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Two-phase flow in high aspect ratio, polymer microchannels for reagent delivery applications

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TWO-PHASE FLOW IN HIGH ASPECT RATIO, POLYMER MICROCHANNELS FOR REAGENT DELIVERY APPLICATIONS

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

In

The Department of Mechanical Engineering

by

Estelle Evans
B.S., Louisiana State University, 2004
December 2006
Acknowledgements

This study would not have been possible without the help of Dr. Dimitris Nikitopoulos, Dr. Michael Murphy, Dr. Steven Soper, the National Science Foundation (EPS-0346411), and the State of Louisiana Board of Regents Fund. In addition, I would like to thank my colleague Namwon Kim, Jason Guy in the chemistry machine shop, the Center for BioModular Multi-Scale Systems, and the people in the MicroSET and Microfluidics Labs. Finally, I would like to thank my family and friends, especially Jeremiah Oertling, for their support.
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Abstract

Multiphase flow in microfluidics is an increasingly growing field, especially in biotechnology. For instance, a steady-state slug flow would benefit lab-on-a-chip drug delivery methods. This flow would not only use minute amounts of reagents, but it would also decrease the sample processing time. Thus, researching a steady-state plug flow in a microchannel is beneficial to the drug delivery field.

Five PMMA, directly-milled microchannels [2: Aspect Ratio 1 (with and without pressure ports), 2): Aspect ratio 2 (with and without pressure ports), and 1: Aspect Ratio 3 (without pressure ports)] were manufactured. These channels were then cleaned, and a PMMA cover slip was thermally bound. In addition, a test setup was constructed to create steady gas and liquid flows to input into the channel. The gas flow is controlled by highly-accurate and a fast gas flow controllers, and a pressurized liquid reservoir maintains a steady liquid flow rate. A microscope equipped with a CCD camera captures images of flow within the microchips.

Two techniques were used to capture flow pictures: a back illumination method with a low recording frequency, and a laser illumination method with a high recorded frequency were used to capture frames. Each channel was tested by using a set liquid flow rate of either 0.05 ml/min (low) or 0.10 ml/min (high). While the liquid flow rate was held constant, the gas flow rate was incrementally adjusted by 0.05 ml/min. Frames were taken at each increment. Bubbly, slug, and annular flow regimes were observed. OPTIMAS, image processing software, was used to extract size distributions of gas bubbles and liquid plugs and to extract bubble velocities. Bubble and plug size distributions were use to assess whether or not the flow is steady state. For the low liquid
flow of 0.05 ml/min, all channels reached a steady state. However, the volumetric flow ratio ranges of steady state are different for each channel. For the high liquid flow rate of 0.10 ml/min, steady flow was not obtained in the AR1 channels. There were some minor differences in stable flow between the non-pressure port microchannels and the corresponding pressure-ported microchannel, probably due to slight differences in machining. The maximum pressure drops in AR1 and AR2 channels were 6 and 3 PSIG.

The extracted velocity data included the velocity at the centroid, minimum and maximum point on the bubble. The bubbles did not deform by much (3%) because these three velocities are relatively equal. In addition, the velocities indicate that the bubble slips in the microchannel.
Chapter 1: Introduction

1.1 Microfluidics in Biotechnology

Since the early 1990’s, microfluidics has become an increasingly popular field in several industries, like biotechnology and micropower generation. For the biotechnology field, microfluidics plays a major role in the lab-on-a-chip industry because of the little amounts of reagents consumed during a chemical analysis. Furthermore, because minute amounts of reagents are consumed, the processing time required for a particular analysis decreases. These benefits of minute sample consumption and decreased processing time arise from the increased surface area-to-volume ratio that exists in microchannel geometries. Because of the benefits of using microscale geometries, microfluidics is a promising field with applications in drug discovery, gene analysis, and clinical diagnostics.

Microfluidics is not just limited to single phase flow in a microchannel. In general, introducing micron-sized bubbles (adding another phase) in the biotechnology field has many applications, ranging from ultrasound contrast agents to drug delivery. Specifically, in drug delivery systems, micron bubbles can be used for reagent separation and reagent mixing.

Besides the advantages of using the micron-sized channels, the microchannel fabrication material itself also plays a vital role in the lab-on-a-chip technology. The first material used for microchannel fabrication was glass because of the well-established photolithographic and chemical etching processes. However, since polymers are biocompatible and possess a wide range of chemical and mechanical properties, they are
beginning to replace glass as the primary substrate material. In addition, there are several inexpensive ways to manufacture polymer microstructures, like injection molding, LIGA process, hot embossing, and micromilling. For injection molding, heated plastic, above the glass transition temperature, is injected into a metal mold insert. When the piece cools, the plastic solidifies, and it can be removed. Because the structures are microscopic, the heated plastic is injected at a high pressure. In the LIGA process, deep X-ray lithography, electroforming, and plastic molding are used to produce structures with micron-level detail and wall roughness in the nanometer range. However, this process is timely and expensive. For hot embossing, a mold insert is pressed into heated plastic. The plastic is at a temperature above the glass transition temperature. Then, the piece is cooled, and the plastic is separated from the tool. In micromilling, a microchannel is directly milled into the substrate material. The channel dimensions are limited by the tools. For instance, the aspect ratio of the channel is limited to the cutting portion of the milling bit. Also, because of the intense milling process, these direct-milled channels have a higher surface roughness, compared to the other methods. As shown, there are several techniques used to manufacture polymer microchannels, and the selected method depends upon the application of the microchip. Because it costs less to manufacture the polymer structures, these devices can be made for single use applications. Thus, they would not need to be cleaned for reuse, saving time and additional chemicals.

To complete the manufactured microchannel, a cover slip must be bonded to the substrate. There are also many methods for this bonding, such as thermal bonding, laminations, adhesives, and surface modifications. Thermal bonding is the most popular
of the methods, but it may cause small narrow channels to collapse. This problem exists because of the temperature and force required for a sufficient bond may deform the channels. Brown et al (2006) report several different treatments to a PMMA microchip for a successful bond. For example, they used surface modifications—air plasma treatment, hydrolysis, and aminolysis—and solvent bonding to increase the cover plate adhesion strength.

1.2 Multiphase-Microfluidic Flow Basics

Several key factors are important when studying a multiphase-microfluidic system. For instance, because the scale for microscopic flow is so small, it is important to address the validity of the basic equations of fluid motion, the Navier-Stokes equations. Also, to assist in characterizing the flow, particular dimensionless numbers are crucial, like the Reynolds’, Capillary, and Weber numbers.

When studying multiphase flows, knowledge of fluid properties, wetting, and surfactants are essential in understanding the resulting interface between the separate phases. Besides the properties exclusive to the phases, it is also important to consider the multiphase co-mingling method. For instance in this study, the two phases are dry-air and de-ionized water; two ways that the dry-air is co-mingled with the water are through a T-junction or a cross junction-type microchannel.

1.2.1 Macroscopic vs. Microscopic Governing Equations

Macroscopic fluid mechanics is based on the continuum assumption. Flow characteristics like density, velocity, and pressure vary continuously from point to point within the flow. In general, this hypothesis is true for microscopic (micron-level) flows. For instance, Nguyen and Wereley (2002) indicate that for a 10µm channel about 30,000
water molecules exist. Therefore, the continuum assumption is valid. However, the validity of the continuum assumption depends upon the packing of the molecules relative to the length scale of the flow. If the molecules are tightly packed, then the continuum assumption is valid, but if they are not closely packed, the continuum assumption may be risky. It typically is not until the nanoscale level that this hypothesis breaks down. At this level, the Knudsen number, a ratio of the molecular mean free path to the characteristic dimension, becomes unity; thus, the assumption is not valid. When the continuum assumption is true, the Navier Stokes equations are used to analyze flows.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x_i} (\rho u_i) = 0
\]

\[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_j u_i) = \rho F_i - \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \tau_{ji}
\]

\[
\frac{\partial}{\partial t} (\rho e) + \frac{\partial}{\partial x_i} (\rho u_i e) = -\rho \frac{\partial u_i}{\partial x_i} + \tau_{ji} \frac{\partial u_i}{\partial x_j} + \frac{\partial q_i}{\partial x_i}
\]

**Equation 1: Navier-Stokes Equations (Conservation of Mass, Momentum, and Energy)**

### 1.2.2 Dimensionless Numbers

Although the continuum assumption governs both the macrofluidic and microfluidic flow, there are some differences in the dimensionless numbers between the large and small scale flows. For example, gravity does not affect the flow in microchannels. Because the wall height is so small, the resulting Bond number, dimensionless number relating the gravitational effects to the surface tension, is less than unity. Thus, the orientation of the channels—vertical or horizontal—does not influence the flow regime. In addition, the Reynold’s number for microchannel flows is usually small because the viscous effects are greater than the inertial ones. The Weber number also involves the inertia of the flow; this dimensionless number is a ratio between the
inertial effects and the surface tension. So, for microfluidic flows where the surface tension dominates, it is small.

While the Reynold’s, Bond, and Weber numbers are small for microfluidic flows, the capillary number can be either small or large depending on the flow characteristics. The capillary number is a ratio of the product of the velocity and viscosity with the surface tension. In addition to these numbers for micro flows, they are specific numbers for multiphase flow, such as the Eotvos number. This is a ratio between the buoyant forces and the surface tension; it is used to characterize the shape of a fluid sphere.

1.2.3 Interfacial Phenomena

When considering a multiphase flow in microchannels, the interface between the phases is important. Parameters that describe the surface and bulk phenomena, and density and viscosity variations between the phases detail multiphase flows. Because a micron-level scale exists, surface tension and viscosity usually govern the behavior of these flows (as shown by the dimensionless numbers). The capillarity is important when considering the interface.

In a liquid, each molecule has a particular potential energy, and the potential energy of the molecules in the bulk portion is less than the energy of the surface molecules. The energy of a bulk molecule is smaller because forces from the neighboring molecules balance out. But, on the surface, there are no neighboring molecules to balance the force, so it is greater. Because the liquid wants to be stable, it will form a spherical interface to minimize the surface energy.
The shape of the interface can be affected by gravity and capillarity (dependent upon surface tension, energy required to increase the fluid surface by one unit). Under a certain length scale, the gravity effect is negligible. This length scale is the capillary length scale, shown below.

\[ L_c = \sqrt{\frac{\gamma}{\rho g}} \]

where
\[ \gamma = \text{surface tension} \]
\[ \rho = \text{density difference between fluids} \]
\[ g = \text{acceleration due to gravity} \]

**Equation 2: Lengths Below this Critical Length are not affected by Gravity**

If the shape of the drop is below this length (true in microchannels), the gravity effect on the interface is negligible, and capillarity governs.

1.2.4 Wetting

Wetting also affects the bubble interface in the microchannel. It implies that there are three interfaces—the two liquids and the solid surface. In order to minimize the energy of the interface, the system will choose an optimum configuration (most often a spherical shape). The spreading parameter for a liquid-gas-solid system is defined as below.

\[ S = \gamma_{\text{sol/gas}} - \gamma_{\text{sol/liquid}} - \gamma_{\text{gas/liquid}} \]

where
\[ \gamma_{\text{sol/gas}} = \text{Interfacial Tension of Solid – Gas} \]
\[ \gamma_{\text{sol/liquid}} = \text{Interfacial Tension of Solid – Liquid} \]
\[ \gamma_{\text{gas/liquid}} = \text{Interfacial Tension of Gas – Liquid} \]

**Equation 3: Spreading Parameter**
If the spreading parameter is greater than zero, then the liquid completely wets the surface. If the spreading parameter is less than zero, than a contact angle is created by the liquid/solid and liquid/gas interfaces. This angle is defined by Equation.

$$\cos \theta = 1 + \frac{S}{\gamma_{\text{liq}/\text{gas}}}$$

**Equation 4: Contact Angle for Spreading Parameter Less Than Zero**

Empirically, criterion states that a liquid will completely wet a solid, characterized by its critical tension $\gamma_c$, if the liquid/gas interfacial tension is lower than the solid critical tension (Zisman 1964). For plastics, $\gamma_c$ equals 30-40 mN/m, causing them to be hydrophobic.

If two liquids are used, each liquid governs the contact angle. Two cases possible cases are one wetting and one non-wetting fluids, or both partially wetting fluids. When only one of the fluids is non-wetting, it is separated from the wall by the wetting fluid. If both are wetting, there is an equilibrium angle.

### 1.2.5 Surfactants

Surfactants have two parts: a hydrophobic tail and a hydrophilic head. Therefore, a surfactant primarily exists on the surface of the fluid, with the hydrophilic head in the aqueous phase, and the hydrophobic tail in the other phase. Moreover, the presence of a surfactant strongly alters the surface properties of the flow.

A surfactant can be used to change the shape of a particular phase. For example in oil and water, a particular surfactant promotes either oil drops in water, or water drops or water drops in oil. Surfactants can also produce drop stability (i.e. avoiding coalescence in an emulsion) in the flow.
1.2.6 Bubble Generation

There are two popular studied geometries of on-chip bubble generation: a tee and a cross junction (Figure 1). The tee junction has one main and lateral channel; whereas, the cross has one main and two lateral channels.

![Diagram of T-Junction and Cross Junction Microchannels](image)

**Figure 1: T-Junction and Cross Junction Microchannels**

If a non-wetting fluid is pumped in through the lateral channels, drops are formed because of the Rayleigh-Plateau instability along the interface of the fluids of the main and lateral channels. Small variations in the local curvature cause pressure fluctuations that grow and break the liquid film into drops. The size of these droplets depends on the flow rate of the phases in the main and lateral channels and the channel size.

The bubble pinching of the flow in the T-junction and cross junction differs. In the cross junction, the necking point it centered in the cross channel (providing that the liquid velocity in the two lateral channels are equivalent). Whereas, in the T-junction the necking point is biased by the lateral channel; it is not symmetric about the channel’s centerline.
1.3 Two-Phase Flow Regimes

When two phases (i.e. liquid and gas, liquid-liquid) exists in a flow, it is known as a two-phase flow. Different types of flow regimes are categorized by the liquid and gas flow rates. In addition, the fluid and channel properties also influence the flow pattern. Shown below are the different types of flow regimes that exist in microchannels, Figure 2.

![Microchannel Flow Regimes](image)

**Figure 2: Microchannel Flow Regimes (From Cubaud and Ho, 2004)**
For laminar flow rate, Cubaud and Ho (2004) indicate there are five types of two-phase flow regimes in microchannels. At the lowest gas flow rate, bubbly flow occurs, and as the gas flow rate continually increases, wedging, slug, annular, and dry regimes can be seen.

- **Bubbly Flow:** Minute, non-uniform gas cavities that are regularly distributed in the liquid phase. This phase exists in a flow with a low gas flow rate.

- **Wedging Flow:** As the gas flow rate increases, the bubbles begin to coalesce. The resulting bubble has spherical-shaped end caps, and it has a diameter that approaches the microchannel’s dimensions.

- **Slug Flow:** These bubbles are similar to the wedging bubbles, except they are longer and their front end caps show a flatter profile.

- **Annular Flow:** As the gas flow rate is increased, the liquid flows along the channel walls, and the gas flow through the middle of the channel. There are no distinct bubbles.

- **Dry Flow:** In this type of flow, the channel is filled mostly with gas, and the liquid is present in a thin layer along the channel walls.

The flow regimes in liquid-liquid are a little different from the liquid-gas. This difference occurs at high flow rates. Liquid-liquid flows have a stratified flow at high lateral channel flow rates, while liquid-gas has an annular flow. These flow regimes are distinguished by eye.
1.4 Past Works

Steady reagent plug generation (ability to create plugs of reagent in a microfluidic channel) is the major goal of this study. Previous works include studying the mixing vortices in plugs, generating the plugs and measuring the contamination between them, and maintaining a steady plug flow within a microchannel.

1.4.1 Mixing Vortices in Liquid Plugs

Gunther et al used particle imaging velocimetry and fluorescence microscopy to study gas-liquid flow for low superficial velocities. The channels used are PDMS (400 µm wide and 150 µm deep) fabricated using a soft lithography. Two designs were used; Design 1 encompassed a predominantly straight channel with wide bends. Design 2 consisted of uniform, river-like bends (Figure 3).

![Design 1 Diagram](image1)

![Design 2 Diagram](image2)

**Figure 3: Gunther et al Two Microchannel Design**

The lengths varied between 150 and 1200mm. The channel has three inlets: 1 is for the liquid, 2 is for the gas, and 3 is for the fluorescent dye. Flow visualization was made
possible by using a continuous dye or dyed microspheres which were then illuminated by YAG lasers, and recorded by a CCD camera.

Gunther et al noted that the segmented gas-liquid flow is broken into 3 categories: bubble, slug/plug and annular. However, this study primarily focuses on the liquid-liquid mixing that occurs in slug flow. In the liquid plugs in the slug flow, a recirculation occurs (Figure 4).

**Figure 4: Plug Mixing Recirculation (From Gunther et al)**

This recirculation can be used for the mixing of reagents. For instance, this experiment used a Rhodamine B dye in ethanol to examine the mixing lengths required for a fluorescence intensity of 1/10th the original value. Also, the mixing times required are based on gas and liquid flow rate adjustments.
Gunther et al found that in the straight channels, the surface roughness of the channel and the compressibility of the air cause a loss of symmetry for the velocity and concentration fields. These asymmetric velocity and concentration fields enhance mixing along the centerline of the channel. The introduction of bends (in the meandering type channel) accelerates the mixing, which is due to the switching of recirculations along the centerline.

In this study, the segmented flow is only for mixing of reagents, not for reagent distribution. Once the reagents are mixed, a separator collects the liquid while the air bubble is discharged at the edge of the channel. Thus, leakage between air bubbles is not considered because the specific volumes of the liquid plugs are not important (all mixed reagent lumped together in the separator).

1.4.2 Macro-Reagent Separation

Linder et al (2005) used cartridges made by injecting reagent plugs, separated by air spacers, into available tubing as a technique for reagent delivery (Figure 5). One end of the cartridge was dipped into the reagents, while the other was connected to a vacuum, using an array of computer-controlled valves. As the valve is opened, the reagent is drawn into the cartridge. After each reagent plug, an air spacer is injected into the tubing. Therefore, this separation method was not an on-chip method, but rather a “macro-separation method.”

After the cartridge was created, it is attached to a microfluidic device. For instance, a PDMS chip contained six inlets and six outlets with a variable channel diameter to carry out an immunoassay. After the cartridge is attached to the device, a vacuum is applied to the outlet, and the flow inside of the cartridge is sucked out of the
Figure 5: Macroseparation Method Utilizing Separate Reagents and Air Spacers (from Linder et al, 2005)

tubing. Linder et al (2005) found that when the channels are rendered hydrophilic (treated with Tween 20 or plasma oxidation), the air plugs flow through the channels smoothly.

Most importantly, Linder et al (2005) addressed the issue of contamination between reagent plugs and the use of liquid spacers, instead of air. Using dyed plugs revealed that residue was left behind the reagent as it traveled through the tube, and contamination resulted because succeeding plugs collected the residue. To quantify this contamination, an experiment using various rinsing plugs of a washing buffer and fluorescein dissolved in 50 mM carbonate buffer was devised. The washing buffer was placed after a plug of fluorescein, which represented the reagent, and the fluorescein intensity of each plug was recorded as it traveled through the microchannel. The washing buffer greatly reduced the cross contamination between plugs. For example, three washing buffer plugs flowed a 31μM fluorescein plug, and fluorescence signals of 7, 0.9
and 0.1% relative to the fluorescein plug were observed. Fluorescence signals detected in further experiments that involved more washing plugs, only appeared in the first three washing plugs. Thus, after the third plug, no signal was detected.

Liquid spacers (as opposed to air) were also investigated. Linder et al used water immiscible liquids (like perfluorodecalin PFD) to replace the air spacer. Not only did the PFD exhibit poor wetting (resulting in irreproducible results), but also increased the elapsed time for the reagent and liquid spacer to flow through the microfluidic device. The viscosity of the liquid spacer creates this increase; the volumetric flow rate of the fluid is inversely proportional to its viscosity. For this case with PFD, air travels 250 times faster for the same pressure drop.

1.4.3 Steady-Bubble Generation Via Cross Junction

Cubaud and Ho (2004) created an on-chip method to generate gas bubbles in deionized water (Figure 6). Their microchannels were made with glass and silicon; the channels were etched at different depths using deep reactive ion etching onto a silicon wafer. This work uses two geometries of microchannels for the test section: 200μm and 525μm square channels; and the geometry of the inlet section for the gas and liquid is 50μm square. After these aspect ratio one channels were etched, Pyrex glass was bonded to the silicon microchip for optical access. Using glass and silicon, results is a molecular smooth microchannel.

Cubaud and Ho (2004) conducted experiments creating different flow regimes by changing the volumetric flow ratio (ratio involving the liquid and gas flow rates). They restricted their experiments to laminar flow, and observed bubbly, wedging, slug,
annular, and dry flow regimes. Because surface tension is dominant in microchannels, the transitions to different flow regimes, do not depend on the channel diameter. Whereas,

![Diagram of Cubaud and Ho's Silicon Microchannel]

**Figure 6: Cubaud and Ho's Silicon Microchannel**

for macro and mini channels (channel height > 1), gravity, shear, and surface tension, cause the flow regime to be dependent on the channel diameter.

\[
\beta = \frac{Q_L}{Q_L + Q_G}
\]

where

- \(Q_L\) = Volumetric Liquid Flow Rate
- \(Q_G\) = Volumetric Gas Flow Rate

**Equation 5: Liquid Volumetric Flow Ratio for Two-Phase Flow**

1.5 Goals of Present Study

The main goal of this study is to expand upon the Cubaud and Ho (2004) experiment. A different substrate material, microfabrication method, and aspect ratio were used. Cubaud and Ho used silicon and glass for their microchannel materials. The channels were etched into the silicon substrate and were of aspect ratio one. This study uses polymethylmethacrylate (PMMA), as the substrate material, and the channels are
directly milled into the PMMA. In addition to aspect ratio one, this study also explores aspect ratios of two and three.

To further Cubaud and Ho’s work, an experiment had to be built. Thus, the second goal of the study was to make a user-friendly experiment that could accommodate a range of volumetric flow ratios. The experiment also must have the ability to accommodate the other chemicals (like flourinert and dodecane), in addition to just de-ionized water and dry air. These other chemicals will be studied under future experiments. In order to maintain a steady two-phase flow, it is important that the experiment have a high level of computer control. Thus, it was necessary that the LabVIEW control the instrumentation.

Data acquisitioning was also part of the experimental design. In order to study the two-phase flow, it was required to retrieve bubble sizes, shapes, and velocities. Also, the size and shape of the filler plug (between the bubbles) was examined. This information was extracted via photographs of the two-phase flow. Thus, it was required to use image-processing software (OPTIMAS), which involves C++ style programming. Once, all raw data was extracted from the images, MATLAB was used to perform statistical analysis.
Chapter 2: Experiment Design

2.1 Gas and De-ionized Water Experiment

Building an easy-to-use and highly controllable experiment to create the steady bubbly flow was one of the major objectives of this study. Figure 7 shows the schematic of dry air and de-ionized water experiment.

Figure 7: Schematic of the Dry-Air and De-ionized Water Experiment

In this schematic, the upper line, consisting of the pressurize water reservoir, flow meter, pressure regulator, and building air supply, is the liquid line. The lower line, composed of dry air canister, three-way solenoid valve, 2 flow controllers, is the gas line. Each of these lines enter separate inlet ports in the microchannel, and they do not meet until they reach the cross geometry in the microchip.
2.1.1 Liquid Line

The liquid line harnesses the building’s air supply to pressurize the water. First, the air enters a 0-150 PSIG pressure regulator. This pressure regulator is set to the required liquid pressure for the microchannel. The pressurized air then enters a liquid reservoir (filled with de-ionized water), which was constructed of PVC with a maximum operating pressure of 300 PSI. The entering air pressurizes the water and pushes the water through a 0-1 Cole-Parmer liquid meter, which has a maximum operating pressure of 100 PSIG, an accuracy of ± 1% full scale, and a response time of 100msec. In addition, this meter also has a 0-5 Vdc output that allows for LabVIEW interaction via compact fieldpoint. After the water leaves the flow meter, it enters the microchannel.

Pressure is the major operational limitation in this design. In order to guarantee safe operation of all the instrumentation, the maximum operating pressure is limited to 90 PSIG. Using a pressure range of 0-90 PSIG with these directly-milled microchannels allows for liquid flow rates of 0.05 ml/min and 0.1 ml/min.

2.1.2 Gas line

A gas canister supplies the dry air required for the experiment. A two-stage pressure regulator is attached to the canister. The air enters a three-way solenoid valve, which operates with a 24 Vdc signal. Depending on the mode of the solenoid valve (off or on), the air either travels to the 0-1 gas controller or the 1-100 gas controller. These Cole-Parmer controllers have a maximum operating pressure of 100 PSIG, an accuracy of ±1% full scale, and a response time of 100 msec. After the air exits the controller, it enters the microchip. As with the case of the liquid line, a 90 PSIG pressure limitation is
also applied to the gas line. In addition, these controllers have a 0-5 Vdc analog input and output signal (allows for LabVIEW control).

2.1.3 Controllability

Controllability was the major governing factor in the instrumentation selection. For instance, the liquid meter and the two gas flow controllers operate based on the laminar flow principle. A laminar flow element, a uniquely designed restriction to cause laminar flow, creates a pressure drop inside the device. The volumetric flow rate is determined by this pressure drop, using Equation 6.

\[
Q = \frac{(P_1 - P_2)\pi r^4}{8\eta L}
\]

where

- \( Q \) = Volumetric Flow Rate
- \( P_1 \) = Static Pressure at Inlet
- \( P_2 \) = Static Pressure at Outlet
- \( r \) = Radius of Restriction
- \( \eta \) = Absolute Viscosity of Fluid
- \( L \) = Length of Restriction

**Equation 6: Operating Principle for Laminar Flow Principle Flow Meters and Controllers**

In addition, because these three instruments are based on a pressure drop measurement, rather than the thermal mass technologies, an ultra-fast response time is provided. For instance, the same flow range meter that uses the thermal mass method for flow measurement has a response time of about 2 seconds. Whereas, these laminar flow method meters have a response time of 100 msec. This is extremely important in providing accurate readings and control, which is necessary for steady-bubble plug flow.

The two gas flow controllers installed in the gas line have normally closed proportional controller valves. The valves (closed off by mechanical spring that holds
and elastomer-tipped plunger on a flow orifice) remain closed until the controller receives a voltage signal, which is the set point provided by the user. A PID loop in the controller continually compares the measured flow rates to the set point, adjusting the voltage signal sent to the valve to maintain the flow set point. Thus, with this PID loop integrated in the controller valve, the gas flow controllers provide precise and accurate gas flow measurement and control. As a side note, a controller was not used on the liquid line, simply because one was not available for such small flow rates. But, the liquid meter and pressure regulating valve allow for precise control and measurement of the liquid flow rate.

Like the gas flow controllers are essential in providing control for the gas line, the pressurized water reservoir is crucial for attaining a steady-state water flow. In order to push the water into the chip, either a syringe pump or a pressurized water reservoir can be used. However, the syringe pump’s inadequate performance produces a highly oscillatory flow, as shown in Figure 8. This figure shows that at even 150 seconds, the syringe pump flow rate has not leveled off (centered around 0.09 ± 0.02 ml/min). This oscillatory response appears to coincide with the turning of the screw. As the flow rate increases the flow rate frequency also increases. Whereas, the flow from the pressurized reservoir peaks at 0.5 ml/min at about 10 seconds, but quickly drops to its steady state value of about 0.108 ± 0.002 ml/min. In addition to the smooth performance, the pressurized water reservoir also has a large capacity of about 90 ml compared to the small 3 ml capacity of the syringe.
Figure 8: Syringe Pump vs. Pressurized Reservoir Steady State Plot, shows that Pressurized Reservoir reaches Steady-State before Syringe Pump

2.2 Liquid-Liquid Experiment Design

In addition to the using dry air and de-ionized water, the experiment is also capable of a liquid-liquid flow. However, because of the pressure limitations in the system (no greater than 90 PSIG), the liquids must be selected wisely. For instance, liquids should be chosen to have about the same viscosity (or less) as de-ionized water because anything greater is difficult to push through the channel with the 90 PSIG pressure limitation.

The below design (Figure 9) shows the configuration for a de-ionized water-liquid experiment. With this configuration, only the gas line has to be modified to
accommodate the liquid. Because de-ionized water would be used in both experiments, the water line remains unchanged.

Figure 9: De-ionized Water and Liquid Experiment

Figure 10: Liquid-Liquid Experiment
The liquid line remains the same as in the de-ionized water and dry air experiments. However, to accommodate the second liquid, the gas line was modified. This “chemical line” (air canister, pressurized liquid reservoir, and rotamer) uses the air that provided the flow for the previous experiment to pressurize a liquid reservoir (similar to the de-ionized water one). The second liquid has its own PVC reservoir, similar to the PVC water reservoir. After the air from the canister pushes the second liquid from its PVC reservoir, the liquid enters a rotamer, which measures the flow. A rotamer was chosen because it is compatible with many liquids, unlike the Cole-Parmer 0-1 ml/min water meter. However, a viscosity and density correction must be applied to the rotamer tube scale reading for the actual liquid flow. This Omega rotamer has a range of 0-1 ml/min of water and an accuracy of ±2%.

If other liquids are required besides de-ionized water, the Cole-Parmer water meter can be replaced with another rotamer (compatible with the liquid). Thus, this experiment has the ability to flow gas-liquid flows and liquid-liquid flows (Figure 10).

2.3 Microchannel

2.3.1 Microfabrication

There are five directly-milled PMMA microchannels that are used in this experiment. Three have the design (non-pressure port) shown in Figure 11, and two have the design (pressure port) shown in Figure 12. Microns are the units used for these drawings. Pressure port and non-pressure port designs are used to prove that the pressure port geometry does not influence the channel’s flow. In addition, three aspect ratios are used for the test channel. All channels have the same dimensions for the smaller
(mixing) section, 50um (±5) x 50um (±5). Aspect ratios 1, 2, and 3 have 200um (±10) x 200um (±10), 300um (±10) x 150um (±10), and 127um (±10) x 381um (±10), respectively, for the test section dimensions. These dimensions were chosen to maintain a constant hydraulic diameter, resulting in similar pressure drops amongst the microchips. Because these chips are micro-machined, they are slightly rougher than other ones manufactured with other methods (see Table 1).

Figure 11: PMMA Microchannel (No Pressure Ports), Units=microns

Figure 12: PMMA Microchannel (Pressure Ports), Units=Microns
Table 1: Bottom and Side Wall Roughness of Different Manufacturing Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Roughness and Root Mean Square</th>
<th>Bottom Roughness</th>
<th>Side wall Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Micro-milling</td>
<td>Ra (nm) 241.36</td>
<td>309.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMS (nm) 302.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot Embossed Brass Mold</td>
<td>Ra (nm) 147.16</td>
<td>331.64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMS (nm) 208.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot Embossed X-Ray LIGA Mold</td>
<td>Ra (nm) 539.99</td>
<td>63.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMS (nm) 688.36</td>
<td></td>
<td>78.77</td>
</tr>
</tbody>
</table>

This table shows the bottom and sidewall roughness (measured by Namwon Kim) of a PMMA microchannel (Figure 13 and Figure 14). Compared to the other methods of brass mold and X-ray LIGA hot embossing, direct micro-milling has the middle bottom roughness and a high side wall roughness. Direct micro-milling produces similar roughness values as a hot embossed brass mold.

2.3.2 Thermal Bonding

After the chips are machined, they are cleaned and thermally bound (according to Table 2) to a 0.125” PMMA cover slip (to close the channel). Before the chip is cleaned, holes (inlet ports, outlet port, pressure ports-if needed-and air holes) are drilled according to Figure 15. Large air holes are drilled around the channel to prevent trapped air during bonding.
Sonication is not used for cleaning the chips because cracking results. Since micro-milling is an intensive process, residual stresses are introduced in the chip. These stresses cause the chip to crack during sonication, regardless of the sonication solution used (i.e. de-ionized water and detergent, or de-ionized water and IPA, etc). Annealing the microchannel at a temperature below the glass-transition temperature of PMMA was attempted to relieve the stresses, but crack-free chips were not produced consistently; thus, the chips were soaked only in a bath of de-ionized water and detergent.

Concerning the chemicals used during the cleaning process, only a critically cleaning detergent was used. Any introduction of chemicals to the microchannel can potentially change the surface energy of the PMMA, or if any chemical residues are left on the channel, they could affect the surface tension of the liquid flowing through the channel. Therefore, through experimentation, de-ionized water and detergent were the minimal treatments capable of fully cleaning the channels. Although the introduction of a detergent to the microchannel could insinuate a possible surfactant contamination on the microchannel, the channels are flushed and soaked at least 1-2 days in de-ionized water after thermal bonding.

After the chip is properly cleaned and all debris is removed (inspect with 5X objective), the cover slip is bound to the PMMA substrate. To guarantee consistent thermal bonding, an aluminum jig (Figure 16) was constructed (courtesy of Namwon Kim). Two glass panes sandwich the microchannel and cover slip. An equal torque is applied to the 4 bonding jig screws to ensure that the cover slip is evenly bound to the substrate.
Figure 15: Diagram of Drilled Holes in PMMA Substrate

Table 2: PMMA Thermal Bonding Procedure

<table>
<thead>
<tr>
<th></th>
<th>Blow with compressed air</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soak</td>
</tr>
<tr>
<td>2</td>
<td>DI water + 1% Detergent</td>
</tr>
<tr>
<td></td>
<td>60 min</td>
</tr>
<tr>
<td></td>
<td>Gentle blow with compressed air and clean with soft #2 artist paint brush until chip clean</td>
</tr>
<tr>
<td>4</td>
<td>Dehydration</td>
</tr>
<tr>
<td></td>
<td>Temp</td>
</tr>
<tr>
<td></td>
<td>95 °C</td>
</tr>
<tr>
<td>5</td>
<td>Bonding jig</td>
</tr>
<tr>
<td></td>
<td>Applied torque</td>
</tr>
<tr>
<td></td>
<td>Finger Tightened</td>
</tr>
<tr>
<td>6</td>
<td>Bonding</td>
</tr>
<tr>
<td></td>
<td>Temp</td>
</tr>
<tr>
<td></td>
<td>118°C</td>
</tr>
<tr>
<td>7</td>
<td>Cooling #1</td>
</tr>
<tr>
<td></td>
<td>Temp</td>
</tr>
<tr>
<td></td>
<td>95</td>
</tr>
<tr>
<td>8</td>
<td>Cooling#2</td>
</tr>
<tr>
<td></td>
<td>Temp</td>
</tr>
<tr>
<td></td>
<td>Room</td>
</tr>
</tbody>
</table>
Because the cover slip is 0.125” thick, sometimes during thermal bonding the cover slip would fall into and block the channel, especially in the inlet, outlet, and/or pressure ports. To stop cover slip collapse, the paper clip insert method was developed. In this method, sections of a paper clip (less than 1/8”) are cut and placed inside the substrate before cover slip placement. Using a steel paper clip along with a magnet (placed under the bonding jig during bonding), the technique prevents the cover slip from collapsing in the ports (Figure 17 and Figure 18). After the microchannel cools down in the oven, the substrate is removed from the bonding jig. The paper clip inserts are removed by tweezers or a magnet.

### 2.4 LabVIEW VI

National Instruments’ LabVIEW was used for better experiment control. The Cole-Parmer controllers and meter, Honeywell pressure transducer, and Peter Paul solenoid valve all used voltage signals sent through a Compact Fieldpoint module (cFP-
Figure 17: Cross Section of Thermal Bonding Paper Clip Insert Layout

(a) Empty Port
(b) Port Filled with Paper Clip Insert

Figure 18: Cross Section of Channel Showing Cover Slip Blocking Port (a) and a Paper Clip Insert Supporting the Cover Slip (b)
1808) to allow the user remote control of the experiment. For instance, the written LabVIEW program, VI, allowed set points for the volumetric flow for the gas controllers, along with outputting the actual volumetric flow. In addition, the liquid flow meter, and differential pressure transducer outputted their volumetric flow and pressure readings, respectively, to the LabVIEW VI. Finally, the solenoid valve was also controlled (ON/OFF) in the VI. Figure 19 shows the voltage signals that are inputted and outputted into each of the instruments. By using LabVIEW, all of the voltage signals for these devices were controlled in a single VI.

Figure 19: Voltage Signals Inputted and Outputted from Instrumentation

In addition to the instrumentation interaction, the LabVIEW VI was also configured to perform basic calculations in the flow. For example, the volumetric flow ratio, superficial gas and liquid velocities were all calculated based on the signals from the gas controllers and the liquid meter. In addition, this VI calculated the hydraulic diameter, which is based on the channel’s dimensions.

Figure 20 and Figure 21 show the graphical user interface window of the VI program. Besides the meter, controllers, pressure transducer, and solenoid valve, the VI
also has the ability to individually control up to four syringe pumps. Although syringe pumps were not used for this experiment (based on their highly fluctuating steady-state), they were implemented for potential future use.
Figure 20: LabVIEW Screen Shot VI; Contains Syringe Pump Initialization and Control
Figure 21: LabVIEW Screen Shot; Contains Solenoid Valve Control, Flow Meter Readout, Flow Controller Control and Readout, Pressure Transducer Readout, and Channel Flow Characteristics
Chapter 3: Back Lamp Illumination Technique

3.1 Background

The back lamp illumination setup was used to determine the bubble size distribution over given time of various flow regimes. This method incorporates a back lamp affixed to the microscope, which results in clear flow images, as shown in Figure 22.

Figure 22: Picture Taken Using Back Lamp Illumination Technique

The shadow along the edges of the bubble indicate curvature. L (appears as lighter color in picture) is the length of the portion of bubble “parallel” to the channel top wall, and R (appears as the darker color in the picture) is the length of the curved portion. This bubble can fill the channel two different ways: bubble can actually be touching the channel walls (forming a contact angle), Figure 23, or the liquid could lubricate the bubble, Figure 24.

A clear contrast between the bubble and background is essential for the image processing. To retrieve the bubble size information, several pictures of each flow were taken and processed with the image processing software OPTIMAS.
Figure 23: Cross-Sectional View of Contact Angle Forming Bubble

Figure 24: Cross-Sectional View of Lubricated Bubble

3.2 OPTIMAS Image Processing

Fundamentally, each image is composed of pixels, and each of these pixels has a pixel value, which represents the brightness of the pixel. For grayscale images (images that consist of shades of gray), pixel values range for 0 (black) to 255 (white); the values in between are shades of gray. OPTIMAS uses this pixel value to isolate objects in an image, and data (sizes, shapes, etc.) is extracted from these isolated objects.

For instance, Figure 25(a) is a raw image captured by the CCD camera. It contains gas bubbles flowing with water through the microchannel. Although this is a clear image, it cannot be used presently for image processing. In OPTIMAS, the user defines a threshold (pixel value); all objects above this threshold are detected. In this
picture, the bubble, liquid, and channel material all have similar gray pixel values. Thus, for just bubble detection, image alterations are necessary.

To create an image containing only the bubbles, a macro (C-style OPTIMAS program) was written to modify the image. First, the image is divided by a “clearfield” (an image with only liquid flowing through the channel,(b)). This removes the liquid and the channel walls (c). Then, the image is inverted (d), which is necessary because the threshold is set to detect all pixels above a particular value. Thus, if one requires bubble detection, the bubbles must be a lighter color (higher pixel value) than the darker (lower pixel value) background. In addition, the bubbles must also be filled to eliminate detection of the “inside area”,(e). Note that the bubbles touching the image border are not filled. Because this macro only detects whole bubbles, these partial bubbles are ignored.

However, if one desires plug detection (portion in between the bubbles), image processing is different. For this case, both channel walls and bubbles are necessary to “bound” the plug. But, from the raw image, the wall edges are not as sharp as the black bubble edges, so image alterations as also essential for this case. To intensify the wall definition, white strips are added to the clearfield image, Figure 26 (a). Then, the bubble image is divided by the clearfield to produce (b). With this picture, all of the areas bounded by the dark sections are detected. So, the plugs are detected, and also the areas in the middle of the bubbles are tracked (this information is used for the apparent void fraction calculations).
Figure 25: Bubble Images for OPTIMAS Processing
3.3 Experimental Results

The bubble characteristics for five microchips were analyzed. There were two microchips at each aspect ratio (1 and 2): one with pressure ports and one without pressure ports, Figure 27. However, at AR3, only a non-pressure ports channel was available. This channel redundancy (pressure port and non-pressure port) will show if the pressure port presence influences the channel geometry.

Figure 26: Plug Images for OPTIMAS Processing

(39)

Figure 27: Five Channel Configurations

For each channel, four bubble characteristic tests were performed (Table 3).
Table 3: Different Bubble Characteristic Test

<table>
<thead>
<tr>
<th>Bubble Characteristic Tests</th>
<th>Microscope Objective</th>
<th>Liquid Flow Rate (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>2x</td>
<td>0.05</td>
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<tr>
<td>Test 2</td>
<td>2x</td>
<td>0.1</td>
</tr>
<tr>
<td>Test 3</td>
<td>4x</td>
<td>0.05</td>
</tr>
<tr>
<td>Test 4</td>
<td>4x</td>
<td>0.1</td>
</tr>
</tbody>
</table>

For each test, the liquid flow rate is held constant while the gas flow rate is gradually adjusted. For instance in Test 1, the liquid flow rate is set at 0.05 ml/min while the gas flow rate is adjusted from 8.0 ml/min to 2.0 ml/min at increments of 2.0 ml/min, and 1.0 ml/min to 0.05 ml/min at increments of 0.05 ml/min. After each adjustment, the flow is given time to stabilize (about 2 minutes).

The objective of Test 1 and Test 2 is to show the entire test section width (Figure 31), which is necessary to prove that the chip has a steady-state flow. However because the resolution is poor (7 microns/pixel), the data has a degree of error, so these images were not OPTIMAS processed. The channels were designed to have widths of 127, 150, and 200 microns, so for each channel each pixel represents 5.5%, 4.6%, and 3.5%, respectively, of the width.

The purpose of Test 3 and Test 4 is to increase the resolution (3 microns/pixel) of the images by using the higher magnification. With the channel widths of 127, 150, and 200, each pixel represents 2.3%, 2%, and 1.5% of the channel width. Thus, the data extracted from these images has a smaller error interval than the 2x. Table 4, Table 5, and Table 5 show some important dimensionless numbers concerning the different microchannels and flow rates.
<table>
<thead>
<tr>
<th>Liquid Flow Rate (ml/min)</th>
<th>Superfical Liquid Velocity (m/s)</th>
<th>Reynold's Number</th>
<th>Capillary Number</th>
<th>Weber Number</th>
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<tr>
<td>0.05</td>
<td>0.021</td>
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Table 5: Dimensionless Numbers for Aspect Ratio 2 Microchannels

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| Eotvos Number          | 0.0030                        |
| Density Ratio (Liquid/Gas) | 830.83                       |
| Viscosity Ratio (Liquid/Gas) | 54.95                        |
Table 6: Dimensionless Numbers for Aspect Ratio 3 Microchannels

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Eotvos Number 0.0022
Density Ratio (Liquid/Gas) 830.83
Viscosity Ratio (Liquid/Gas) 54.95
3.3.1 Microchannel Flow Phenomena

During the data collection process, flow phenomena including bubble formation (at the cross), bubble coalescence (at the mixing to test section expansion), pressure port interfaces, and complete channel bubble filling were noticed (Figure 28). In (a), the bubble interface can be seen at the channel’s cross. This particular picture, taken at a low liquid flow rate, shows the dry air (horizontal channel) meeting two lateral channels of de-ionized water. As the liquid flow rate increases, the top interface (of top liquid channel and the gas) and the bottom interface (of bottom liquid channel with the gas) start pinching off the gas flow. After the bubble is formed at the cross, it travels to the test section by passing through and an expansion (b). At the expansion, several small bubbles coalesce to form a larger bubble. For most of the cases studied, this bubble completely fills the width of the channel.

For the channel with pressure ports, leakage into the pressure port is important. This side leakage could adversely affect the bubble flow by diverting the liquid for the test section into the pressure port channel. Any diversion of the liquid could cause slight differences in the bubble regimes. In (c), the test channel (larger, horizontal channel) and the pressure port channel (smaller, vertical channel) are visible. Rhodamine B was added to the de-ionized water to enhance the interface. Thus, some leakage into the side port is evident. However, this is expected because it is impossible to realistically remove all leaks from the pressure port line. In addition, it has been seen that the pressure port interface reached a steady state and stops moving, like (c).
<table>
<thead>
<tr>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d)</td>
<td>(e)</td>
<td>(f)</td>
</tr>
</tbody>
</table>

(a) Bubble Interface at Channel’s Cross  
(b) Bubble Coalescence at Test Section Expansion  
(c) Pressure Port Interface  
(d) AR1 Bubble Completely Filling Channel  
(e) AR2 Bubble Completely Filling Channel  
(f) AR3 Bubble Completely Filling Channel  
(g) AR3 Bubble Not Completely Filling Channel

**Figure 28: Flow Phenomena Pictures**
In (d), (e), (f), and (g), show pictures of de-ionized water (dyed with Rhodomine B) and air bubbles. These pictures show that for AR1 and AR2, gas bubbles completely fill the channel, which is evidenced by completely dark bubbles. If the bubbles were not completely filling, there would be less contrast between the air bubble and liquid plug. This occurs for AR3. Picture (f) shows that the channel for AR3 is completely filled by the bubble, but (g) shows that the bubble does not completely fill the channel (indicated by the bubble’s light color). For AR3, it was noted that sometimes the bubbles fill the channel, (f), and sometimes they do not, (g). This was not the case for AR1 and AR2; the bubbles always filled the channel. This type of behavior probably results from the channel’s geometry at the expansion, not gravity. For instance, AR3’s test section has a depth of 381 microns, and the cross section has a depth of 50 microns, Figure 29. As the bubbles exit the 50 micron deep channel, they begin to coalesce in the 381 micron deep test section (b). After the bubble reaches a certain size, it breaks off (because flow instability) and flows down the channel (c). For AR1 and AR2, the bubble breaks off after it completely fills the channel (shown by Figure 29 (d) and (e)). But for AR3, bubble breaks off before completely filling the channel. This size of bubble break off depends on the flow trying to stabilize. The flow rate of the two phases—liquid and gas—and the channel dimensions influence the flow stability.

The final important observation noted during data collection is the requirement to ‘prime’ flow. If one is using a chip that has just been thermally bound and cycled with de-ionized water, one must ‘prime’ the flow to achieve a steady-state plug flow. Priming
Figure 29: Cross-Section of AR3 Expansion, Units=microns

involves flowing both the liquid and gas phases in the chip for about 2 hours before performing any tests. Although the exact reason why priming is necessary is unknown, one speculation is the existence of air pockets in chip that arise during thermal bonding. These are air pockets that are trapped in the chip by the cover slip during the thermal bonding process. In order to remove the pockets, one must cycle the chip with the two-phase flow (bubble completely channel filling) to completely flush the pockets out. A simple de-ionized water flush will not guarantee a flushing because it compresses the trapped pockets, rather than removing them.
Figure 30: Unprimed Slug Flow

Figure 30 shows an unprimed flow. The bubbles’ trailing edges are dragging within the microchannel. Besides the bubble’s appearance, this flow is noticeable because the gas flow controller shows wide variations, about ±0.5 ml/min.

3.3.2 Flow Regime Results

Regardless of the channel dimensions, all channels show the same flow regime for the same volumetric flow ratios. However, for the higher liquid flow case, many of the resulting flows are not as controllable as the low liquid flow rate counterparts.

Bubbly Flow

Although bubbly flow could not be completely obtained in the experiment (resulting from the liquid pressure line limit of 100 PSIG), the captured pictures appear to show the bubbly/slug regime transition, Figure 31 and Figure 32, which is approximately at a ratio of 0.75.
Figure 31: Bubbly/Slug Flow Regime Transition

Figure 32: Bubbly/Slug Flow Regime

In these images as in all images, the flow travels from the right side to the left. The bubbles appear to form as a large “bubbly” flow at the bubble generation section, but as they travel down the channel, they begin to coalesce.
Slug Flow

Ranging from 0.75 to 0.05, slug flow is the dominant regime in the microchannels. In some cases, it is regular, (Figure 33), while in other cases it is erratic, (Figure 34).

Figure 33: Regular Slug Flow Beta=0.2

When the liquid was held a constant rate of 0.05 ml/min, the aspect ratio 1 channels had slug flow regular range from 0.18-0.35, but when the liquid was increased to 0.1 ml/min, a stable, regular regime was not attained for any volumetric flow ratio. For the aspect ratio 2 channels, the slug regular range was broader, from about 0.16-0.35. Also, at a liquid setting of 0.1 ml/min, the channel did have a stable flow for a range 0.28-0.5.

When comparing steady-state bubble flow in aspect ratio 1 and 2 chips, not only does aspect ratio 2 have a broader range, but it also has a faster steady-state response. During the aspect ratio 1 experiments, it took between 2-15 minutes for the flow to stabilize, but during the aspect ratio 2 experiments, it took no longer than a minute. Thus,
the difference in the channel geometry affects the steady-state flow in the PMMA channels because the larger aspect ratio promotes a steadier flow.

**Annular Flow**

When the volumetric flow ratio approached 0.005, the slug flow transitioned into annular, Figure 35. In this flow regime, the bubbles are not distinct because the channel is most filled with one fluid. Necking is visible since the channel is not completely dry.

**Figure 35: Annular Flow Regime Beta=0.04**
Figure 36: Flow Pattern Map for AR1 and AR2 Channels

3.3.3 Aspect Ratio One Microchannels

3.3.3.1 No Pressure Ports

At each set volumetric flow ratio, the bubble area, bubble length, and bubble perimeter were extracted from the recorded images. Based on a collection of pictures, the averages and standard deviations of each of these values were calculated.

Liquid Flow Rate=0.05ml/min

At this set liquid flow rate the flow was steady-state at a volumetric flow ratio of 0.18-0.32 (Figure 39, Figure 40, Figure 40, Figure 41, and Figure 42). Outside of this flow ratio results in unsteady flow Figure 37 and Figure 43). All of these figured include histograms for both the gas bubble and liquid plug. In addition, the average, standard deviation, 90% and 95% confidence intervals are reported. Regarding the histograms,
they are all unit less because each value was characterized by the average value. This was done to center the values around 1 in order to easily portray stability.

Figure 37 shows histograms for the flow at Beta=0.5, with (a) as the 2x view and (b) as the 4x view. These views show that the flow begins regularly, but as it traverses down the channel, it begins to coalesce. To better understand how the areas, perimeters, and Y lengths were calculated, (c) is shown. For a flow ratio of 0.5, neither the gas bubble flow or the liquid plug flow was steady. The characteristic bubble area, perimeter, and Y length ranged from 0.5 to 4, not centered around the mean value of 1 (d-f). The standard deviations for the bubble regime are high; for instance, the area standard deviation is almost the average value. The same is true for the liquid plugs which show a characteristic value distribution of 0.5 to 4 (g-i). Graphs (j-l) show the ratio of bubble/plug values. These indicate the relationship between the area, perimeter, and Y length of the bubbles and plugs. The wide range (0-25) also indicate and unsteady flow.

Conversely, for volumetric flow ratios of 0.14-0.33, the flow approaches steady state, (Figure 39, Figure 40, Figure 40, Figure 41, and Figure 42). In these images, (a) gives the 2x view, and (b) gives the 4x view. For all of the bubble values (d-f) in the steady state range, the histograms show a tight interval around 1 with about a width of about 20% (±10%). All of these graphs show a prominent peak around 1. All values deviate less than 7% of the corresponding averages. In addition to the bubbles, a steady plug flow is also noted (g-i). The plots are typically tightly packed around 1. However, there appears to be a little more variation than the bubbles (the histogram peaks are a little wider). This may indicate a slight slipping of the some bubbles through the channel.
Figure 37: AR1 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.5, Bubble Count= 346, Plug Count=111 (Histograms are characterized by the average value)
The Bubble/Plug Ratio histograms display that the area, perimeter, and Y length for the bubbles is greater than the values for the plugs. Also, as the gas flow rate increases, the bubble values increase (bigger bubbles) greater than the plugs. It is interesting to note that as the bubbles get bigger, the plugs get smaller. This is intuitive because the gas flow rate is increasing as the liquid flow rate remains constant.

In Figure 43, at a beta ratio of 0.11, the flow enters an unstable bubble regime where histogram peaks begin to broaden. In (a) the 2x view, some of the bubbles are significantly larger than the others. The bubble histograms (d-e) reflect this size difference with the about a 25% standard deviation in the area and perimeter. This unsteady bubble regime also influences the liquid plug flow (g-i). However, it is not drastically affected because areas, perimeters, and Y lengths are only slightly greater that the plug flow for Beta=0.18. Although the plug characteristics remain relatively unchanged, the variable bubble lengths cause a broadening in the Bubble/Plug Ratio histogram(j-l).

**Liquid Flow Rate=0.10 ml/min**

At this set liquid flow rate, the flow did not reach stability at all, which is shown by Figure 44, Figure 45, and Figure 46. In these figures, (2) represents a 2x image while (b) displays a 4x image. The bubble histograms are shown in (d-f); the plug histograms shown in (g-i), and the Bubble/Plug Ratio histograms in (j-l). For all of the values in both bubble and plug cases, the flow varies with standard deviations around 50% for the bubble areas, 25% for the bubble perimeters, and 30% for the bubble Y lengths. For the plug flows, the area varies about 50%, the perimeters about 30%, and the Y lengths about 50%.
Figure 38: AR1 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.33, Bubble Count= 1147, Plug Count= 1054 (All histograms are characterized by the average value)
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<th>Bubble Y Length (µm)</th>
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</tr>
</tbody>
</table>

Figure 39: AR1 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.15 ml/min, Beta=0.25, Bubble Count= 1053, Plug Count= 979 (All histograms characterized by the average value)
Figure 40: AR1 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.20, Bubble Count=1058, Plug Count=1000 (All histograms characterized by the average value)
### Statistic Data

<table>
<thead>
<tr>
<th></th>
<th>Bubble Area ($\mu m^2$)</th>
<th>Bubble Perimeter ($\mu m$)</th>
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<th>Plug Area ($\mu m^2$)</th>
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<td>1235</td>
<td>445</td>
<td>15,000</td>
<td>930</td>
<td>180</td>
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<tr>
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<td>68</td>
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<td>2800</td>
<td>110</td>
<td>52</td>
</tr>
<tr>
<td>90% CI</td>
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<td>112</td>
<td>46</td>
<td>4700</td>
<td>190</td>
<td>86</td>
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<tr>
<td>95% CI</td>
<td>10,440</td>
<td>134</td>
<td>54</td>
<td>5600</td>
<td>220</td>
<td>103</td>
</tr>
</tbody>
</table>

Figure 41: AR1 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.25 ml/min, Beta=0.18, Bubble Count=1225, Plug Count=1179 (All histograms characterized by the average value)
Figure 42: AR1 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.30 ml/min, Beta=0.14, Bubble Count=649, Plug Count=772 (All histograms characterized by the average value)
Figure 43: AR1 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.40 ml/min, Beta=0.11, Bubble Count=552, Plug Count=711 (All histograms characterized by the average value)
Figure 44: AR1 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.70, Bubble Count=357, Plug Count=33 (All histograms characterized by the average value)
Figure 45: AR1 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.33, Bubble Count=583, Plug Count=130 (All histograms characterized by the average value)
Figure 46: AR1 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.50 ml/min, Beta=0.18, Bubble Count=666, Plug Count=187 (All histograms characterized by the average value)
This instability of the flow depends upon the liquid velocity, not the time. For these 0.10 ml/min tests, the flow rates for gas and liquid remained constant, although a steady bubble/plug flow was not achieved. Even at lower velocities for AR1, stability is hard to reach; the flow takes a while (sometimes as much as 20 minutes) to obtain steady state. Then, at a higher liquid velocity, this flow has more energy, so stability is not possible. In some of the cases for the 0.1 ml/min liquid flow rate, the flow was allowed an hour to steady, but stability was never reached.

3.3.3.2 Pressure Ports

**Liquid Flow Rate=0.05 ml/min**

Like the microchip without pressure ports, this channel reached steady flow at the range of 0.2-0.33 (Figure 48, Figure 49, and Figure 50). Unsteady flows occurred at Beta=0.50 (Figure 47), Beta=0.14 (Figure 52), and a steady/unsteady transition at Beta=0.18 (Figure 51). In these figures, (a) refers to the 2x view; (b) refers to the 4x view; (d-f) refer to the bubble values; (g-i) refer to the plug values; and (j-l) refer to the Bubble/Plug Ratio histograms. Like the microchip without pressure ports, this one has small standard deviations for the average area, average perimeter, and average bubble length for the steady state bubble regime. However, the stability range for this channel is slightly smaller than the non-pressure port channel. The presence of the ports may create this variation, but it is more likely that these small differences occur from microchip to microchip (caused by slight differences in the polymer or in the machining processes).

For the unsteady bubble flow in flow ratio=0.50 (Figure 47), all the bubble values (area, perimeter, and Y length) and the plug values (area, perimeter, and Y length) vary at
about 50% from the average. The bubbles start out small and begin to coalesce as they flow down the channel. Because of this unsteady bubble behavior, the plug values also vary greatly. These variations are shown in histograms (d-l). These have broad peaks not centered around 1, the average value.

For the steady flows of Beta=0.20 to 0.30, the bubble variations for the area, perimeter, and Y length are less than 4% of the average (d-f). However, the plug variations in area, perimeter, and Y length are all about 20% (g-i). This stays constant for the steady range; it does not change as the gas flow rate increases. Because the flow is regular, this 20% standard deviation probably results from some of the bubbles sliding through the channel. Although the bubbles are all around the same size, the size of the liquid plug between them would be larger in sections where the bubbles are spaced apart and smaller where the bubbles are closer together.

As the gas flow rate increases to 0.25 ml/min, the steady bubble flow breaks down. The standard deviation in the bubble area, perimeter, and Y length increases to about 20% (d-f), and the standard deviation in the plug characteristics increases to 50% (g-i). All of these changes are reflected in the Bubble/Plug Ratio histogram (j-l). Finally, as the gas flow rate increases to 0.30 ml/min (Figure 52), the values for the bubble and plug further increase.

Although the pressure ports do not appear to affect the flow regime, these microchips produce a smaller bubble than the non-pressure port microchip. For instance, at a flow ratio of 0.25, the non-pressure port chip has an average area of about 72,000 square microns, an average perimeter of 1200 microns, and an average length of 455 microns, and the pressure port chip has a average area of about 50,000 square microns, an
average perimeter of 945 microns, and an average length of 323 microns. Therefore, the pressure port microchannel bubbles are about 70% of the non-pressure port counterpart microchannel. This difference in size could be caused by the pressure ports; however, when comparing the values for the plugs, the sizes are very close to one another (indicates no leakage). For instance at AR1 no pressure ports at Beta=0.25, the area average is 27,000 square microns, the perimeter is 1030 square microns, and the Y length is 245 microns. For the pressure port version, the area is 31,250 square microns, perimeter is 1130 microns, and the Y length is 303 microns. Because of the similarity in plug characteristics for the pressure port and non-pressure port, there is no evidence of fluid leakage into the lateral pressure channels.

**Liquid Flow Rate=0.1 ml/min**

As in the high liquid flow rate case of the non-pressure port channels, the high liquid flow rate pressure port channels do not reach stability (Figure 53, Figure 54, and Figure 55), regardless of the time allotted for flow development (up to 1 hour). The following tables on these figures show the average area, average perimeter, average bubble length, and the corresponding standard deviations.

This table shows that the standard deviations of the area, perimeter, and length are high—as much as 50%. This unsteady bubble flow agrees with the unsteady flow in the non-pressure port microchip. Also, as with the data from the low liquid flow rate of 0.05 ml/min, the bubbles in the high liquid flow pressure port microchips are smaller than the non-pressure port microchip. For instance at a flow ratio of 0.33, the non-pressure port average area, average perimeter, and average length are 72,700 square microns, 1218 microns, and 463 microns, respectively. In addition the plugs have an average area of
Figure 47: AR1 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.50, Bubble Count=803, Plug Count=672 (All histograms characterized by the average value)
Figure 48: AR1 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.33, Bubble Count=1486, Plug Count=1310 (All histogram characterized by average values)
### Table 1: Summary of Image Data

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<tr>
<th>Statistic</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
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<td>8950</td>
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<td>154</td>
</tr>
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<td>95% CI</td>
<td>2750</td>
<td>55</td>
<td>16</td>
<td>10,665</td>
<td>480</td>
<td>184</td>
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</tbody>
</table>

Figure 49: AR1 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.15 ml/min, Beta=0.25, Bubble Count=1206, Plug Count=1297 (All histograms characterized by the average value)
### Figure 50: AR1 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.20, Bubble Count=959, Plug Count=1201 (All histograms characterized by average value)

<table>
<thead>
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<th>Statistic Data</th>
<th>Bubble Area ($\mu m^2$)</th>
<th>Bubble Perimeter ($\mu m$)</th>
<th>Bubble Y Length ($\mu m$)</th>
<th>Plug Area ($\mu m^2$)</th>
<th>Plug Perimeter ($\mu m$)</th>
<th>Plug Y Length ($\mu m^2$)</th>
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<tr>
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<td>49</td>
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<td>81</td>
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<td>74</td>
<td>25</td>
<td>7859</td>
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<td>87</td>
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<td>9360</td>
<td>379</td>
<td>160</td>
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</table>
Table 1: Statistical Data

<table>
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<tr>
<th>Statistic</th>
<th>Bubble Area (μm²)</th>
<th>Bubble Perimeter (μm)</th>
<th>Bubble Y Length (μm)</th>
<th>Plug Area (μm²)</th>
<th>Plug Perimeter (μm)</th>
<th>Plug Y Length (μm)</th>
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<tr>
<td>Average</td>
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<td>12,000</td>
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<td>120</td>
</tr>
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<td>90% CI</td>
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<td>19,800</td>
<td>480</td>
<td>201</td>
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<tr>
<td>95% CI</td>
<td>28,650</td>
<td>380</td>
<td>170</td>
<td>23,600</td>
<td>570</td>
<td>240</td>
</tr>
</tbody>
</table>

Figure 51: AR1 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.25 ml/min, Beta=0.18, Bubble Count=959, Plug Count=1140 (All histograms characterized by the average value)
Figure 52: AR1 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.30 ml/min, Beta=0.14, Bubble Count=761, Plug Count=989 (All histograms characterized by the average value)
65,900 square microns, an average perimeter of 1500 microns, and an average Y length of 470 microns. Conversely, the pressure port microchannel has an average area of 58,730 square microns, 1070 microns, and 383 microns. Also, the liquid plugs have an average area of 54,100 square microns, an average perimeter of 1410 microns, and an average Y length of 448 microns. Therefore, the bubbles in the pressure port are about 80% of the bubbles in the non-pressure port microchannels. Whereas, the plugs in the pressure port channel are only slightly larger (about 10% area-wise) than the ones in the non-pressure port chip. The perimeter and Y length of the plugs are about the same. Thus, the bubbles changed from non-pressure port to pressure port channel, but the liquid plugs remained about the same.

Figure 53, Figure 54, and Figure 55 are the histograms of the area, perimeter, and bubble length (d-f) at particular flow ratios. As the flow ratio decreases, the bubbles get larger. All flow ratios have a high standard deviation, thus, none are steady. In addition, at these flow ratios, the liquid plugs are also unsteady (g-i). The instability of the bubble and plug also shows in the Bubble/Plug Ratio histograms (j-l).

3.3.4 Aspect Ratio Two Microchannels

Similar to the aspect ratio one microchannels, the average area, average perimeter, and average length were also extracted from the taken images.

3.3.4.1 No Pressure Ports

Liquid Flow Rate=0.05 ml/min

This microchannel reaches stability relatively quickly, about 1 minute, and the stable volumetric flow ratio range is 0.09-0.33 (Figure 57, Figure 58, Figure 59, Figure 60, Figure 61, Figure 62, and Figure 63). The flow is unsteady at a flow ratio of 0.50 and
### Figure 53: AR1 Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.50, Bubble Count=309, Plug Count=150 (All histograms characterized by the average value)

<table>
<thead>
<tr>
<th>Statistic Data</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>53,800</td>
<td>1000</td>
<td>354</td>
<td>99,000</td>
<td>1900</td>
<td>710</td>
</tr>
<tr>
<td>StanDev</td>
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<td>301</td>
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<td>56,300</td>
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<td>330</td>
</tr>
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<td>40,500</td>
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<td>233</td>
<td>92,600</td>
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<td>277</td>
<td>110,300</td>
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<td>647</td>
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</tbody>
</table>
Figure 54: AR1 Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.33, Bubble Count=579, Plug Count=400 (All histograms characterized by the average value)
Figure 55: AR1 Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.30 ml/min, Beta=0.25, Bubble Count= 668, Plug Count= 337 (All histograms characterized by the average value)
0.07 (Figure 56 and Figure 64). These figures also show the histograms of the average velocity, average perimeter, average length, standard deviations, and a 90% and 95% confidence interval.

At volumetric flow ratio of 0.5, the flow is unsteady with a high standard deviation in the size (about 50%). The bubble histograms (d-f) show characteristic values ranging from 0.5 to 2.5, and these values are not centered 1. The plug histograms (g-i) also indicate unsteady flow because the histograms range from 0 to 2.5 for the characteristic values; they also are not centered 1. Thus, because both bubble and plug vary, the Bubble/Plug Ratio histograms (j-l) do not have a narrow peak.

The standard deviation for the flow ratios of 0.33 and 0.25 (Figure 57 and Figure 58) is high, but after inspecting the histograms, stability is thrown off by a few bubbles that lie outside the size distribution of most of the flow. These flows are still considered steady because only four bubbles of about 1000 lie outside the range. As in AR1 microchannels, the liquid plugs are not as steady as the bubbles. Plug histograms (g-i) all have narrow peaks, but they are wider than the bubble counterparts. As before, this variation may occur from bubbles slipping in the microchannel.

The flow ratios of 0.20 to 0.07 (Figure 59, Figure 60, Figure 61, Figure 62, and Figure 63) show steady flows because the standard deviations are relatively low (vary about 10% for the bubbles). These bubble histograms (d-f) are all tightly packed around 1. As with the other cases, the liquid plugs generally remain the same size as the gas flow rate increases. These have the same fluctuations as in the other cases (around 20% standard deviations), however, they are all centered around 1. The Bubble/Plug Ratio
histograms (j-l) reflect the size variations in the bubbles and plugs. As the gas flow rate increases, the Bubble/Plug Ratio peak width increases.

As the gas flow rate further increases to 0.60 ml/min, the flow departs steady flow. The bubble standard deviations of the area, perimeter, and Y length vary about 25%. The bubble histograms (d-f) show a broadened peak, ranging from 0.2 to 1.4. The liquid plug standard deviations for the area, perimeter, and Y length vary about 50%; these histograms (g-i) also show a broadened peak from 0.5 to 1.5. Finally, considering the histograms for the bubbles and plugs, the Bubble/Plug Ratio histograms (j-l) are display widened widths.

**Liquid Flow Rate=0.1 ml/min**

High liquid flow tests were also performed on the aspect ratio two microchips. However, unlike the aspect ratio one channels, these channels had stability for a range of 0.4 to 0.7.

Figure 65, Figure 66, Figure 67, Figure 68, Figure 69, and Figure 70 show the histograms of the average area, average perimeter, and average bubble length, and they include the standard deviation, 90% and 95% confidence intervals. In these figures, (a) represents the 2x view; (b) represents the 4x view.

AR2 no pressure port high flow has a stability range of 0.70 to 0.40 (Figure 65, Figure 66, and Figure 67). Throughout this flow range, the bubbles have a maximum standard deviation of about 11%. All of the bubbles in flow ratio 0.7 falls within a close range (3%) around the average. The standard deviations for flow ratios 0.4 and 0.5 are broader than 0.7, but this is due to one or two bubbles lying outside the narrow range of
Figure 56: AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.50, Bubble Count= 526, Plug Count= 506 (All histograms characterized by the average value)
<table>
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<th>Statistic Data</th>
<th>Bubble Area ($\mu m^2$)</th>
<th>Bubble Perimeter ($\mu m$)</th>
<th>Bubble Y Length ($\mu m$)</th>
<th>Plug Area ($\mu m^2$)</th>
<th>Plug Perimeter ($\mu m$)</th>
<th>Plug Y Length ($\mu m$)</th>
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</thead>
<tbody>
<tr>
<td>Average</td>
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<td>1025</td>
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<td>29,900</td>
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</tr>
<tr>
<td>StanDev</td>
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<td>16,300</td>
<td>233</td>
<td>113</td>
</tr>
<tr>
<td>90% CI</td>
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<td>136</td>
<td>26,800</td>
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<tr>
<td>95% CI</td>
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<td>331</td>
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<td>32,000</td>
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<td>222</td>
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</table>

Figure 57: AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.33, Bubble Count= 1059, Plug Count= 1354  (All histograms characterized by the average value)
Figure 58: AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.15 ml/min, Beta=0.25, Bubble Count=1268, Plug Count=1563 (All histograms characterized by the average value)
<table>
<thead>
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<th>Statistic Data</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
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</tr>
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<td>4700</td>
<td>91</td>
<td>37</td>
</tr>
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<td>9260</td>
<td>170</td>
<td>72</td>
</tr>
</tbody>
</table>

Figure 59: AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.20, Bubble Count= 903, Plug Count= 1287 (All histograms characterized by the average value)
Figure 60: AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.25 ml/min, Beta=0.18, Bubble Count= 815, Plug Count= 1053 (All histograms characterized by the average value)
Figure 61: AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.30 ml/min, Beta=0.14, Bubble Count=1119, Plug Count=1136  (All histograms characterized by the average value)
Figure 62: AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.40 ml/min, Beta=0.11, Bubble Count= 827, Plug Count= 844 (All histograms characterized by the average value)
### Statistic Data

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
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<td>16,600</td>
<td>794</td>
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<td>210</td>
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<td>4610</td>
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<td>36</td>
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<td>59</td>
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<td>25,550</td>
<td>411</td>
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<td>70</td>
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</tbody>
</table>

**Figure 63:** AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.50 ml/min, Beta=0.09, Bubble Count= 523, Plug Count= 781 (All histograms characterized by the average value)
Figure 64: AR2 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rates=0.60 ml/min, Beta=0.07, Bubble Count= 455, Plug Count= 442 (All histograms characterized by the average value)
the area, perimeter, and bubble length of the majority of the bubbles. This can be seen in the bubble histograms (d-f).

For the Beta =0.7 liquid plugs, the standard deviation of the area is high about 50%. However, as the gas flow rate increases, to 0.15 ml/min, the plug standard deviation drops to about 10%. Regardless of the plug standard deviations, the plugs are centered around 1 in the histograms (g-i). As the gas flow rate further increases above 0.15 ml/min, the size range of the bubbles and plugs increases, causing an unpredictable slug flow.

3.3.4.2 Pressure Ports

Liquid Flow Rate=0.05 ml/min

Experiments were also performed on and aspect ratio two chip with pressure ports (Figure 71, Figure 72, Figure 73, Figure 74, Figure 75, and Figure 76). These figures include histograms of the average area, average perimeter, and average bubble length. They also include standard deviations, 90% and 95% confidence intervals. The stability range (0.14-0.33) for this microchannel is slightly smaller then the non-pressure port AR2 microchip.

At the volumetric flow ratio of 0.5 the flow is unsteady with a high (about 50%) standard deviation in the bubbles. Similarly, the plug standard deviation is also high (about 50%) for the average, perimeter, and Y length. The broad histograms (d-i) for the bubbles and plugs are not centered at the average value, 1.
When the flow ratio decreases to 0.33, the flow becomes stable with a low standard deviation (shown in Figure 72 (d-i)). These plots of the bubble histograms are tightly packed around 1 ±10%. The plots of the plug histograms have a similar shape, but these plots have a wider peak. This steady-state behavior continues as the volumetric flow ratio decreases to 0.14. At this value, the flow appears to transition to an unstable regime, signified by the broadened histogram plots and the increased standard deviation.

In comparison to the AR2 non-pressure port channels, the pressure port channel produces a slightly smaller bubble size. For example at a flow ratio of 0.20, the non-pressure port microchip has an average area of 72,000 square microns, an average perimeter of 1300 microns, and an average bubble length of 515 microns. Furthermore for the plug, the average area, perimeter, and Y length are 18,000 square microns, 775 microns, and 181 microns, respectively. For the pressure port microchip, the average area is 68,000 square microns; the average perimeter is 1400 microns, and the average bubble length is 513 microns. In addition for the plug, the average area, perimeter, and Y length are 18,750 square microns, 898 microns, and 211 microns, respectively. Thus, for the aspect ratio two microchannels, the bubbles in the pressure port chips were just a minute amount smaller than the ones in the non-pressure port chips while the plug flow between the two cases is almost the same value. This was different for the bubbles in the aspect ratio one case. In this experiment, the bubbles in the pressure port channel were about 70% the size of the non-pressure port channel.
Figure 65: AR2 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.70, Bubble Count= 390, Plug Count= 314 (All histograms characterized by the average value)
Figure 66: AR2 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.50, Bubble Count=367, Plug Count=335 (All histograms characterized by the average value)
Figure 67: AR2 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.15 ml/min, Beta=0.40, Bubble Count= 410, Plug Count= 348 (All histograms characterized by the average value)
Figure 68: AR2 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.33, Bubble Count= 463, Plug Count= 512 (All histograms characterized by the average value)
<table>
<thead>
<tr>
<th>Statistic Data</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>89,950</td>
<td>1652</td>
<td>647</td>
<td>77,500</td>
<td>1747</td>
<td>624</td>
</tr>
<tr>
<td>StanDev</td>
<td>14,340</td>
<td>224</td>
<td>97</td>
<td>11,800</td>
<td>233</td>
<td>92</td>
</tr>
<tr>
<td>90% CI</td>
<td>23,580</td>
<td>369</td>
<td>160</td>
<td>19,500</td>
<td>383</td>
<td>151</td>
</tr>
<tr>
<td>95%CI</td>
<td>28,100</td>
<td>440</td>
<td>191</td>
<td>23,230</td>
<td>457</td>
<td>180</td>
</tr>
</tbody>
</table>

Figure 69: AR2 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.25 ml/min, Beta=0.28, Bubble Count= 428, Plug Count= 463 (All histograms characterized by the average value)
Figure 70: AR2 No Pressure Port, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.30 ml/min, Beta=0.25, Bubble Count= 518, Plug Count= 707 (All histograms characterized by the average value)
Liquid Flow Rate=0.1 ml/min

An experiment was also performed on the pressure port AR2 microchannels at a constant liquid flow rate of 0.1 ml/min (Figure 77, Figure 78, and Figure 79). Unlike the non-pressure port aspect ratio two channel, the stability range is smaller—0.5-0.7. The flow is unsteady beneath this ratio. Figure 78 and Figure 79 show the histograms of the area, perimeter, Y length. In addition to these values, they also show the standard deviation, 90% and 95% confidence, respectively), the bubble histograms (d-f) show a tight distribution around the average value 1 (with a 3% standard deviation). Plug histograms (g-i) mimic this shape, but have a wider distribution around 1 (with a 15% standard deviation). The Bubble/Plug Ratio broadened histograms (j-l) exemplify the bubbles’ tight distribution and the plugs’ wide distribution. As the gas flow rate increases to 0.15 ml/min (Figure 79), the standard deviation for the bubbles and plugs increase as the flow’s stability breaks down.

In AR2 non-pressure ports at Beta=0.50, the average bubble area, perimeter, and Y length are 84,530 square microns, 1560 microns, and 609 microns, respectively. In addition, the average plug area, perimeter, and Y length are 110,000 square microns, 2250 microns, and 866 microns. In AR2 pressure ports at Beta=0.50, the average bubble area, perimeter, and Y length are 43,250 square microns, 1020 microns, and 356 microns, respectively. The average plug area, perimeter, and Y length are 82,390 square microns, 1867 microns, and 661 microns, respectively. The bubbles in AR2 non-pressure port are almost twice the size of the comparable flow in the pressure ported channel. In addition, the plugs are also about 25% larger in the non-pressure ported channels. This
Figure 71: AR2 Pressure Port, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.50, Bubble Count= 730, Plug Count= 475 (All histograms characterized by the average value)
Figure 72: AR2 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.33, Bubble Count=1034, Plug Count=818 (All histograms characterized by the average value)
Figure 73: AR2 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.20, Bubble Count= 944, Plug Count= 971 (All histograms characterized by the average value)
Table 74: AR2 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.30 ml/min, Beta=0.14, Bubble Count= 499, Plug Count= 693 (All histograms characterized by the average value)
<table>
<thead>
<tr>
<th>Statistic Data</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>105,000</td>
<td>2020</td>
<td>770</td>
<td>17,670</td>
<td>909</td>
<td>202</td>
</tr>
<tr>
<td>StanDev</td>
<td>22,620</td>
<td>370</td>
<td>158</td>
<td>5110</td>
<td>117</td>
<td>47</td>
</tr>
<tr>
<td>90% CI</td>
<td>32,210</td>
<td>608</td>
<td>261</td>
<td>8400</td>
<td>192</td>
<td>77</td>
</tr>
<tr>
<td>95% CI</td>
<td>44,340</td>
<td>725</td>
<td>311</td>
<td>10,000</td>
<td>229</td>
<td>91</td>
</tr>
</tbody>
</table>

Figure 75: AR2 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.40 ml/min, Beta=0.11, Bubble Count=434, Plug Count=621 (All histograms characterized by the average value)
Figure 76: AR2 Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.50 ml/min, Beta=0.09, Bubble Count=340, Plug Count=540 (All histograms characterized by the average value)
discrepancy is fairly large, the presence of the pressure ports probably would not contribute to this large of a difference. Perhaps, the flow was not completely settled in the AR2 pressure port channel.

3.3.5 Aspect Ratio 3 Microchannels

Liquid Flow Rate=0.05 ml/min

At this constant liquid flow rate, AR3 microchannels have a steady-state range from 0.50 to 0.20. As with the AR2 channels, the steady state almost appeared instantly after the flow rates were adjusted into this steady state range. However, based on the Rhodamine B dye experiment, these bubbles do not always fill the channel completely. Thus, if a fully-channel filling bubble is desired for the flow, this channel should not be used.

Figure 80, Figure 81, Figure 82, and Figure 83 show the steady flow range (0.50 to 0.20) of the AR3 microchannels. For all of the volumetric flow ratios in this steady regime, both the bubble and plug histograms (d-f) show a very tight distribution (± 5%) centered around 1. The AR3 plug behavior differs from the plugs in AR1 and AR2. For instance, in the AR3 channels, the plugs have a very tight standard distribution (less then 5%); whereas, in AR1 and AR2, the plugs had a standard distribution of about 20%.

As the gas flow rate increases to 0.25 ml/min (Figure 84), the flow departs steady-state. The standard deviations of the bubbles and plugs are about 50%. In addition, the wide histograms (d-i) are not centered at 1.
<table>
<thead>
<tr>
<th>Statistic Data</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>33,470</td>
<td>832</td>
<td>281</td>
<td>102,000</td>
<td>2150</td>
<td>798</td>
</tr>
<tr>
<td>StanDev</td>
<td>770</td>
<td>26</td>
<td>5</td>
<td>17,440</td>
<td>263</td>
<td>121</td>
</tr>
<tr>
<td>90% CI</td>
<td>1265</td>
<td>43</td>
<td>7</td>
<td>28,690</td>
<td>434</td>
<td>198</td>
</tr>
<tr>
<td>95%CI</td>
<td>1507</td>
<td>52</td>
<td>9</td>
<td>34,170</td>
<td>517</td>
<td>236</td>
</tr>
</tbody>
</table>

Figure 77: AR2 Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.70, Bubble Count=390, Plug Count=460 (All histograms characterized by the average values)
<table>
<thead>
<tr>
<th>Statistic Data</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>43,280</td>
<td>1020</td>
<td>356</td>
<td>82,390</td>
<td>1867</td>
<td>661</td>
</tr>
<tr>
<td>StanDev</td>
<td>990</td>
<td>40</td>
<td>6</td>
<td>11,160</td>
<td>173</td>
<td>76</td>
</tr>
<tr>
<td>90% CI</td>
<td>1635</td>
<td>66</td>
<td>10</td>
<td>18,360</td>
<td>285</td>
<td>125</td>
</tr>
<tr>
<td>95% CI</td>
<td>1950</td>
<td>78</td>
<td>13</td>
<td>21,900</td>
<td>339</td>
<td>150</td>
</tr>
</tbody>
</table>

Figure 78: AR2 Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.50, Bubble Count=367, Plug Count=578 (All histograms characterized by the average values)
Figure 79: AR2 Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.15 ml/min, Beta=0.40, Bubble Count= 410, Plug Count= 643 (All histograms characterized by the average value)
Liquid Flow Rate=0.10 ml/min

Figure 85, Figure 86, and Figure 87 show a steady-state distribution (Beta=0.70 to 0.40) for high flow AR3 channels. Similarly to the AR3 low flow channels, the bubble and plug histograms (d-i) have a close distribution (± 5%) around the average value of 1. In addition, the corresponding Bubble/Plug Ratio histograms are show (j-l). As the volumetric flow ratio decreases to 0.33 (Figure 88), the steady-state flow breaks down. This is evident from the broad histograms (d-i) and standard deviations.

3.3.6 Pressure Measurements

The pressure measurements are essential in determining the flow conditions. These channels were designed to give the same pressure drop, regardless of the aspect ratio, because the hydraulic diameter was conserved. However, this is before channels were thermally bond to cover slips. During the bonding process, the channel dimensions can change because the channel is heated above the glass transition temperature. Although these channels were designed to have the same pressure drop, the actual measured pressure drop did not exactly match among the channels. The pressure drop in the aspect ratio one channel was a little greater than the pressure drop across the aspect ratio two channels (Figure 89). For aspect ratio one, the high liquid flow rate information for annular flow was not captured because the microchannel could not sustain both a high liquid and gas flow within the pressure limits of 100 PSIG. Figure 89 also shows the flow regimes that occur when the pressure changes take place. The highest pressure drops in the microchannel occur during the irregular slug and annular flow regimes.
Figure 80: AR3 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.50, Bubble Count=490, Plug Count=110 (All histograms are characterized by the average value)
Figure 81: AR3 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.33, Bubble Count= 389, Plug Count= 134 (All histograms are characterized by the average value)
Figure 82: AR3 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.15 ml/min, Beta=0.25, Bubble Count=230, Plug Count=129 (All histograms are characterized by the average value)
<table>
<thead>
<tr>
<th>Statistic</th>
<th>Bubble Area ($\mu m^2$)</th>
<th>Bubble Perimeter ($\mu m$)</th>
<th>Bubble Y Length ($\mu m$)</th>
<th>Plug Area ($\mu m^2$)</th>
<th>Plug Perimeter ($\mu m$)</th>
<th>Plug Y Length ($\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>102,000</td>
<td>2206</td>
<td>921</td>
<td>46,000</td>
<td>1316</td>
<td>510</td>
</tr>
<tr>
<td>StanDev</td>
<td>1800</td>
<td>62</td>
<td>16</td>
<td>770</td>
<td>34</td>
<td>12</td>
</tr>
<tr>
<td>90% CI</td>
<td>2961</td>
<td>101</td>
<td>26</td>
<td>1270</td>
<td>56</td>
<td>19</td>
</tr>
<tr>
<td>95% CI</td>
<td>3530</td>
<td>121</td>
<td>31</td>
<td>1510</td>
<td>67</td>
<td>23</td>
</tr>
</tbody>
</table>

Figure 83: AR3 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.20, Bubble Count=350, Plug Count=184 (All histograms are characterized by the average value)
<table>
<thead>
<tr>
<th>Statistic Data</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>75,450</td>
<td>1700</td>
<td>695</td>
<td>36,700</td>
<td>1150</td>
<td>429</td>
</tr>
<tr>
<td>StanDev</td>
<td>42,440</td>
<td>825</td>
<td>370</td>
<td>18,700</td>
<td>323</td>
<td>160</td>
</tr>
<tr>
<td>90% CI</td>
<td>69,820</td>
<td>1358</td>
<td>610</td>
<td>30,750</td>
<td>532</td>
<td>263</td>
</tr>
<tr>
<td>95% CI</td>
<td>83,190</td>
<td>1618</td>
<td>727</td>
<td>36,640</td>
<td>634</td>
<td>313</td>
</tr>
</tbody>
</table>

Figure 84: AR3 No Pressure Ports, Liquid Flow Rate=0.05 ml/min, Gas Flow Rate=0.25 ml/min, Beta=0.18, Bubble Count= 344, Plug Count= 211 (All histograms are characterized by the average value)
Figure 85: AR3 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.05 ml/min, Beta=0.70, Bubble Count= 410, Plug Count= 41 (All histograms are characterized by the average value)
Figure 86: AR3 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.10 ml/min, Beta=0.50, Bubble Count= 500, Plug Count= 185 (All histograms are characterized by the average value)
<table>
<thead>
<tr>
<th><strong>Statistic Data</strong></th>
<th><strong>Bubble Area (µm²)</strong></th>
<th><strong>Bubble Perimeter (µm)</strong></th>
<th><strong>Bubble Y Length (µm)</strong></th>
<th><strong>Plug Area (µm²)</strong></th>
<th><strong>Plug Perimeter (µm)</strong></th>
<th><strong>Plug Y Length (µm)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>58,282</td>
<td>1396</td>
<td>568</td>
<td>83,840</td>
<td>2001</td>
<td>843</td>
</tr>
<tr>
<td>StanDev</td>
<td>2280</td>
<td>60</td>
<td>21</td>
<td>5470</td>
<td>119</td>
<td>51</td>
</tr>
<tr>
<td>90% CI</td>
<td>3756</td>
<td>98</td>
<td>34</td>
<td>9000</td>
<td>195</td>
<td>84</td>
</tr>
<tr>
<td>95% CI</td>
<td>4475</td>
<td>117</td>
<td>40</td>
<td>10,722</td>
<td>233</td>
<td>99</td>
</tr>
</tbody>
</table>

Figure 87: AR3 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.15 ml/min, Beta=0.40, Bubble Count= 515, Plug Count= 278 (All histograms are characterized by the average value)
Figure 88: AR3 No Pressure Ports, Liquid Flow Rate=0.10 ml/min, Gas Flow Rate=0.20 ml/min, Beta=0.33, Bubble Count=519, Plug Count=341 (All histograms are characterized by the average value)

<table>
<thead>
<tr>
<th>Statistic Data</th>
<th>Bubble Area (µm²)</th>
<th>Bubble Perimeter (µm)</th>
<th>Bubble Y Length (µm)</th>
<th>Plug Area (µm²)</th>
<th>Plug Perimeter (µm)</th>
<th>Plug Y Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>62,230</td>
<td>1480</td>
<td>603</td>
<td>66,440</td>
<td>1691</td>
<td>687</td>
</tr>
<tr>
<td>StanDev</td>
<td>17,060</td>
<td>350</td>
<td>157</td>
<td>20,000</td>
<td>362</td>
<td>179</td>
</tr>
<tr>
<td>90% CI</td>
<td>28,070</td>
<td>574</td>
<td>260</td>
<td>32,900</td>
<td>595</td>
<td>295</td>
</tr>
<tr>
<td>95% CI</td>
<td>33,440</td>
<td>684</td>
<td>300</td>
<td>39,200</td>
<td>709</td>
<td>351</td>
</tr>
</tbody>
</table>
Once the pressure start dropping between the irregular slug and regular slug, the flow enters the steady flow region.

**Figure 89: Pressure Drop Measurement as Function of Capillary Number**
Chapter 4: Laser Illumination Technique

4.1 Background

Because the CCD camera has its frame rate limitations, it cannot be used to extract velocities of the bubbles, which requires two successive images of the same bubble. The maximum attainable frame rate is 46 Hz; thus, one image is taken approximately every 0.02 seconds. For bubbles that have expected velocities of about 0.5 m/s (based on Equation 7), this rate is not sufficient.

\[ V_B = J_G + J_L \]

\[ V_B = \text{Velocity of Bubble} \]

\[ J_G = \text{Superficial Gas Velocity} \]

\[ J_L = \text{Superficial Liquid Velocity} \]

Equation 7: Projected Bubble Velocity

For instance, if the bubbles move at 0.5 m/s, then every 0.02 seconds the bubble moves about 10 mm, and this distance is about the length of the entire test section. Therefore, since no available objective captures the entire test section, it is impossible to catch successive images of the same bubble with this continuous frame rate.

Although the continuous frame rate of the camera is too low, the camera also operates in a triggered double exposure mode, which has an inter-frame time as low as 200 nanoseconds. Therefore, at this time interval, a bubble moving at 0.5 m/s will move about 0.1 microns. Thus, in combination with a pulsed two-headed laser, it is possible to determine velocities.

Figure 90 shows a schematic of how the camera and two laser heads work together. Also, in a collection of the recorded images, the odd-numbered images have laser 1 as the illumination source, and the even numbered images have laser 2 as the
illumination source. Although, this is called a “triggered double exposure mode”, each captured image is separate and distinct.

### 4.2 Image Processing

In order to extract the velocities of the bubbles, one requires two successive images of the same bubble.

![Figure 90: Schematic of the Laser Illumination Setup](image)

**Figure 90: Schematic of the Laser Illumination Setup**

From these images, the image processing program, OPTIMAS reduces the coordinates of the centroid, maximum, and minimum points of the bubble in each frame. Assuming that acceleration remains constant during the time interval between the captured images, Equation 8 calculates the bubble velocity.

![Figure 91: Two Successive Raw Velocity Images](image)

**Figure 91: Two Successive Raw Velocity Images**
\[ V_B = \frac{d}{t} \]

where

\begin{align*}
    d &= \text{distance the bubble moves} \\
    t &= \text{time of bubble motion}
\end{align*}

**Equation 8: Bubble Velocity, Assuming Constant Acceleration**

Therefore, an OPTIMAS macro was written to calculate the velocities. This laser illumination method uses the pulses of two laser heads, and although the Q-switch delays (definition of) are set the same, the images look a little different. Thus, two clearfields are required, and the program was written to divide the laser 1 illuminated images by the first clearfield, and the laser 2 images by the second clearfield. After the bubbles in the images are isolated, the colors are inverted, and the bubbles are filled, as the bubble characteristics macro. When the bubble alterations are complete, the macro then extracts the coordinates of the centroid, maximum, and minimum point of the bubble. With knowledge of the positions and time interval between the images, the velocities are calculated based on Equation 8.

### 4.3 Experimental Results

#### 4.3.1 Bubble Velocity vs. Volumetric Flow Ratio

Figure 92 and Figure 93 show the velocity distribution of the centroid versus the volumetric flow ratio for aspect ratio 1 and 2 channels. No data is reported for aspect ratio 3 channels because the bubbles were too large for capturing using the 10X objective. For future reference a smaller objective (4X) should be used. These results plotted in these graphs do not match with the Equation 7 because the characteristic velocity value approximately equal to one. In addition, as the volumetric flow ratio increases (gas flow decreases), the characteristic velocity increases. This is true
regardless of the channel depth, set liquid flow rate, or even the presence of pressure ports. This indicates fluid lubrication along the channel walls and corner flow of the liquid. If the fluid lubricated the bubble in the channel, the bubble would slip through the channel, rather than dragging on the rough side walls.

![Bubble Velocities for AR1 Microchannels](image)

**Figure 92: Bubble Centroid Velocity vs. Volumetric Flow Ratio**

4.3.2 Velocity Statistics

Statistical analysis of the velocities were also performed for the bubbles, shown in Table 7, Table 8, Table 9, Table 10, Table 11, Table 12 and Table 13. The data for all cases shows that the velocity of the centroid, minimum, and maximum relatively match. Some variation exists, which would indicate the bubble changing shape as it moves through the channel, but not by much. For example, most of the differences between the
The centroid, maximum and minimum point are between 1 and 2 mm/s. That is not much in the flows that move between 0.08-0.33 m/s. At the lowest of 0.08 m/s, this small 1 mm/s variation is only about 3% of the flow. However, there are cases as, the 0.05 ml/min flow in aspect ratio one non-pressure port chip. For example, at a volumetric flow ratio of 0.5,

![Bubble Velocity for Aspect Ratio 2 Microchannels](image)

Figure 93: Bubble Centroid Velocity vs. Volumetric Flow Ratio

Table 7: Average Values and Standard Deviation of AR1 No PP, Liquid Flow Rate=0.05ml/min

<table>
<thead>
<tr>
<th>Beta</th>
<th>Average Centroid Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Maximum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Minimum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.11719</td>
<td>0.02341</td>
<td>0.04343</td>
<td>0.061764</td>
<td>0.12324</td>
<td>0.008992</td>
</tr>
<tr>
<td>0.33</td>
<td>0.13189</td>
<td>0.02961</td>
<td>0.14507</td>
<td>0.006972</td>
<td>0.1471</td>
<td>0.008003</td>
</tr>
<tr>
<td>0.25</td>
<td>0.17135</td>
<td>0.10025</td>
<td>0.16618</td>
<td>0.016946</td>
<td>0.19941</td>
<td>0.18881</td>
</tr>
<tr>
<td>0.2</td>
<td>0.17769</td>
<td>0.023343</td>
<td>0.19656</td>
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</tr>
<tr>
<td>0.18</td>
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<td>0.31686</td>
<td>0.30835</td>
</tr>
<tr>
<td>0.14</td>
<td>0.26755</td>
<td>0.016316</td>
<td>0.27847</td>
<td>0.014947</td>
<td>0.27847</td>
<td>0.010301</td>
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<tr>
<td>0.11</td>
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<td>0.001645</td>
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<td>0.007659</td>
<td>0.3303</td>
<td>0.007657</td>
</tr>
</tbody>
</table>
Table 8: Average Values and Standard Deviations of AR1 No PP, Liquid Flow Rate=0.1ml/min

<table>
<thead>
<tr>
<th>Beta</th>
<th>Average Centroid Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Maximum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Minimum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.16456</td>
<td>0.0082836</td>
<td>0.17042</td>
<td>0.011325</td>
<td>0.16358</td>
<td>0.014392</td>
</tr>
<tr>
<td>0.5</td>
<td>0.18441</td>
<td>0.012585</td>
<td>0.19117</td>
<td>0.0077329</td>
<td>0.1841</td>
<td>0.017584</td>
</tr>
<tr>
<td>0.4</td>
<td>0.20691</td>
<td>0.0097001</td>
<td>0.21317</td>
<td>0.0063074</td>
<td>0.20975</td>
<td>0.0053669</td>
</tr>
<tr>
<td>0.33</td>
<td>0.23183</td>
<td>0.020093</td>
<td>0.24521</td>
<td>0.014471</td>
<td>0.23516</td>
<td>0.0066196</td>
</tr>
<tr>
<td>0.25</td>
<td>0.24366</td>
<td>0.018887</td>
<td>0.25892</td>
<td>0.007589</td>
<td>0.25696</td>
<td>0.011953</td>
</tr>
<tr>
<td>0.2</td>
<td>0.28015</td>
<td>0.012985</td>
<td>0.28217</td>
<td>0.0045065</td>
<td>0.28217</td>
<td>0.004507</td>
</tr>
<tr>
<td>0.18</td>
<td>0.33407</td>
<td>0.059464</td>
<td>0.31406</td>
<td>0.03367</td>
<td>0.37594</td>
<td>0.12578</td>
</tr>
</tbody>
</table>

the maximum point velocity was 0.04 while the minimum and centroid velocities were around 0.12. Usually at this flow ratio and liquid flow rate, the bubbles are unsteady, as shown by the previous bubble statistics chapter. In unsteady flow, the bubbles are of many different sizes and tend to coalesce. Perhaps, when these images were recorded at this flow rate, the some of the bubbles passing through the recorded region on the chip were slowing down (as indicated by the low maximum point velocity), as a preparation for coalescence.

Table 9: Average Values and Standard Deviations of AR1 W/PP, Liquid Flow Rate=0.05 ml/min

<table>
<thead>
<tr>
<th>Beta</th>
<th>Average Centroid Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Maximum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Minimum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.099123</td>
<td>0.0093536</td>
<td>0.0953</td>
<td>0.013699</td>
<td>0.097465</td>
<td>0.0057887</td>
</tr>
<tr>
<td>0.33</td>
<td>0.19408</td>
<td>0.27213</td>
<td>0.19654</td>
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<td>0.1835</td>
<td>0.26599</td>
</tr>
<tr>
<td>0.25</td>
<td>0.15103</td>
<td>0.020109</td>
<td>0.14737</td>
<td>0.022307</td>
<td>0.13696</td>
<td>0.012218</td>
</tr>
<tr>
<td>0.2</td>
<td>0.17176</td>
<td>0.016184</td>
<td>0.16465</td>
<td>0.012695</td>
<td>0.16178</td>
<td>0.014396</td>
</tr>
<tr>
<td>0.18</td>
<td>0.20117</td>
<td>0.0309</td>
<td>0.20177</td>
<td>0.030153</td>
<td>0.18496</td>
<td>0.026091</td>
</tr>
<tr>
<td>0.14</td>
<td>0.22024</td>
<td>0.029387</td>
<td>0.21814</td>
<td>0.021736</td>
<td>0.21556</td>
<td>0.014491</td>
</tr>
<tr>
<td>0.11</td>
<td>0.24876</td>
<td>0.05117</td>
<td>0.23889</td>
<td>0.044068</td>
<td>0.24207</td>
<td>0.044642</td>
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</tbody>
</table>
### Table 10: Average Values and Standard Deviations of AR1 W/PP, Liquid Flow Rate=0.1 ml/min

<table>
<thead>
<tr>
<th>Beta</th>
<th>Average Centroid Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Maximum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Minimum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.22584</td>
<td>0.017649</td>
<td>0.22742</td>
<td>0.013263</td>
<td>0.20826</td>
<td>0.017212</td>
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<tr>
<td>0.33</td>
<td>0.24341</td>
<td>0.031049</td>
<td>0.27006</td>
<td>0.054432</td>
<td>0.22065</td>
<td>0.083125</td>
</tr>
<tr>
<td>0.25</td>
<td>0.28508</td>
<td>0.019118</td>
<td>0.29303</td>
<td>0.015538</td>
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<tr>
<td>0.18</td>
<td>0.34212</td>
<td>0.018662</td>
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<td>0.11</td>
<td>0.37303</td>
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<td>0.37362</td>
<td>0.0081871</td>
<td>0.37362</td>
<td>0.0081862</td>
</tr>
</tbody>
</table>

### Table 11: Average Values and Standard Deviations of AR2 No PP, Liquid Flow Rate=0.05 ml/min

<table>
<thead>
<tr>
<th>Beta</th>
<th>Average Centroid Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Maximum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Minimum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.088404</td>
<td>0.026943</td>
<td>0.068247</td>
<td>0.026577</td>
<td>0.085615</td>
<td>0.0061057</td>
</tr>
<tr>
<td>0.33</td>
<td>0.10414</td>
<td>0.030606</td>
<td>0.083542</td>
<td>0.026341</td>
<td>0.10494</td>
<td>0.012076</td>
</tr>
<tr>
<td>0.25</td>
<td>0.1242</td>
<td>0.027293</td>
<td>0.10211</td>
<td>0.021545</td>
<td>0.12506</td>
<td>0.014589</td>
</tr>
<tr>
<td>0.18</td>
<td>0.1379</td>
<td>0.034635</td>
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<td>0.018957</td>
<td>0.14762</td>
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</tr>
<tr>
<td>0.14</td>
<td>0.17865</td>
<td>0.016122</td>
<td>0.16605</td>
<td>0.0062527</td>
<td>0.17688</td>
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</tr>
<tr>
<td>0.11</td>
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<td>0.020219</td>
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<td>0.006251</td>
<td>0.17688</td>
<td>0.0062518</td>
</tr>
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</table>

### Table 12: Average Values and Standard Deviations of AR2 W/PP, Liquid Flow Rate=0.05 ml/min

<table>
<thead>
<tr>
<th>Beta</th>
<th>Average Centroid Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Maximum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Minimum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33</td>
<td>0.10532</td>
<td>0.011182</td>
<td>0.10288</td>
<td>0.0062521</td>
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<td>0.0054147</td>
</tr>
<tr>
<td>0.25</td>
<td>0.12261</td>
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<td>0.11642</td>
<td>0.010369</td>
</tr>
<tr>
<td>0.18</td>
<td>0.15495</td>
<td>0.0095637</td>
<td>0.16028</td>
<td>0.0048433</td>
<td>0.15161</td>
<td>0.0076573</td>
</tr>
<tr>
<td>0.14</td>
<td>0.17253</td>
<td>0.012323</td>
<td>0.1841</td>
<td>3.40E-17</td>
<td>0.1841</td>
<td>0.01083</td>
</tr>
</tbody>
</table>
Table 13: Average Values and Standard Deviations of AR2 W/PP, Liquid Flow Rate=0.1 ml/min

<table>
<thead>
<tr>
<th>Beta</th>
<th>Average Centroid Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Maximum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
<th>Average Minimum Point Velocity (m/s)</th>
<th>Standard Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.13268</td>
<td>0.013982</td>
<td>0.13339</td>
<td>0.0092018</td>
<td>0.12705</td>
<td>0.0076672</td>
</tr>
<tr>
<td>0.33</td>
<td>0.15447</td>
<td>0.014762</td>
<td>0.15284</td>
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<td>0.14472</td>
<td>0.012597</td>
</tr>
<tr>
<td>0.25</td>
<td>0.17699</td>
<td>0.011803</td>
<td>0.18096</td>
<td>0.0080038</td>
<td>0.17013</td>
<td>0.010899</td>
</tr>
<tr>
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<td>0.1918</td>
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<td>0.18</td>
<td>0.21845</td>
<td>0.019518</td>
<td>0.21713</td>
<td>0.0082214</td>
<td>0.20793</td>
<td>0.011967</td>
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<tr>
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<td>0.013026</td>
<td>0.23431</td>
<td>0.010011</td>
<td>0.2284</td>
<td>0.013223</td>
</tr>
<tr>
<td>0.11</td>
<td>0.28033</td>
<td>0.010521</td>
<td>0.27407</td>
<td>0.0068273</td>
<td>0.26907</td>
<td>0.011568</td>
</tr>
</tbody>
</table>

4.3.2 Void Fraction Measurement

From the images captured using the back illumination method, the liquid and gas time-average void fraction was calculated using Equation 9. Equation 9 is derived from the values obtained during image processing and some basic assumptions. The values extracted from the image are shown in Figure 94 (a); they include the length of the bubble and the length of the “core” of the bubble. It was assumed that the bubble completely fills the channel and has a cross section that looks like Figure 94 (b).

Equation 9 separates the bubble into 2 sections: the ‘barrel’ middle section and either the spherical or ellipsoidal end caps. The first part of the numerator in Equation 9 is the volume of the barrel section, and the second part of the numerator is the volume of
\[\varepsilon_g = \frac{\left(\frac{\pi}{4} \sum d^2 + \sum (h + dh - 4r^2)\right) L_{\text{core}} + \frac{4}{3} \sum \pi wh L_{\text{cap}}}{TwhL_{\text{channel}}}\]

where

\[d = \text{Length of Shadowed(Curved) Bubble Section} = w - l\]
\[l = \text{Core Width}\]
\[h = \text{Channel Height}\]
\[r = \frac{d}{2}\]
\[L_{\text{core}} = \text{Core Length}\]
\[w = \text{Channel Width}\]
\[L_{\text{cap}} = \text{Cap Length} = \frac{\text{Bubble Length} - \text{Core Length}}{2}\]
\[L_{\text{channel}} = \text{Channel Length}\]

Equation 9: Time-Averaged Gas Void Fraction

Figure 94: (a) Values Reduced from OPTIMAS, (b) Cross-Section View of Bubble in Channel (Cubaud and Ho, 2004)

the sphere. The numerator is the bubble portion of the flow, and the denominator is the entire channel volume multiplied by number of frames (time). There is an error using this method for the OPTIMAS processed pictures. The data output from OPTIMAS is only for bubbles that appear entirely in the image. Bubbles that only partially appear are
ignored, like the section of bubble at the bottom of Figure 94 (b). Thus, because some bubble portions are thrown out, this void fraction is not completely accurate. Figure 95 shows the apparent liquid fraction (based on Equation 10).

\[ \varepsilon_L = 1 - \varepsilon_G \]

**Equation 10: Apparent Liquid Fraction**

![Graph showing Apparent Liquid Fraction vs. Homogeneous Liquid Fraction](image)

**Figure 95: Apparent Liquid Flow Ratio vs. Homogeneous Liquid Flow Ratio**

This figure shows that regardless of the type of chip or the velocity of flow, the homogeneous and apparent flow ratios approach the line y=x as both of the ratios increase (towards the bubbly regime).
Chapter 5: Conclusion

Two-phase flow in microchannels has become an increasingly popular field, especially in the area of biotechnology. This experiment explored just one application of using multiphase flow in a drug delivery system. Unlike previous studies that use PDMS channels, silicon wafers and methods like etching or lithography, this study used directly-milled PMMA substrates for the microchannels. Also, these microchannels were not restricted to an aspect ratio of one; aspect ratios of two and three were also used. In addition to the basic channels of aspect ratio one, two, and three, corresponding channels with pressure ports were made. Comparing the flows between the pressure-ported and non-pressure-ported channels, one can establish whether or not the pressure port presence influences the two-phase flow in the channel.

A cleaning method was also devised to remove all of the machining oils from the PMMA substrates. Sonication was not used in this method because of substrate cracking; rather, a gentle cleaning method involving minimal detergent amounts, long de-ionized water soakings, soft paint brush scrubbing, and compressed air cleans was devised. After the microchip is cleaned, a PMMA cover slip must be bound to it. Thus, a thermal bonding procedure was devised, which consists of placing the chip in the convection oven for a 20 minute dehydration period (95°C), a 30 minute bonding period (chip is sandwiched in the bonding jig—constructed by Namwon Kim) at 118°C, a 30 minute cooling period at 95°C in the oven, and a cooling to room temperature (in oven, door slightly ajar) for 2.5 hours. In order to present inlet and outlet port collapse during bonding, a paper clip insert method was devised. Basically, snippets of paper clips (about
1/16”) are placed in the ports before bonding. During bonding, these paper clips, in combination with a magnet, prevent the cover slips from falling and clogging the channel. After bonding, these inserts are removed by using tweezers or magnets.

The conducted experiments consisted of using dry air and de-ionized water for the two phases of the flow. An experiment was built to allow maximum control of these two phases. High control of the two phases is required to achieve steady-state slug flow. Two gas controllers provide a high level of control for the dry air. These controllers have a fast response (100ms) and a high accuracy (+/- 1%). A pressurized water reservoir provided an extremely steady liquid flow rate (+/- 0.002 ml/min) for several hours continuously.

Extracting size distributions of the bubbles and plugs and reducing bubble velocities were the two main experimentation goals. A back illumination was used to obtain the size distribution data, and laser illumination was used to obtain the velocities. These two methods were performed on five microchannels (AR1 pressure port and no pressure port, AR2 pressure port and no pressure port, and AR3 no pressure port) at two constant liquid flow rates: low of 0.05 ml/min and high of 0.10 ml/min. During a test, the liquid flow rate is held constant as the gas flow rate is adjusted incrementally by 0.05 ml/min to obtain a specific volumetric flow (beta) ratio. The different objectives used to observe the flow were 2x (ensure steady state), 4x (OPTIMAS processed for size distributions) and 10x (OPTIMAS processed for velocities).

The most important observation noted during preparation for an experiment was the ‘priming’ time required for new chips. All new chips must be cycled with multiphase
flow for at least 2 hours. If the chips are not cycled, the multiphase flow is erratic, and the dry air supply continuously fluctuates. Although the exact reason for this ‘priming’ is not known, a speculation involves the trapped air pockets residing inside the channel from thermal bonding.

For the back illumination method, it was found that all chips show steady flow for a given beta ratio. However, flow stability does not depend on the beta ratio, rather it depends on the liquid’s velocity. For instance in AR1 channels, at a beta ratio of 0.33 for a low liquid flow rate of 0.05 ml/min, the flow is stable (signified by the size distributions in the histograms). However, is the same beta ratio of 0.33 is used for the high liquid flow rate of 0.10 ml/min, the flow is erratic. Thus, the liquid’s velocity influences the flow stability. Figure 96 shows steady-state beta ratio ranges.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Port Type</th>
<th>Liquid Flow Rate</th>
<th>Beta Ratio Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR1</td>
<td>No Pressure Port, Liquid Flow Rate=0.05 ml/min</td>
<td>0.18-0.32</td>
<td></td>
</tr>
<tr>
<td>AR1</td>
<td>No Pressure Port, Liquid Flow Rate=0.10 ml/min</td>
<td>No SST Flow</td>
<td></td>
</tr>
<tr>
<td>AR1</td>
<td>Pressure Port, Liquid Flow Rate=0.05 ml/min</td>
<td>0.20-0.33</td>
<td></td>
</tr>
<tr>
<td>AR1</td>
<td>Pressure Port, Liquid Flow Rate=0.10 ml/min</td>
<td>No SST Flow</td>
<td></td>
</tr>
<tr>
<td>AR2</td>
<td>No Pressure Port, Liquid Flow Rate=0.05 ml/min</td>
<td>0.09-0.33</td>
<td></td>
</tr>
<tr>
<td>AR2</td>
<td>No Pressure Port, Liquid Flow Rate=0.10 ml/min</td>
<td>0.40-0.70</td>
<td></td>
</tr>
<tr>
<td>AR2</td>
<td>Pressure Port, Liquid Flow Rate=0.05 ml/min</td>
<td>0.14-0.33</td>
<td></td>
</tr>
<tr>
<td>AR2</td>
<td>Pressure Port, Liquid Flow Rate=0.10 ml/min</td>
<td>0.50-0.70</td>
<td></td>
</tr>
<tr>
<td>AR3</td>
<td>No Pressure Port, Liquid Flow Rate=0.05 ml/min</td>
<td>0.20-0.50</td>
<td></td>
</tr>
<tr>
<td>AR3</td>
<td>No Pressure Port, Liquid Flow Rate=0.10 ml/min</td>
<td>0.40-0.70</td>
<td></td>
</tr>
</tbody>
</table>

Figure 96: Steady-State Volumetric Flow Ratios for the Different Microchannels
There is a difference between the steady flow in the pressure port and the corresponding non-pressure port channels. The pressure port channels have a smaller stability range; this is always at the lower end. The existence of pressure ports may cause this variation, but this difference may also be caused by slight machining differences in each of the chips. In addition for a given liquid flow rate, for all steady flow cases, the plug size is about the same regardless of the presence of pressure ports. Thus, no fluid is leaking out of the port. So, these changes in the steady-state range are most probably caused by machining variations amongst microchannels, not by pressure port presence.

Although a steady state flow was attained for most of the microchannels, the flow was most easily achieved in the AR2 and AR3 chips. For both of these cases, the flow stabilized with 1 minute. Whereas, in the AR1 case, the flow would take an upwards of 20 minutes to stabilize. However, Rhodomine B dye showed that the slug flow in the AR3 channel is not always completely filling. Therefore, if a completely bubble-filled channel is required, AR3 chips are not recommended.

The channels were all designed with the same hydraulic diameter to dictate similar pressure drops. However, based on the retrieved pressure data, the pressure drops did not match. Although the channels were designed to have similar pressure drops, these dimensions were pre-bonding. During bonding, the channels shrink. Any change in the dimensions would create a different pressure drop amongst channels. Figure 89 indicates that the pressure drop not only depends on the flow rate but also the phase. The maximum pressure drop recorded by AR1 chips was 6 psig, and the maximum pressure drop for AR2 was 3 psig.
The velocity of the centroid, minimum, and maximum point were found using the laser illumination technique. By examining these results, it appears that the bubbles do not deform within the microchannel (about 3%). In addition, there is evidence that the bubbles slide through the channel based on Figure 92 and Figure 93. Finally, the apparent time-averaged volumetric flow ratio was calculated. The calculation assumed that the bubble could be broken into 2 portions: a ‘barrel’ mid-section and two spherical or ellipsoidal end caps. As the apparent flow ratio and homogeneous flow ratio increase, there relationship the values become equivalent (nearing bubbly flow).

For future use, different fluids should be used in the experiment (besides dry-air and de-ionized water). When selecting these chemicals, one should consider the pressure limitations of the system. None of the operating equipment should be exposed to pressures in excess of 100 psig. Thus, any fluid that has a greater viscosity than water is not recommended because it would require pressures greater than 100 psig to push through this particular channel. Considering the microchannels, a tee design (as opposed to a cross bubble generation section) should be researched. The problem with the cross design is the length of the channels. The longer these small inlet channels are, the greater the pressure drop. Using cross geometries require more channel length than the tee geometry. So, if the tee geometry was used, higher flow rates in the liquid is attainable (because of the shorter channel, less pressure drop).
Bibliography


Appendix

List of Microchannels

AR1 B-1-1-DM-PM-2-PP2-C
AR1 B-1-1-DM-PM-1-PP0-C
AR2 B-1-2-DM-PM-1-PP0-C
AR2 B-1-2-DM-PM-1-PP0-C
AR3 B-1-3-DM-PM-1-PP0-C

List of Programs

OPTIMAS:
Bubble_plug_single_08122006_22.mac
Bubble_plug_velocity_08112006_22.mac
Microbubbleseperate2.mac
Microbubbleseperate.mac
Microbubbledataanalysisang.mac
Findnextpage.mac
Findnestpage2.mac
Microbubblelevel234.mac

MATLAB:
Testingeg2.m
Elal.m
Stat.m
LabVIEW_processing(name of chip)_4x_liq_(liquid flow rate).m
Conversion.m
LabVIEW_processing_velo.m
Velo.m
Map.m
Lab.m
Pressure.m
Vita

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