An Experimental Investigation of Droplet Detachment in High-Speed Microchannel Air Flow

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Abstract
This paper experimentally investigates the mechanism of water droplet detachment in a confined microchannel under highly inertial air flow. Experimental observations show that as the Reynolds number in the channel is increased, the droplet transitions from a nearly spherical droplet to a high aspect ratio slug. Scaling arguments are then made to address this behavior in an order of magnitude sense. These results show that although shear stress at the droplet-air interface may contribute to droplet elongation, the major mechanism of droplet detachment appears to be the pressure drop across the droplet. This pressure drop is a result of a highly inertial air flow being squeezed through a narrow gap between the droplet and the adjacent microchannel wall. This pressure difference creates a force imbalance across the droplet that overcomes the surface tension force pinning the droplet at the injection site, thereby leading to droplet detachment. A formulation of a nondimensional number is then presented that relates the pressure force acting across the droplet to the surface tension force at the droplet wall interface, which indicates that detachment occurs when this number is of order 1.

Introduction
Two-phase, confined microchannel flow devices may offer an opportunity to mix different reactants with increased throughput and reduced mixing times. The idea is to deliver two droplets to a collision zone and promote mixing under highly inertial conditions as opposed to mixing driven by mass diffusion. Using a gas for the continuous phase offers the benefits of reduced pressure drop through the device as compared to two-phase liquid-liquid flows with the same flow rate. Such inertia-based, gas-liquid, micro-mixing devices have not been fully realized under laboratory conditions due to a lack of understanding of the collision process when the two phases differ significantly. Droplet collisions in unconfined flows, however, have been studied extensively for a number of decades [1 – 2]. Droplet collision at low velocity was investigated by [3] and on a single interface surface by [4]. The presence of a wall, or walls, introduces added complexity and the resultant collision outcome – droplet coalescence, separation, or bounce – is difficult to predict. Droplet collision in two phase liquid-liquid microchannel flows was examined by [5 – 6], but the process has not been fully mapped for confined microchannel flows. Adding two different immiscible phases with considerably different properties, such as air and water, adds to the complexity even further.

Before droplet collision occurs, each droplet must first be detached and entrained into a high speed gas flow. Providing a controlled and predictable detached droplet is a prerequisite to droplet-droplet collisions and therefore the detachment process must first be well understood and characterized. The detachment process was investigated numerically by [7] and experimentally by [8 – 9] but to date the detachment mechanism remains unclear. This paper experimentally investigates the droplet detachment process in high speed gas flows using a T-junction configuration and attempts to understand the parameters that govern droplet detachment and detached droplet shape. An experimental setup was developed that allows different air flow velocities to detach water droplets. The detached droplet is visualized through the use of a high speed camera and the resulting images are used to assess droplet geometric features. First order scaling
arguments are then made to qualitatively assess the measurements and observations of the experiments. The results appear to indicate that droplet detachment is driven by pressure differences across the droplet as opposed to shearing stresses. The pressure difference provides the force necessary to overcome the surface tension force at the droplet-wall interface.

Device Fabrication

Prior to device microfabrication, the microchannel geometry must first be designed. A standard T-junction configuration was designed where the gas flow is normal to the liquid injection site. The channel length leading up to the injection site was designed such that the gas flow is fully developed under the range of gas velocities considered. Sufficient length was then added past the injection site such that the droplet growth and detachment process occurs unhindered by downstream channel features. Large plenums were added to the air and liquid inlets to facilitate the creation of gas and liquid tubing ports. Figure 1 below shows the channel geometry and pertinent dimensions.

Figure 1. Layout and dimensions of PDMS microchannel used for droplet detachment and collision experiments.

The microfabrication process first involves creating a negative mold of the microchannel geometry on a silicon substrate. A standard 4” diameter, 500μm thick silicon wafer was used. The wafer is cleaned and prepared using standard procedures. A negative near UV resist is then spin coated onto the wafer to a thickness dictated by the microchannel depth. SU8-2050 Microchem resist was used and the thickness was maintained at 100μm, resulting in a square 100x100μm channel. The spin coated wafer was then baked to remove the solvents in the resist. Once the resist is hardened, the wafer was placed in a Karl Suss MA6 mask aligner and exposed to 392nm radiation through a mask containing the microchannel image. Since the smallest feature size on the microchannel was 20μm, a photoplotted, 7mil film mask was used as an alternative to a chromium mask. The exposed wafer is then developed using the appropriate developer solution and baked at the prescribed temperature and duration.

Once the negative microchannel mold was complete, the PDMS solution was prepared. Sylgard 184 silicone elastomer base was mixed with Sylgard 184 silicone elastomer curing agent and Dow Corning OS-10 thinner, each at a 1 to 10 weight ratio to the base. The thinner was added to the solution to reduce the mixture viscosity and ensure that the solution is wicked into all features. The wafer was not treated with silane prior to pouring the PDMS since increasing the hydrophobicity of the silicon substrate may lead to incomplete feature resolution. Increasing the hydrophobicity of the silicon surface by vapor deposition of silane reduces the ability of the PDMS solution to wick into small corners and radii. Once the PDMS solution was poured into silicon and SU8 mold, the assembly was placed in a vacuum desiccator to promote solvent vaporization and air bubble removal. The assembly was then placed on a hot plate in ambient surroundings and baked at 95°C for approximately 3-6 hours. Once fully cured, the PDMS was peeled from the silicon substrate.

The available real estate on a 4” silicon wafer allows a number of devices to be created in a single soft lithography process. Each device is cut from the PDMS in a rectangular shape and prepared for fluid and gas porting. A 2mm diameter belt-hole puncher was used to core the PDMS device at each gas and fluid inlet. The core was then removed using tweezers. Each device was then cleaned with methanol and prepared for bonding.

A 1”x3” standard microscope slide was spin coated with a 1μm thick layer of PDMS. The glass slide provides a rigid substrate to bond each device to and promotes light transmission for microscope visualization. Each device and glass slide was placed in a Harrick Plasma plasma cleaning machine. A flow of oxygen was ionized using the integrated RF generator which briefly renders the PDMS surface hydrophilic. Each device was then bonded to a glass slide and baked at 120°C for 8 hours to improve bond strength. The finished device is then checked for dimensional integrity using a microscope and checked for leaks using a pressure source and flow meter.
Experimental Setup

The experimental setup used to investigate the detachment process in the PDMS T-junction microchannel required monitoring and controlling gas and liquid flow rates, channel pressure drop, and inlet temperature and pressure. Measurements were made and recorded using a host of transducers and data acquisition equipment. Droplet growth and detachment was visualized using a high speed camera. Dry, filtered supply air and distilled water were used for the continuous and dispersed phases, respectively. A schematic of the setup is shown in Figure 2.

Gas inlet pressures were regulated using Omega I/P 710 pressure regulators. Prior to integration, the regulator was calibrated such that the current pressure relationship was established. Once integrated, the regulator was powered using an Agilent 6627A DC power supply and current was measured using an Agilent 34970A data logger such that real time pressure measurements could be made.

Gas flow rates were measured and recorded using a Sensirion ASF 230 gas flow meter and information was transferred through a RS232 connection. This particular meter uses an internal heat transfer element and differential temperature sensor to measure the flow capacitance. The software then converts, displays, and records this measurement in standard cubic centimeters per minute (SCCM) of N₂. Since the flow meter sits immediately downstream of the pressure regulator, the regulator pressure is used in conjunction with the constant pressure specific heat ratio of N₂ to air to convert the displayed flow rate measurement to actual air flow rate.

Pressure drop across the channel was measured using a Validyne P855-D differential pressure transducer. The high pressure side was connected at the device inlet and low pressure side was connected at the device outlet. The transducer produces a voltage signal in response to the pressure acting at the low and high end. The voltage was measured using the Agilent data logger and instrument calibration data was used to convert the signal into a pressure drop.

Liquid was introduced into the device using a Harvard Apparatus syringe pump. The pump is capable of proving constant volume displacements at rates less than 1 μl/hr. High dimensional tolerance glass syringes were used with the pump. Since liquid flow rate measurements were not critical in this experiment, the actual liquid flow rate was determined based entirely on the syringe pump displacement rate.

A Nikon Eclipse TI-U inverted microscope was used to visualize the droplet dynamics. A Vision Research Phantom V7.1 high speed camera was connected to one of the microscope ports to record the detachment process. The camera is capable of frame rates in excess of 100,000 pps, thereby providing the ability to view the droplet growth, detachment, and entrainment in great detail. Image information is sent to a dedicated computer through an Ethernet cable. Resulting images were then used to make measurements of droplet length and height at the point of detachment for different gas flow rates.

Gas and liquid flow were connected to the microfluidic device using 0.030” ID, 1/16” OD PEEK tubing. The 2mm holes punched in the PDMS prior to bonding provide a leak free fit, provided the thickness of the PDMS was adequate for self sealing. It was found that a PDMS layer of 0.15” was more than sufficient under the inlet pressure ranges considered for these tests.

Experimental Results

With the microfluidic device fabricated and all sensors and transducers integrated into the setup, experiments were conducted for a range of air flow rates. The range of Reynolds numbers considered (Re_DH based on the average channel velocity of air, channel hydraulic diameter, and properties of air at inlet temperature) was 90 to 250. The water flow rate...
was maintained at 1 μl/hr (Reynolds number ~ 0.005) for all cases in an effort to minimize liquid inertia in the injection channel. Within the ReDh range, 14 different flow velocities were examined. At each data point, high speed camera images were used to measure droplet characteristic length scales. The length scales considered important in the experiment were droplet height and length. Height was measured relative to the wall in which the droplet was in direct contact with and is therefore normal to the flow direction. The length considered was the flattened portion of the droplet opposite the wall and parallel to the flow direction. The droplet tail, which extends a behind the droplet, was not considered in the measured length, only the portion that contributes to the droplet height. The tail does, however, create a smooth transition into the reduced gap area between the droplet and adjacent wall. Once detached, the tail is severed but the droplet height and flattened length remain. Thus, the height and length measurements shown below in Figure 3 provide the representative droplet aspect ratio.

Figure 3. Droplet height and length measured at detachment. The length refers only to the flattened portion of the droplet and does not include the tail.

The variation of droplet height and length for each channel Reynolds number (ReDh) are shown in Figure 4. The data indicates a linear decrease in droplet height with increased gas flow and is consistent with measurements made by [8]. The droplet length, however, does not elicit a linear behavior. The droplet length remains relatively constant up a ReDh of 200 but then begins growing at a fast rate with increasing flow velocity and the droplet begins to take on a slug like geometry. The evolution of the process is shown in Figure 5 for different ReDh.

Figure 4. Plot showing droplet height and length at detachment for different channel Reynolds numbers (ReDh).

Figure 5. High speed camera images of droplet geometry for different channel Reynolds numbers (ReDh).
Results Discussion

Based on the experimental measurements and observations, it is clear that the air velocity changes the morphology of the droplet. For low \( \text{Re}_{\text{Dh}} \), the aspect ratio of the droplet, defined as droplet flattened length to droplet height, is nearly unity. Note that the tail of the droplet is not considered in this ratio (see Figure 3). As the air flow velocity increases, the droplet height decreases while the length increases, yielding an exponential growth of the aspect ratio. As the droplet first begins emerging from the injection site, it is faced with a choice – continue lateral growth or begin growth in the longitudinal direction. Because the droplet is in contact with three walls of the channel, lateral growth requires the droplet to overcome the surface tension in the lateral direction and to force the incoming air flow through a smaller flow area. The liquid flow rate in the injection channel (\( \text{Re}_{\text{Dh}} \sim 0.005 \)) does not provide sufficient inertia for overcoming both the surface tension and the force required to decrease the momentum of the incoming air flow. If the air flow is shut off, the droplet will grow in the lateral direction, impeded only by surface tension forces, and maintain a nearly spherical shape. The other choice is longitudinal growth. Growing in a direction opposite the air flow is not physically possible. Growing in the direction of air flow requires only overcoming surface tension at the wall interfaces. It is important to note that the flattened portion that is created on the droplet, defined as its length, does not provide a surface tension force in the lateral direction since this force acts laterally only. It therefore appears that the path of least resistance is longitudinal growth, creating an increased flattened section in the flow direction.

The actual droplet evolution is a combination of both lateral and longitudinal growth, as shown in Figure 6. Lateral growth occurs first as the droplet emerges from the injection site. As this occurs, the droplet experiences viscous dominated drag due to the air flow that must navigate around the droplet. This can be viewed analogous to the drag on a cylinder in cross flow. At very low Reynolds number, the drag is dominated by shearing forces on the surfaces causing the droplet to deform and stretch. The longitudinal stretching creates a pressure drop through the gap due to air flow in a confined space, similar to hydrodynamic buoyancy. It is believed that this pressure difference across the front and rear of the droplet causes it to ultimately detach. Thus, friction drag contributes to the lateral growth and hydrodynamic buoyancy detaches the droplet.

Figure 6. High speed camera images of droplet growth and detachment for a channel Reynolds number (\( \text{Re}_{\text{Dh}} \)) of 118.
To validate this argument, a first order scaling analysis is conducted that compares the relative magnitude of the forces occurring in the gap between the droplet and adjacent wall. The simplified cartoon shown below depicts the relevant velocity and length scales used in the analysis.

![Figure 7. Simplified flow schematic with relevant length and velocity scales used in the scaling analysis of the mass and momentum conservation equations.](image)

Since only forces are considered, the conservation of mass and momentum equations are used. For an assumed 2D flow in Cartesian coordinates with negligible lateral pressure gradient, the mass and longitudinal momentum equations are as follows:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}
\]

\[
\frac{u}{\partial x} + \frac{v}{\partial y} = -\frac{1}{\rho} \frac{d p}{d x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \tag{2}
\]

Although the air flow upstream of the droplet is fully developed, the flow in the narrow gap between the droplet and adjacent wall is not since the flow must accelerate to compensate for the reduced flow area. Therefore, the inertia terms appearing on the left side of the momentum equation cannot be neglected. The terms on the right side of the momentum equation represent the force contributions due to axial pressure drop, normal viscous force, and tangential viscous force. The relative magnitudes of each term in the momentum equation can be quickly assessed by scaling arguments. The assumed velocity and length scales in the gap are as follows:

\[
u \sim U \frac{D}{d} \]

\[
x \sim L \]

\[
y \sim d \]  

[3]

In the above equation, \( U \) represents the average velocity in the channel upstream of the droplet. The lateral velocity scale cannot be determined directly. Instead, the mass conservation equation is used by inserting the known scales as follows:

\[
\frac{U D}{d} \sim \frac{v}{d} \]

\[
v \sim \frac{U D}{L} \]  

[4]

Substituting this result into the momentum equation yields the following:

\[
\left( \frac{U D}{d} \right) \left( \frac{U D}{d} \right) \sim \frac{1}{\rho} \frac{d p}{d x} \left( \frac{U D}{d} , \frac{U D}{d} \right) \]

[5]

This result shows that, in a scaling sense, both inertia terms are of the same magnitude. Additionally, the viscous terms are also of the same magnitude since \( L \) is on the same order as \( d \). This viscous stress acting in the lateral direction does not contribute to droplet detachment since it acts normal to the flow direction. To balance the forces occurring in the gap, there are three possibilities: the inertia terms are balanced by the pressure in the gap, the inertia terms are balanced by the viscous stress in the gap, or the pressure is balanced by the viscous stress in the gap. The former implies a situation indicative of high speed flow while the latter implies a low speed flow (Stokes flow) or fully developed flow (Poiseuille) condition.

Intuitively, the stretching of the droplet with increased air velocity implies a shearing stress. Balancing the inertia terms to the tangential shear stress results in the following:
This scaling result in Equation 6 implies that the Reynolds number in the gap, based on the gap velocity and gap length scale, should be proportional to the gap length to gap height ratio. Using the experimental results, this relation is plotted in Figure 8 below.

\[
\frac{\left(\frac{U D}{d}\right)^2}{L} \sim \nu \frac{U D}{d} \frac{L}{d^2}
\]

\[
\left(\frac{U D}{d}\right) \frac{U D}{d} \sim \frac{U D}{d}
\]

\[
\frac{U D}{d} \sim \frac{L}{d}
\]

\[
\text{Re}_d \sim \frac{L}{d}
\]

[6]

The scaling result in Equation 7 implies that the Reynolds number in the channel is the same order as the ratio of the pressure drop in the gap to the shear stress in the gap. A similar result is obtained for fully developed pipe where the proportionality constant is the friction factor. The difficulty in applying this result directly based on the experimental data is that the pressure drop across the droplet was not measured and would be very difficult to measure due to the small length and time scales associated with droplet detachment. If the argument is made that this pressure drop can be estimated based on laminar flow friction data, then this ratio could be estimated. Assuming fully developed flow in the gap, the pressure drop can be estimated as follows:

\[
\Delta p = 4 \frac{f}{\text{Re}_d} \frac{L}{d} \frac{1}{2} \rho V^2
\]

[8]

In this equation, \( f \) is the friction factor, \( \text{Re}_d \) is the Reynolds number based on the gap velocity and hydraulic gap diameter, and \( V \) is the average flow velocity in the gap. Applying Equation 8 to the scaling result in Equation 7 yields the results shown in Figure 9.

Figure 8. Plot showing ratio of droplet length to droplet height for different Reynolds numbers in the droplet-wall gap (\( \text{Re}_d \)).

The data shows that there is clearly a linear relationship between the \( \text{Re}_d \) and the gap length to height ratio above \( \text{Re}_d \sim 200 \). Furthermore, this proportionality is of order unity for \( \text{Re}_d > 200 \), with a 25% change in \( \text{Re}_d \) giving a 25% change in the length to gap ratio, as predicted by the scaling argument. This suggests that the interface viscous stresses do play a role in droplet deformation and detachment, but these stresses alone do not tell the complete story.

Another scaling argument can be made by balancing the inertial and pressure terms. This results in the following:
The results indicate a better balance between inertia and pressure compared to inertia and viscous stress. In fact, the ratio of the Reynolds number in the channel to the pressure/viscous stress ratio is of order 1 as predicted by scaling. This suggests that within the gap, the pressure drop is due to the inertia of the incoming flow. This highly inertial flow causes shear stress at the wall and results in an increased pressure drop that is analogous to a hydrostatic distribution in a column of fluid.

Using these results, similar ratios can be determined that include both the droplet and gas flow and not just the gas flow alone. The dominant force keeping the droplet from detaching is the surface tension force at the droplet-wall interface. Conventional non-dimensional parameters that are used in microchannel liquid flows are the Capillary number and Weber number. The Capillary number assesses the dominance of the viscous forces at the droplet interface to the surface tension forces. A value of unity implies these forces are balanced. The Weber number relates the dominance of the droplet inertia to the droplet surface tension. For the detachment process, relating the viscous stress and inertia of the high speed air flow to the surface tension of the droplet for the Capillary and Weber number, respectively. This type of ratio may be more applicable since both phases are included. A Capillary number greater than unity implies the air subjects larger viscous forces on the droplet compared to the droplet surface tension force. The viscous stress in this case is due to the squeezed air flow in the narrow gap. Similarly, a Weber number greater than unity suggests the air imposes a greater inertial force in comparison to the droplet surface tension force. The inertia in this case is due to the air flow upstream of the droplet. If the modified Capillary number or modified Weber numbers exceed unity, the droplet should detach. The mechanism for detachment, however, is different. These modified Capillary and Weber numbers can be written as follows:

\[
Ca_{mod} = \frac{\mu U D}{\sigma h^2 Lw}
\]  

\[
We_{mod} = \frac{\rho U^2 h w}{\sigma h}
\]

In the above relations, \(\sigma\) and \(w\) are the liquid surface tension and channel depth, respectively. Using the experimental results, the modified Capillary and Weber numbers are plotted versus the channel Reynolds number, \(Re_{Dh}\), in Figure 10 and Figure 11.
These results indicate that the modified Capillary number is two orders of magnitude less than 1 but the modified Weber number is nearly 1. This suggests that the inertia of the air is nearly sufficient to detach the droplet.

Based on the scaling results of an inertia-pressure balance in the air flow, a new non-dimensional number, the Drag number ($Dr$), can be formulated by comparing the gap induced pressure drop across the droplet to the surface tension force at the droplet-wall interface [8]. This number can be succinctly written as follows:

$$Dr = \frac{\Delta pdw}{\sigma^* h}$$  \[11\]

Using the experimental data, the Drag number is plotted versus the channel Reynolds number and is shown below in Figure 12.

![Figure 12. Plot showing Detachment number (De) for different channel Reynolds numbers (ReDh).](image)

These results show that not only is the Drag number of order 1, it is almost exactly 1 at a channel Reynolds number of 200 where the droplet length begins to grow in proportion with the channel Reynolds number, as shown in Figure 4. It remains uncertain, however, if the Drag number is the sole contributor to this behavior. It can be concluded that for confined, high speed microchannel flows, the pressure drop across the droplet is likely responsible for the detachment of the droplet.

**Conclusion**

The understanding of liquid droplet detachment in high speed, confined, microchannel gas flows is critical in the realization of an inertia-based micromixer. This paper presented experimental results of water droplet detachment in air flows where the droplet geometry was characterized for various gas velocities. The results indicate that when the Reynolds number in channel exceeds 200, the droplet begins to take the shape of an elongated slug and does not remain a nearly spherical droplet. These results were then qualitatively assessed using simple scaling arguments based on the forces induced by the gas on the droplet. Particular attention was given to the reduced flow area between the droplet and adjacent microchannel wall prior to detachment. The scaling analysis, together with the experimental results, indicates that droplet detachment is facilitated by the pressure drop occurring in the droplet-wall gap. The pressure drop in the gap is manifested by the inertia of the incoming air flow that must accelerate through this confined space. When the surface tension pinning the droplet at the injection site is not sufficient to balance this force, detachment occurs. This does not imply that other forces, such as the form drag on the droplet or shearing force at the droplet air interface, do not contribute to the detachment process. The argument is made, however, that the dominate force causing detachment is the inertia driven pressure drop in the droplet-wall gap. Additional test are needed to see if this balance is true for different channel aspect ratios. If the channel width is much larger than the channel depth, the pressure drop across the droplet may be superseded by shearing forces at the droplet air interface. Regardless of the actual detachment mechanism, increasing the continuous phase velocity changes the droplet geometry by reducing the lateral height and increasing the longitudinal length. An investigation into the droplet collision process will determine what type of droplet geometry facilitates increased mixing rates, which is ultimately a major driving force in micromixer design.

**References**


