vertical Tubes"


18. Weisman, J., Duncan, D., Gibson, J. and Crawford, T., "Effects of Fluid Properties and Pipes Diameter on Two-Phase


Figure A1: Calibration curve for air flow in size A rotameter
Figure A2: Calibration curve for air flow in size B rotameter
Figure A3: Calibration curve for air flow in size C rotameter
Figure A4: Calibration curve for air flow in size D rotameter
Figure A5: Calibration curve for air flow in size F rotameter
Figure A6: Calibration curve for air flow in size G rotameter
Figure A7: Calibration curve for acetic-acid flow in size C rotameter.
Figure A8: Calibration curve for acetic-acid flow in size 8 rotameter.
Figure A9: Calibration curve for water flow in size C rotameter.
Figure A19: Calibration curve for water flow in size E rotameter.
## Surface Tension Measurements

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<th>Measured Surface Tension (Dyne/cm.)</th>
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<tr>
<td></td>
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<td></td>
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All measurements were done with the Cenco Tensiometer 70545.