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Anisa Hofert April 6, 2020

Flow of Quasi-2D Emulsion Droplets Through Small Openings

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a thesis submitted to the Faculty of Emory College of Arts and Sciences
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Abstract

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We examine how various parameters affect the flow rate of quasi-2D soft particles moving through tight openings. To observe this, we create thin hopper-shaped chambers which have a small exit for the particles to flow through. We fill the chambers with monodisperse oil-in-water emulsions with a soap surfactant. We use microscopy to observe the oil droplets moving through the chamber, looking at deformation, particle flow, and outflow rate. We find that the exit size of the chamber is more important in determining the flow rate of the droplets than the number of droplets in the chamber. This means that the exit flux of the droplets is constant. There is a linear relationship between exit flux of the droplets and opening size. The flux goes to 0 when the ratio of the width of the opening and the diameter of the droplets (w/d) is less than 0.49 when extrapolated. The position of maximum deformation is also dependent on the w/d, with larger w/d having more deformation before the opening than at the opening.

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1.Background

1.1 Motivation

Throughout history there have been many studies about granular flow. Cereals and grains were historically kept in large containers and their flow was studied to best understand how to transport expansive quantities. These studies not only assist farmers and their ability to store food in a more efficient way, but they can also be models for some more complicated situations (1). The flow and dynamics of herd animals has been modeled to follow the patterns of granular flow and even people can behave in similar ways (2). Vehicular and pedestrian traffic patterns can be simplified using particle flow and even in emergency evacuations, modeling particle flow can help us understand how to facilitate people through emergency exits, saving their lives. Hard particles are always used to simulate these situations (2).

The flow of soft particles is a more recent field that takes into account deformations. Here the openings can be smaller than the particles and the limiting factor becomes more about the deformation capacities of the particles than the formation of arches to create clogging situations. This slight departure from the study of ideal granular spherical particles is a step towards a more generalized and complicated understanding of particle flow. Including a larger range of material deviations and opening sizes allows for a larger range of possible applications.

1.2 Particle Flow

As particle flow became a field of interest, people want to understand how quickly particles flow out, and some empirical laws were found for the flux rate for varying experimental setups. In all the setups, hard or granular particles are placed in a large container with a small bottleneck opening as seen in figure 1 and their flow through that opening is measured. A lot of people studied

this in the 1940's and 1950's (3-6) and suggested that the flow of particles through openings or flux L could depend on variables such as the height of the packing above the opening h (3), the width of the opening w (3-6), the diameter of the particles, d (4-6), the density of the bulk of particles ρ_B (6), and the area, A and perimeter P of the opening for 3D chambers (5-6) among other parameters. However, these early relations from Refs. (3-6) have been replaced by Beverloo's law.

Table 1. Parameters for flow eqns.

Weight of grain discharged over time	L
Height of the grain above the opening	h
Width of the opening	w
Diameter of the particles	d
Density of the bulk of particles	ρ_B
Area of the opening	A
Perimeter of the opening	P

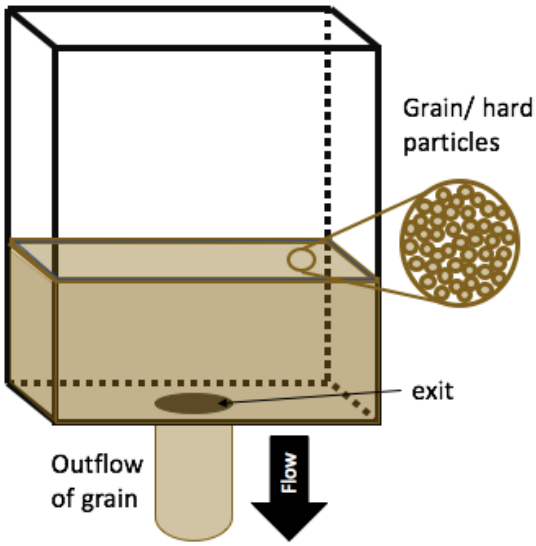

Figure 1 The basic experimental setup for experiments looking at the flow of granular materials.

1.3 Beverloo Laws

Wim A. Beverloo was a scientist in the 1950s and 1960s. He studied the flow of granular particles specifically using seeds in three dimensional hoppers similar to the one seen in figure 1. Beverloo laws describe the flux of the particles as a function of the width of the opening and the diameter of the particle. These parameters are often divided to give a ratio called the *w/d* ratio. The original paper studied seeds or varying shapes and other granular objects as they pass through a circular orifice at the bottom of a cylindrical container. In the Beverloo experiments, the openings are much larger than the size of the particles. The experiment is performed with a three-

dimensional setup and the general equation Beverloo and his team determined for the outflow of particles is

$$L = 35\rho_B\sqrt{g}(w - kd)^{2.5}$$

Here, L is the weight discharged per unit time, g is the gravitational force and k is a constant that is determined by the material. For most of the materials studied in the experiments, k is 1.4. This means that the chamber is likely to clog if the *w/d* ratio is less than 1.4 (7). The equation holds for containers of any shape, including a quasi 2D particle system (8). Simulations modeling soft particle flow through chambers with varying outflow angles showed that sharper angles increased the flow rate by a scale factor, changing the proportionality constant like the one in equation 1 depending on the angle (9).

1.4 Soft Particle Flow

In order to look at deformation and smaller chamber openings, soft particles can be used instead of granular ones. Often times hydrogel particles are used. While the flow patterns of granular particles have been well established, there is not much research in soft particles and their flow. Beverloo laws have been extended to soft particles in hoppers with *w/d* ratios of 2.2 and above. In a study of outflow for soft hydrogel particles, clogging was not observed until a *w/d* ratio of about 2 (10) whereas for granular particles the ratio is closer to 5 (7). The Beverloo laws in this case have parameters that are quite different from those of granular particles. While models could be developed for *w/d* ratios greater than 2, the lower ratios between 1.5 and 2.2 were found to have quite a few differences in flow through tight spaces. Intermittent clogging can be observed, where the particles are stopped but begin to flow again after a few seconds. These intermediate clogging episodes have been seen in other experiments such as animal flow (2) and can make modeling soft particle flow challenging.

1.5 Emulsions

Emulsions are a mixture of two insoluble materials where droplets of one material are suspended in the other. These are often stabilized with a surfactant. The surfactant forms micelles which are spherical layers of the surfactant which can be filled by the emulsified liquid, creating the droplets as seen in figure 2. These provide protection for the barrier between the two immiscible substances being mixed and stop the emulsified material from coalescing and forming a single larger droplet (11).

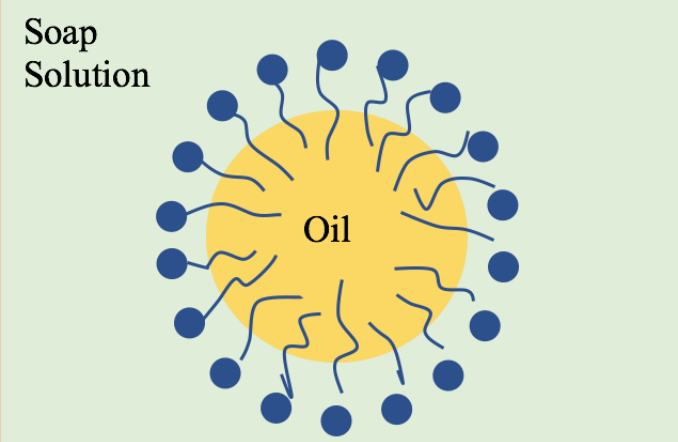

Figure 2. Here we see a representation of a droplet of emulsified oil in a soap solution.

Emulsions can be made to have droplets of homogenous or heterogeneous size. Monodisperse emulsions have droplets that are all of the same size and polydisperse emulsions have droplets of multiple sizes. There can be bidisperse samples where there are two different sizes of droplets or other droplet size distributions. All of these can be used to model different scenarios.

Emulsions can be used to model soft particles in flow experiments. Instead of having the droplets flow down and out of a chamber, like hydrogel particles used in other soft particle experiments, the emulsion droplets will flow up through a tight opening. The buoyant force on the emulsion droplet acts like the gravitational force that is working on the hydrogel particles. The buoyancy force is equal to the weight of the displaced liquid, so it works similarly to the gravitational force.

The difference here is that there is also the actual weight of the droplet, so the net gravitational force on a droplet is $\Delta\rho\, V\, g$ in terms of the difference of density, volume of the droplet V, and gravity g. The pressure that builds up near the opening from the force of the droplets below can lead to the droplets having fairly high area fractions as in figure 3. This means they are tightly packed and have a high force pushing against each other. The excess pressure can also help push the droplets through. This will follow the pressure law

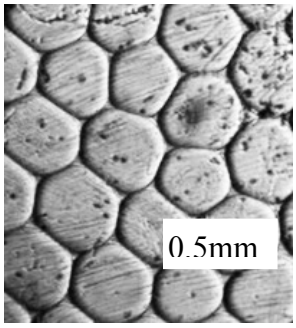

Figure 3 Droplets with a high area fraction

$$P = \Delta\rho g h$$

Here $\Delta\rho$ is the difference between the density of the liquids, g is the gravitational force, and h is the height of the mass of droplets. Something else to consider with emulsions is the attractive hydrodynamic interactions between the droplets. This attraction could help pull remaining droplets through the opening as the prior droplets pass due to these hydrodynamic interactions (9).

1.6 This Experiment

In the experiment, we use emulsions to model soft particles. These particles flow through quasi-2D hoppers with a small opening. The opening of the hopper will be about the size of the droplet or smaller and have a geometry of one straight side and one 45-degree corner as in figure 4. The droplets will flow up through the chamber and I will observe them using microscopy. The

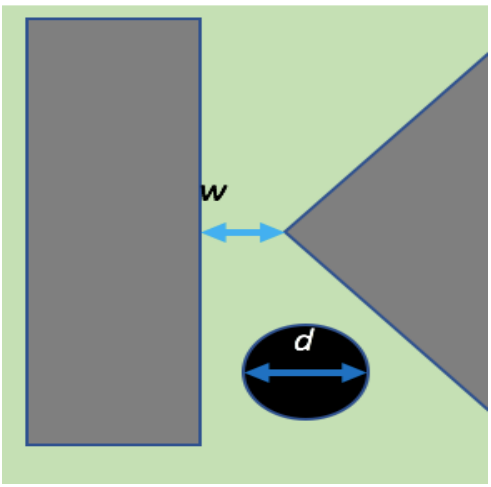

figure 4a

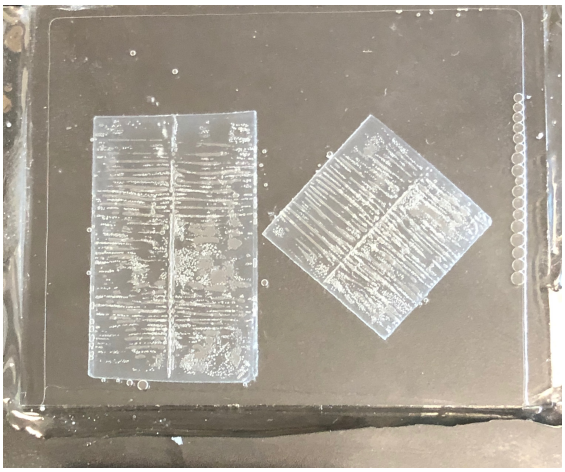

figure 4b

Figure 4a A representation of one of the chambers. The distances w and d are marked.
Figure 4b is a picture actual chamber where the droplets flow up through the tight opening created by the pieces of tape. The flow of the droplets is upward.

emulsion droplets flow up through the opening and we determine the flow rate and deformation using particle tracking. We will determine which parameters affect the deformation and the particle flow. With this chamber shape, the pressure law will be

$$p \sim \Delta\rho g\sqrt{N}$$

because in an isosceles right triangle, the height of the bulk of droplets is proportional to the square root of the number of particles *N*. The density of the oil in this experiment is 0.85g/ml and that of the surfactant solution is close to 1g/ml, leaving a $\sim\Delta\rho$ of 0.15g/ml.

2 Methods

2.1 Microfluidic Devices and Creating Emulsions

2.1.1 Creating emulsions:

To model soft particles, I make emulsions and watch their flow through hoppers. To determine flow rates and clogging, I use a single size of monodisperse particles and observe their behavior through varying sized openings. I generate emulsions of silicone oil in soapy water using

a microfluidic device. The soapy water solution is made by combining 2.5g of Fairy liquid soap per 100g of distilled water. Here the soap is used as a surfactant to stabilize the emulsions and stop them from coalescing. Two syringe pumps are connected to the microfluidic device using capillary tubes. The tubes are connected to other syringe caps which lead to glass tubes. These glass tubes intersect with each other on a glass slide, mixing the oil and the soap solution. They are then

Figure 5 The microfluidic device. The oil comes in one tube, the soap comes in the other and they emulsify and leave into the collecting test tube.

connected to an exit tube. The emulsified oil exits here into the collecting test tube. This can be seen in figure 5. I remake this device after a few batches of droplets because it can get clogged from the small tubes (12).

This soap solution is loaded into a pump connected to the microfluidic device and a silicone oil pump is connected to the other end. The pumps connect in the device and as oil is pushed into the flow of the soapy water solution, it becomes emulsified. In order to control the size of the droplets, the flow rates of the oil and soapy water solution can be modified. In order to produce the desired size of monodisperse droplets, the flow rate was kept constant at 0.2ml/h for the oil and 2ml/h for the soapy water solution, leaving droplets of about 500µm in diameter. After a few minutes of running the pumps, I place a piece of a pipette tube inside of a vial filled with the surfactant solution. The exit tube of the microfluidic device is positioned so that the droplets fall

into the smaller pipet tip inside the larger vial. This helps to make it easier to collect the droplets when they are to be loaded into the chamber.

Another method for generating emulsions is using a dropper to squeeze oil into a surfactant solution. Here, the size of the dropper tube will determine the size of the droplets due to surface tension. I decided against this method because it can be difficult to change the sizes of the droplets (13).

2.1.2 Emulsion coalescence and size

In testing different sizes of droplets, I find that larger droplets tend to coalesce within seconds when placed on a microscope slide. This could be due to a low surface tension compared to the weight of the droplet or because the droplets with larger micellar borders have more points of possible failure in their protective layer. It is also possible that the larger surface area leads to more opportunities for the surfactant surface to fail. To increase the size of the droplets, I tried changing the concentration of the surfactant as well as using other surfactants such as sodium dodecyl sulfate and pluroinic p123. All of these have the same coalescent droplets that result from the 2.5g soap solution. Using mineral oil also doesn't provide more stability than silicone oil, so I continued with silicone. Therefore, I limit the largest size droplet to 500 microns in diameter.

2.2 Chamber Development

2.2.1 Creating chambers

In order to make a quasi-two-dimensional droplet, the chambers must be thinner than the diameter of the droplet. To accomplish this, I begin by cutting two strips of double sided waterproof tape that were two inches long, and I stick them together to make a double layer. Next, I do this for two one-inch pieces of tape. After cleaning a two-inch by three-inch glass slide with

isopropyl alcohol, I place the double layer tape pieces on the slide such that the two-inch piece is vertical and the one inch piece is diagonal with the corner being nearest to the longer tape section.

In order to measure the opening which must range from several hundred microns to about a millimeter, a template is used. The template is cut from transparency film using a laser cutter. It is shaped like the chamber with two right triangles connecting at a small point which will be the opening size. The flat side of the template is pushed up against the vertical two-inch tape. the smaller piece can then be placed in the open space on the right so that the distance between the pieces is set by the template. The template can be seen in figure 6.

Figure 6 The template for creating the chambers.

The distance between the corner of the one-inch piece and the side of the two-inch piece is the chamber size and is measured to determine the width of the opening. I clean a second glass slide and place it on top, covering the tape on the bottom slide, but offset from the original slide to assist in loading. The overall setup can be seen in figure 4b. Once the second glass slide is in place and securely attached, I cover the outside edges of the chamber in Norland UV epoxy #68 adhesive and place the entire chamber under an ultraviolet light for forty-five minutes or until the glue is hardened.

2.2.2 Chamber considerations and testing

2.2.2.1 Material Development

In creating the optimal chamber, I have to take into account the accuracy of the chamber. The only parameter that I want to change is the opening size between the two tape pieces. The shape and thickness should remain the same for each chamber. Previous examples use transparency film with a layer of glue in place of the tape, but controlling the thickness of the glue

layer is an added challenge and can lead to variability in the chambers. Another option to create the chamber is using parafilm which can be melted to adhere to the glass. This would theoretically allow for a more consistent thickness, but when the parafilm is melted, it can spread out between the glass pieces which could close the small opening. After trying these various materials, I determined the tape along with the template gives me the most accurate and replicable chambers.

2.2.2.2 Shape Development

When designing chambers, I look to prior hopper designs. The goal is to establish an area of the chamber where droplets can be loaded, one where they flow through a tight opening and one where they can go once they get through the opening. Originally, I had two isosceles triangular chambers connected by a thin passageway as in figure 7a. In testing I noticed that there needs to be a pathway that connects the bottom and top chambers in order to let the air out and allow for flow of fluid in the chamber. Once the flow bridge is added the chamber shape looks like figure 7b. This allows for quick flow and it accomplished the basic requirements, the difficulty comes in positioning the chamber opening. If the divider that creates the center opening is slightly

tilted, the opening size will change as the droplets move through the opening leading to inconsistent results. To resolve this issue, I reduced the length of the tight area so that the droplets were squeezed by two corners as can be seen in figure 7c. Because lining up the corners exactly was fairly challenging, I decided that the chamber shape did not need to be symmetrical, so, a long

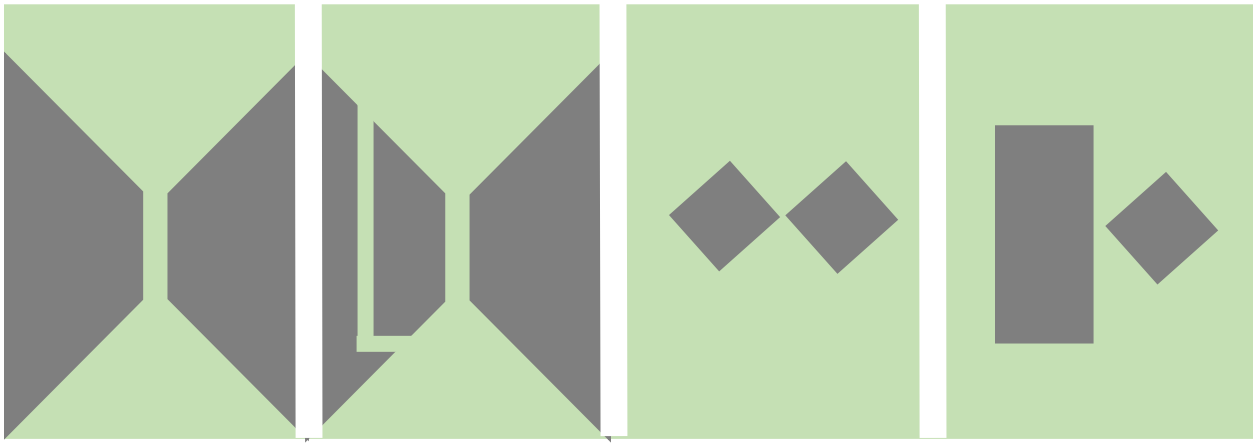

Figure 7a Figure 7b Figure 7c Figure 7d

Figure 7 Schematics of the progression of the chamber design. Leftmost (a) is the first design and rightmost is the final (d). The grey indicates a blocking material that does not allow liquid or droplets to pass and the green indicates the soapy solution containing the emulsions.

vertical wall could be paired with a corner to give a more consistent shape to the chamber. I used a template to help keep the distances in a good range, but with this simple design, there is not much meaningful variation in the chamber shape. The angle of the incoming wall can change, but generally this can be accounted for in determining the pressure.

2.3 Loading chambers

Once both the emulsions and the chambers are prepared, the chambers must be loaded with the droplets. To prepare the emulsion solution to be put in the chamber, glycerol is added to

the surfactant solution in a ratio of about 0.3ml of glycerol for every ml of surfactant. This gives

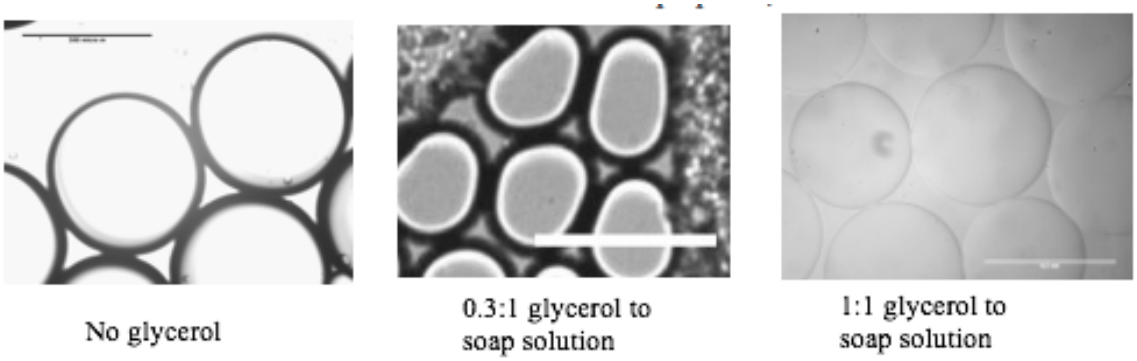

Figure 8 Droplets with varying levels of glycerol added after they emulsion has been created. The middle image with a ratio of 0.3:1 glycerol to soap solution was the final product. The scale bars are all 500 microns

an index of refraction that better matches the silicone oil, creating a clearer distinction. This can be seen in figure 8. I mix the glycerol into the surfactant and into the pipet tip containing the emulsions with a long metal stick. To get the glycerol into the smaller pipette tip, I pull the tip up and down a few centimeters so that the droplets do not come out, but the glycerol can get in.

Once everything is well mixed, I load the surfactant glycerol liquid to almost fill the chamber using a pipette. I lower the pipette tip into the vial, but not inside the inner tube and retrieved some of the surfactant and glycerol solution without the droplets. I place the tip of the pipette at the opening and release liquid into the chamber. The liquid moves slowly and sometimes air bubbles are created. I wait for these to flow to the top of the chamber and add more surfactant liquid until the chamber is full. I scrape the smaller bubbles off the top edge using a small metal spatula. This helps to not absorb the liquid and stops the small air bubbles from falling back into the chamber. Once the chamber is full of liquid, I quickly wipe once over the opening edge of the chamber to remove a small amount of the liquid, giving space for the droplets.

To add the droplets, I slowly pull the inner tube up and down a few times to allow the larger droplets to get to the top of the bulk and the smaller droplets to go to the bottom. After the droplets have been positioned, I place the vial under a pipette stand. After attaching a pipet to the pipet

stand, I slowly lower the pipette into the small inner tube inside the vial. Once the pipette tip is positioned in the center of the bulk of droplets, I slowly open the plunger of the pipette and draw in about 100 droplets. I remove the pipet from the inner vial and place the tip at the opening of the chamber. I then pipette the droplets into the space above the chamber, concentrating them above the small opening. Once the chamber is full, I wipe the excess droplets with a small metal spatula and dry the area above the opening with a towel, making sure not to absorb any of the liquid that is inside the chamber. Once it is fairly dry, I glue the top and place it under the ultraviolet light for abut 35 minutes or until it is dry.

2.4 Microscopy

In trying to record a video of the droplets moving, I need to have the chamber upright during the microscopy so that the droplets can flow. To do this, I removed the light from the microscope and placed it on its end so that the stage is perpendicular to the table. I next tape the chamber on to the stage so that the droplets are in the bottom area and can flow up. I use a 1.6 magnification lens and a ThorCam camera to record the droplets' flow. As the light source, I use a snake-lamp. To help with the tracking, I place the lamp such that the droplets have a black ring on the outside and a white ring on the inside of the droplet. Once the lamp is positioned, I monitor the droplets as they flow through the opening. Once I can see the bottom boundary of the droplets, I watch to see if the flow has slowed down. If it is slow, I begin to record at 5 frames per second. If the droplets are still moving quickly as the boundary approaches the tight opening, I record until all the droplets have gone through.

2.5 Particle Tracking

I use IDL software to track the particles. To do particle tracking, I use a pre-made tracking code. This code looks at the white ring that I created by positioning the snake lamp. First, I change

the exposure and contrast of the video so that all the droplets are surrounded by a completely white barrier. Next, I measure the approximate size of the droplets and restrict the tracked particles to be around that size. I then adjust the tracking to ensure that each droplet is being followed through the video. In order to get a good picture of both individual droplet motion and deformation as well as flow of the entire mass of droplets over time, I look at a multitude of parameters and averages for those parameters.

3 Results and Analysis

3.1 Video Observations and Clogging

Out of the many videos that I took, four videos with varying *w/d* ratios had adequate lighting conditions to allow for particle tracking and analysis. The first video is of a chamber with an initial condition of 15 droplets inside the opening and a *w/d* ratio of 1.11. The second video started with 12 and had a *w/d* ratio of 0.98. The third video began with 5 droplets and had a *w/d* ratio of 0.64. The fourth and final video began with 25 droplets and had a *w/d* ratio of about 0.57. These were measured by taking the average of the diameter of a few droplets in the chamber and dividing the width of the opening by that number. Figure 9 shows images from each video as the droplets move through the chambers.

Clogging is observed in the chambers with *w/d* ratios of 0.64 and 0.57. Figure 10 shows the final clogging of the droplets from the videos that observed clogging. Minor intermittent clogs were observed but in order to determine a permanent clog, the droplets were observed for over 5 minutes without moving through the chamber. The chamber with a *w/d* of 0.64 clogged with 4 droplets left and the chamber with a *w/d* of 0.57 clogged with 8 droplets left. The pressure upwards from the chamber with 8 droplets is $\sqrt{2}$ times that of the chamber with 4 droplets due to the square

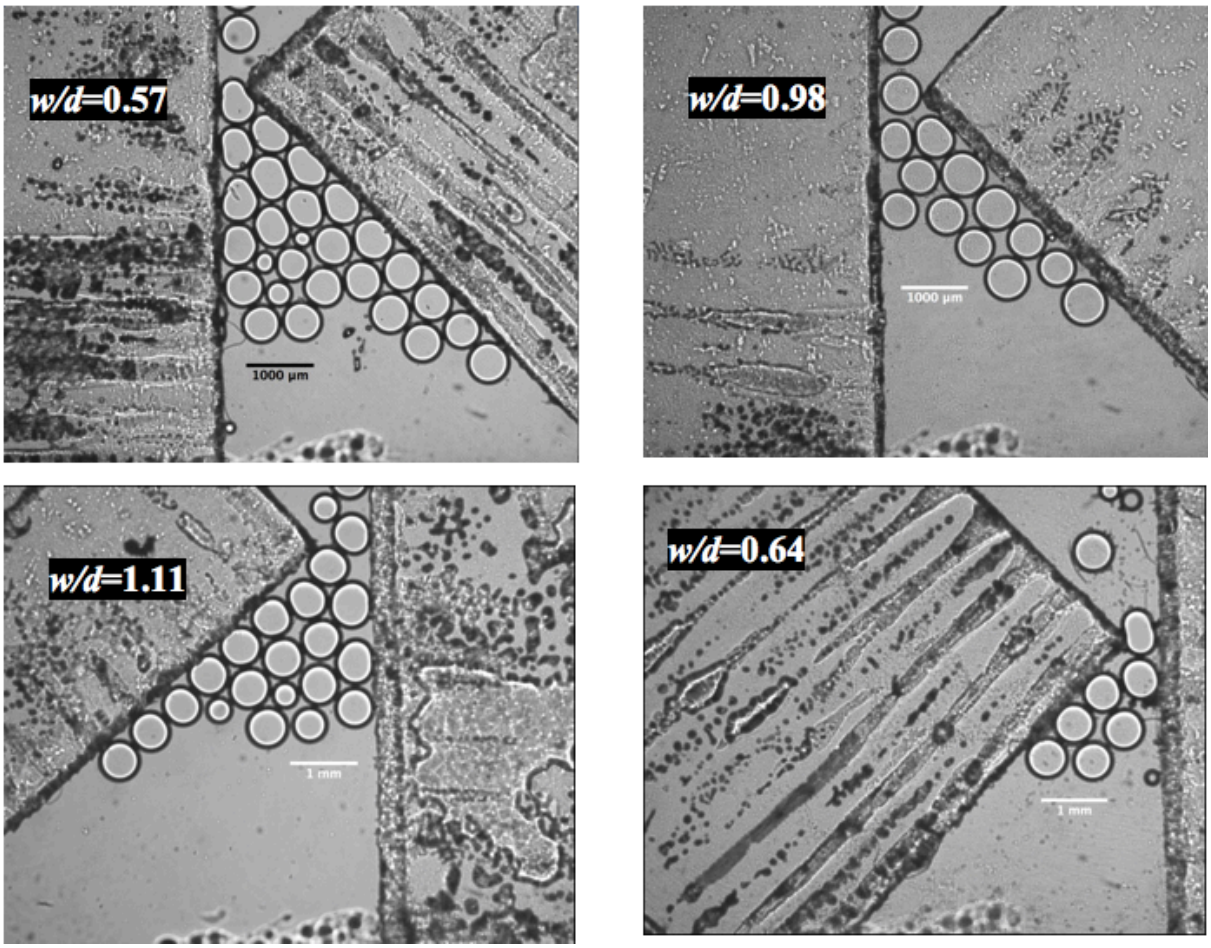

Figure 9 The four videos analyzed in this experiment. This is the first frame of each video. The *w/d* ratio is labeled for each video. Recall that the oil droplets are less dense than water, so they are moving upward in these images.

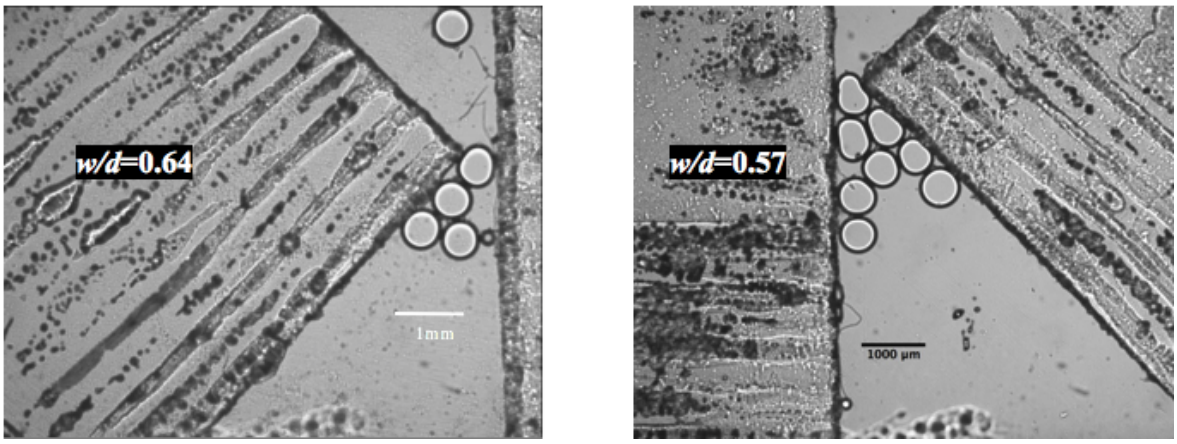

Figure 10 The two clogged chambers in their final clogged state. These chambers remained in this configuration for at least 5 minutes before it is determined to be a final clog.

root pressure law. As the chamber opening was decreased, more pressure was needed to deform the droplets and push them out of the opening. More droplets remain in the chamber with the tighter opening as more energy is required to fit the droplet though it.

3.2 Deformation

To visualize deformations of the droplets, I examine the ratio of the moment of inertia of the droplets, giving a ratio of the short principle axis to the long one. The ratio will be between 1, indicating a perfect circle, and 0, indicating a line segment. For each video, I look at droplets at the minimum moment of inertia to determine how the *w/d* ratio affects the deformation of the droplets. Figure 11 shows the droplet with the minimum ratio i.e. the most deformed droplets observed in each video.

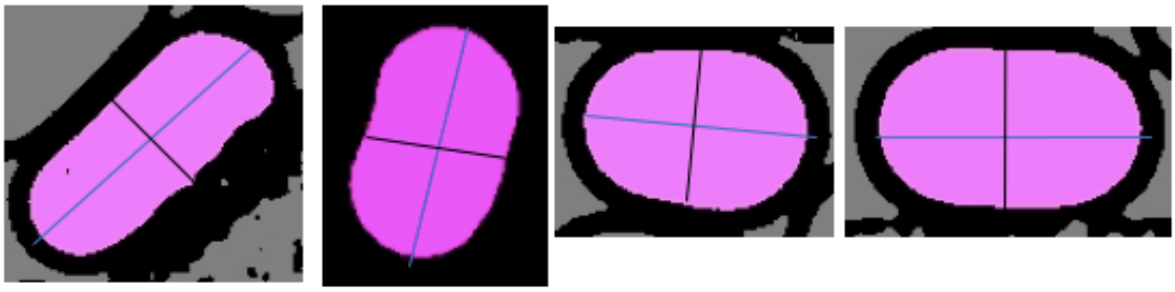

Figure 11a *w/d*=0.57 $\frac{I_1}{I_2} = 0.16$

Figure 11b *w/d*=0.64 $\frac{I_1}{I_2} = 0.28$

Figure 11c *w/d*=0.98 $\frac{I_1}{I_2} = 0.31$

Figure 11d *w/d*=1.11 $\frac{I_1}{I_2} = 0.37$

Figure 11 The droplets with the smallest moment of inertia ratio from each video. This would indicate the droplets that are the most squished and deformed into a more elliptical shape and less of a circular shape. In the images, the black lines show I_1 and the blue show I_2

Next, for each video, I plotted the average moment of inertia ratio as a function of the position in the chamber. These can be seen in figure 12. As we can see, each chamber does have a dip in the ratio around the opening which is marked with a dashed vertical line. For various reasons, in the chambers with a larger *w/d* ratio, the droplets tend to have the most deformation before the opening. This is likely because two droplets will wedge into the space before the opening, with

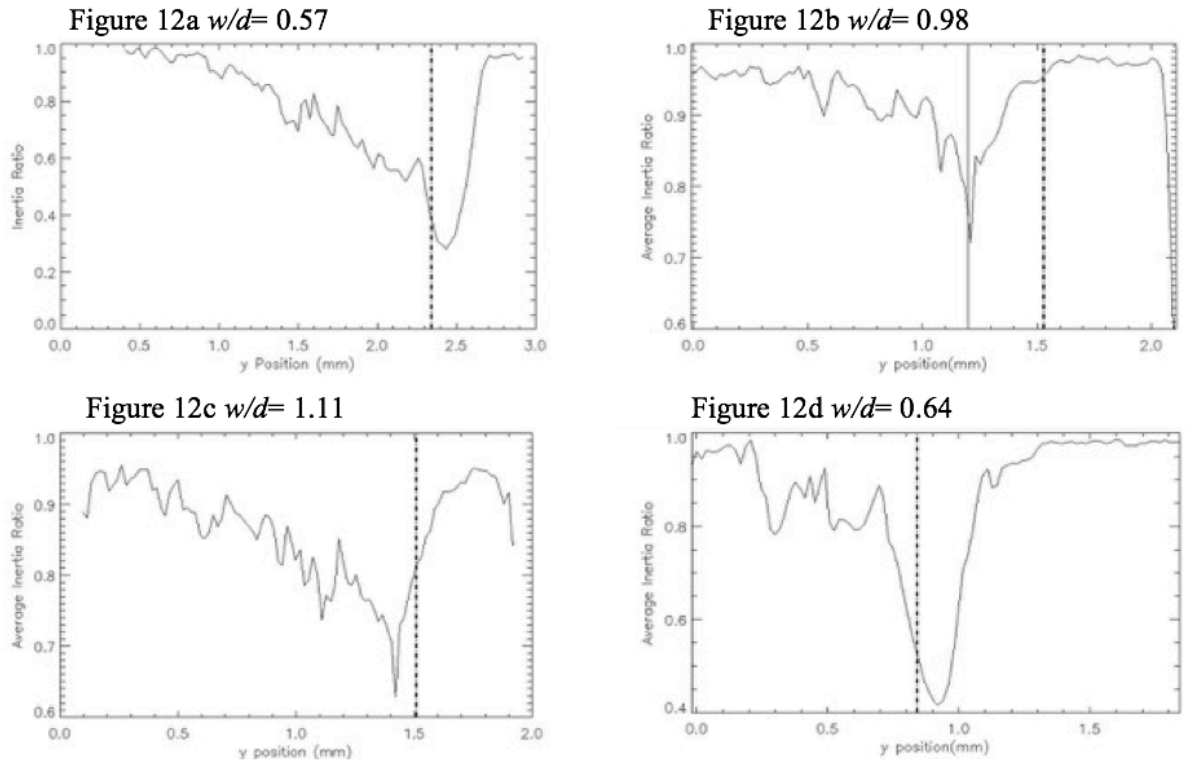

Figure 12 The average moment of inertia ratio along the chamber. Recall this ratio is 1 for circular droplets. The dips show more extreme deformation. The dashed lines show where the openings of the chambers are located.

each droplet deforming the other as in figure 13. The chambers with smaller *w/d* ratios have minima closer to the exit as each droplet is squished the most at that point.

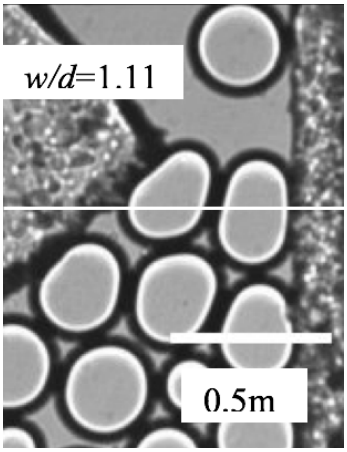

Figure 13 The droplets are deformed before the opening in larger *w/d* chambers. The horizontal white line below the narrowest point shows the location where droplets have the largest deformation

As the droplets move, their deformation requires energy as it changes the surface energy from the minimum which would occur with a circular droplet. The buoyant force and the pressure from other droplets both push the particle through the opening, making up for the increase in surface energy. Once the droplet reaches the maximum deformation, the deformation begins to decrease as the droplets comes out the other side of the opening. Here, the droplet actually reduces

the surface energy by moving through the opening because it becomes more circular as it moves through. At this point, the surface energy, along with the buoyancy and the pressure push the

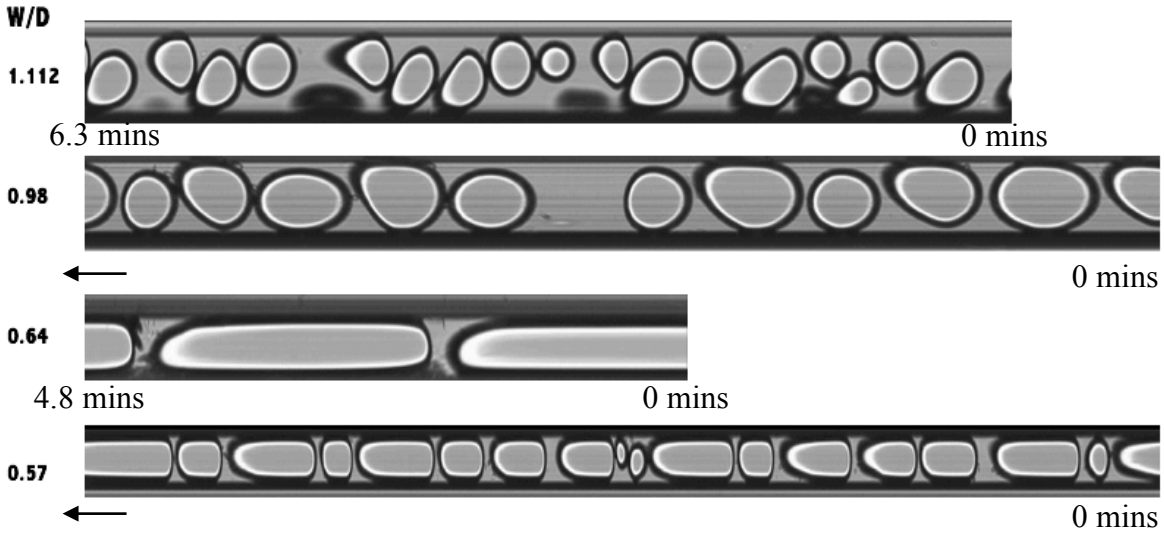

Figure 14 The opening of the chamber at each frame of the video. The longer the droplet, the longer it took to get through. The shorter image indicates a shorter video.

droplet up together. This should lead to faster motion in the second part of the exit after the droplet has gone most of the way through. In order to look at this in the videos, I take all the *x* values at the opening position of the chamber and stack them such that the *y* axis of the resultant picture is time. The bottom row of pixels is the *x* values of the opening at time zero and the top row is the *x* values of the pixels at the final time. This allows me to track what is happening at the opening as the video progresses, showing me how long the droplets take to pass through the opening. The larger the droplets appear on the resulting image, the longer they took to pass through the opening. Since the droplets are monodisperse, the size in the new composite *x* position vs time graph is completely dependent on the flow rate of the droplets. These are seen in figure 14. In these images, we can see that the droplets are longer at the beginning and shorter

at the end, indicating that they were moving slower at the beginning, taking more frames to capture, and faster in the second half, as predicted. This is more prominent for chambers with smaller *w/d* ratios.

3.3 Individual Droplet Motion

In order to observe droplet flow through the opening, we look at the motion of individual droplets. As the droplets move through the chamber as seen in figure 15 we notice that the flow

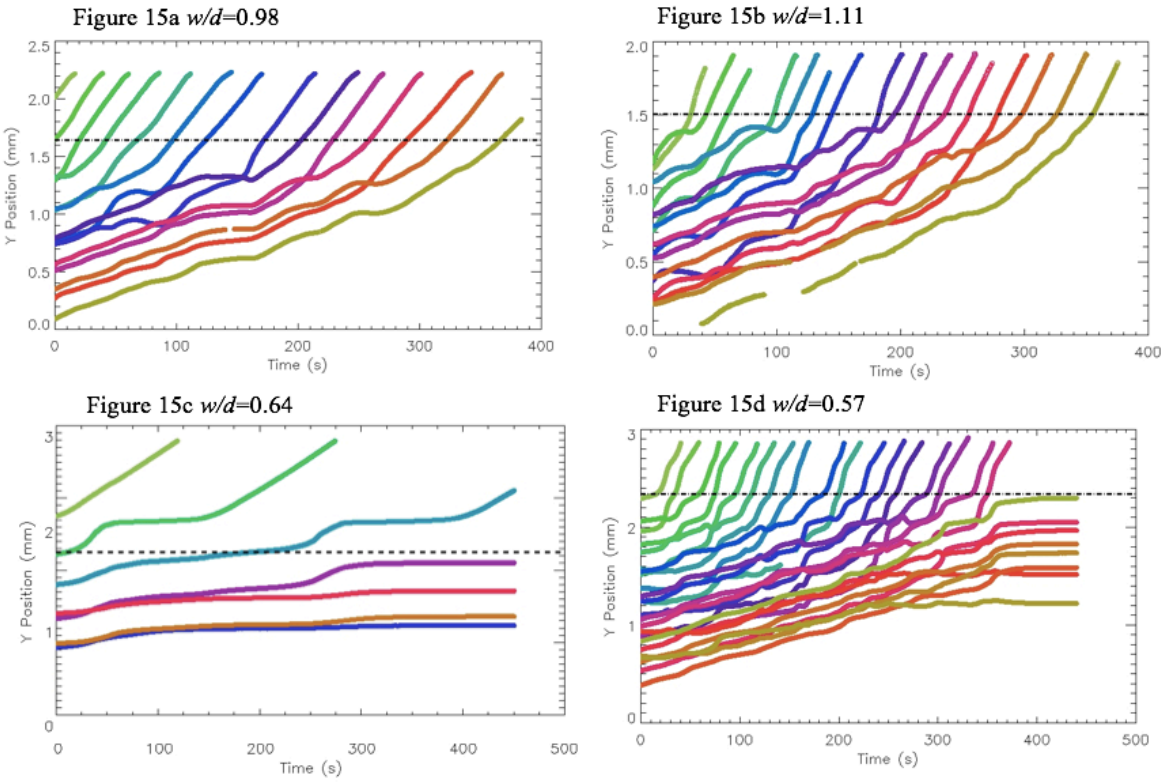

Figure 15 The motion of each droplet over time. Every line represents a different droplet and clogging can be observed in c and d. The horizontal dashed indicates the opening. The trajectories above that line are the ones that have exited the hopper.

of droplets is fairly unorganized before the opening, above the indicator for the opening. This would tell us that the droplets can flip so that one that was below is above. There is also not a consistent way to tell which droplets will reach the opening first from analyzing initial position in the bulk. Generally, bulk flow is not linear and droplets in the bulk move slower than the ones that

have left the opening where they all move at a fairly constant terminal velocity. This can also be observed by looking at figure 16. Here we see the average velocity of the droplets as a

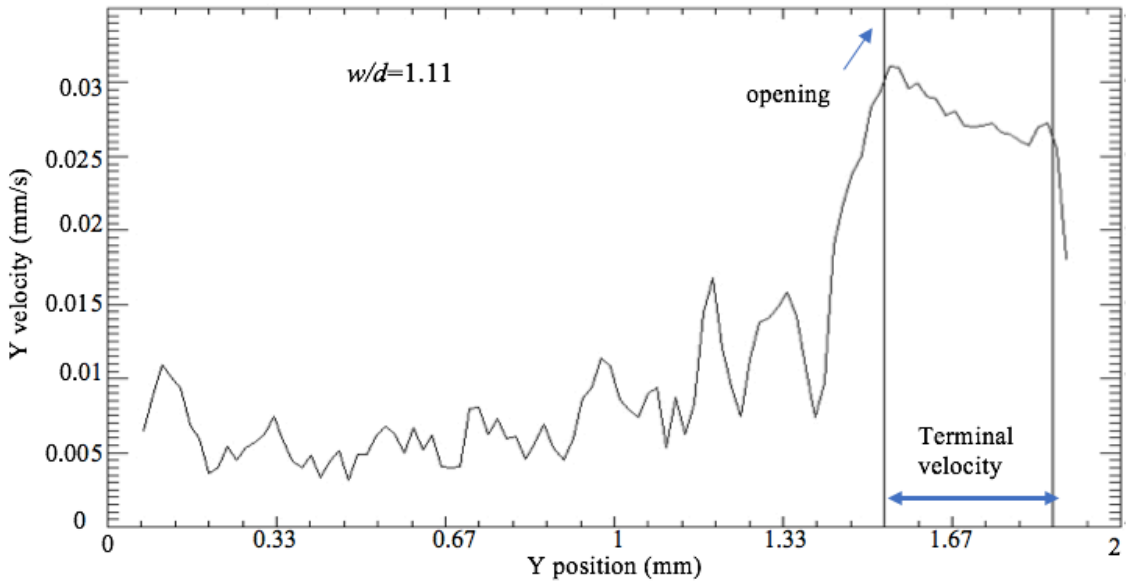

Figure 16 The vertical velocity is low below the first line, indicating the opening. These droplets are being slowed down by the exit hole. After the droplets exit, their velocity increases and levels off, showing the terminal velocity. On average the terminal velocity is 0.025 mm/s.

function of the position. Near the opening, we see the droplets slow and after the opening, as with figure 15 we see that the droplets settle into a fixed and fairly constant terminal velocity. From these graphs, we can clearly see that the restriction affects the motion of the droplets before the opening, slowing down the flow with the deformation. Even in cases with an opening larger than the droplet size or a *w/d* of greater than 1 as in figure 15b, the droplets still move slower than before the opening.

Looking at the videos of the droplets we see that this makes sense due to the geometry of the opening. When the opening is larger than the diameter of the droplets, two droplets will wedge into the area before the opening, creating a constriction for each other. This can be seen in figure

13. In these cases, many times a momentary clog can occur, but due to the low friction, from what we observe, one droplet will overtake the other and the chamber will become unclogged.

3.4 Droplet Flux

In order to see how the flow of the droplets is affected by the pressure, I look at the number of droplets left in the chamber over time as seen in figure 17. For each chamber, it is predicted that

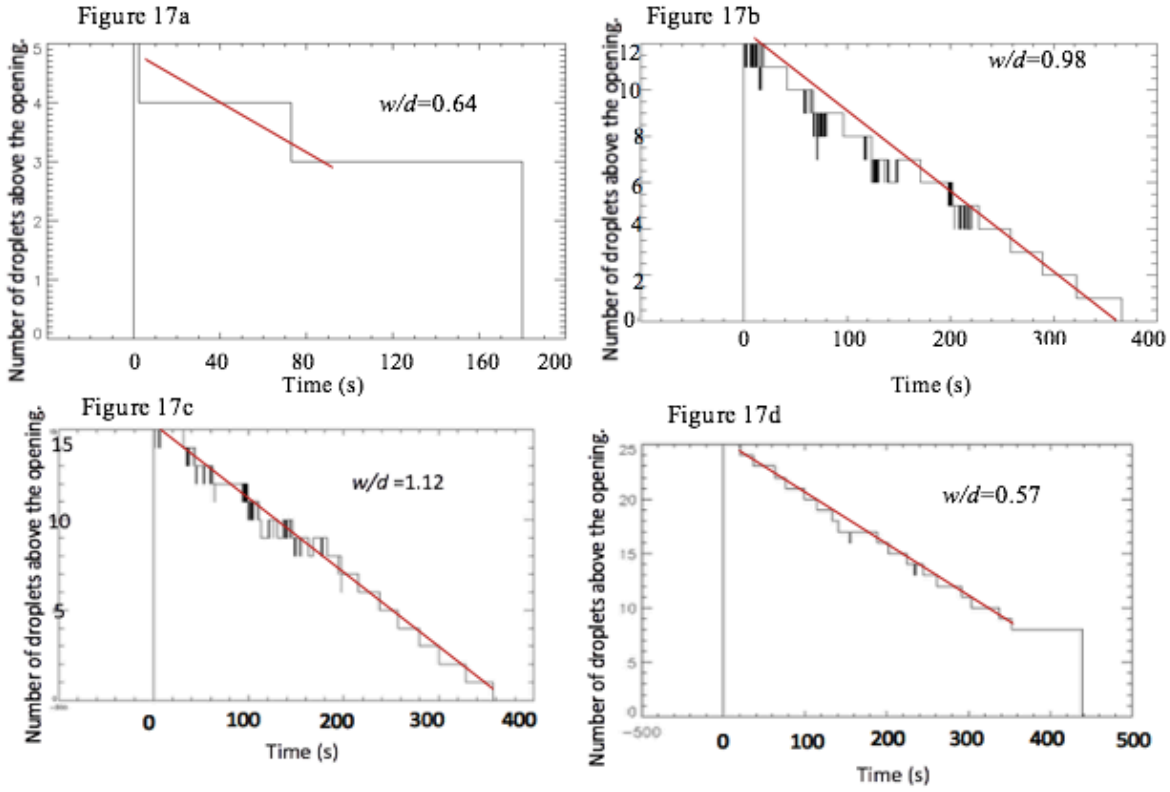

Figure 17 The number of droplets that has passed through the opening is shown over time. These show a fairly linear flux. This means that the number of droplets does not greatly affect the exit velocity. The red lines are the best fit lines that were used to determine the exit flow rate of the droplets.

the flow of the droplets would decrease as the number of particles is reduced. This is because the pressure from the droplets below is decreased, leading to a smaller pressure and thus a smaller velocity. However, as seen in figure 17, the number of droplets in the chamber seems to not affect the velocity. Each droplet moves out with a fairly similar speed to the other droplets no matter how many droplets are in the chamber. This is likely due to the scale at which we are looking. If there were an order of magnitude more droplets in the chamber, the difference in pressure would

possibly be more apparent; that is, we would expect to see some dependence of the flux on the number of droplets in the chamber.

Since the motion of the droplets is not greatly affected by pressure in this range, I wanted to see what other parameters were influencing the motion. The biggest factor in determining the

speed of exit flux is the *w/d* ratio. figure 18 shows that larger *w/d* leads to a faster outflow of the droplets. This seems to be a fairly linear relationship as well. We can see that the *w/d* greatly affects

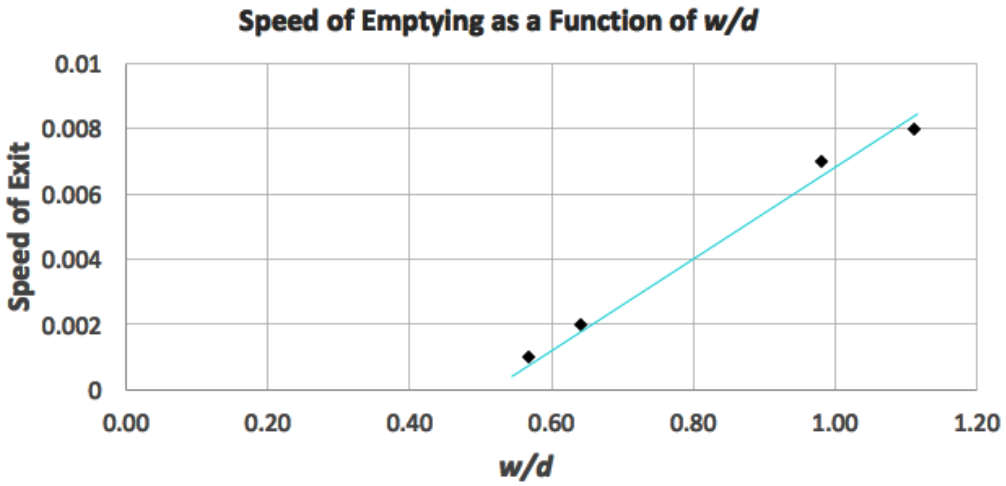

Figure 18 The exit flux of the droplets in units of droplets per second has a fairly linear relationship with the *w/d.*

the flow rate of the droplets. Beverloo found that there was a power law relationship between the mass flow rate of the particles and the *w/d*. Beverloo's law was determined to show that

$$L \sim \left(\frac{w}{d} - k\right)^{2.5}$$

where *k* is generally 1.4. In this experiment with emulsions, the resulting equations is

$$L \sim \left(\frac{w}{d} - 0.49\right)^{1}$$

A significant difference between soft particles or emulsions and hard particles is the *w/d* ratio at which no flow occurs. In Beverloo's experiment, the flow rate stops when *w/d* is equal to *k,* the material parameter. None of the granular materials studied by Beverloo had a *k* less than 1.3. In this experiment, when the relationship between the *w/d* and the exit flux is extrapolated, the flow stops at *w/d*=0.49. This means that the droplets can squish through the opening even when they are close to twice the size of the opening in diameter. For granular flow, *k* describes the material parameter of the particles and it indicated at which *w/d* the flow would not occur. For granular particles that don't squish, any *w/d* less than 1 would clearly stop the flow, but here we see the deformation property of the soft particles allows for flow with smaller *w/d* ratios. In Beverloo's equation we can also see that his fit was to a power of 2.5. The fit for this experiment was linear, with a power of 1. The power in Beverloo's experiment was determined mainly using dimensional analysis and confirmed using experimental methods. It is possible that the difference in the power could be due to the change from a 3D system in Beverloo's experiment to a 2D system in this experiment (7).

4 Conclusion

Droplets have different motion and behavior as they go through different parts of the chamber. When the droplets are moving through the chamber before the exit, they move slower, and when they pass through the exit, they speed up to a terminal velocity of around 0.025 mm/s as modeled in figures 15 and 16. The deformation of the droplets also changes depending on the position. For droplets in chambers with larger *w/d* ratios, the maximum deformation occurs slightly before the opening because the droplets compress each other in the space before the opening. In chambers with smaller *w/d*, the maximum deformation occurs closer to the opening. This can be

seen in figure 12. When looking at the total flow of droplets, it appears from figure 17 as if the pressure the other droplets in the chamber is not a significant factor in determining the velocity. The outflow of the droplets from the chamber seems to be fairly linear. The *w/d* ratio is a factor that does affect the outflow rate. There is a linear relationship between the *w/d* ratio and the flux of the droplets through the opening shown by figure 18. Overall, soft particles allow for deformation, so as long as there is enough force to overcome the surface energy change caused by changing the shape. The softness of the particles affects the flow of the droplets, allowing for flow with much smaller *w/d* ratios.

5 Future Work

In this paper, I looked at the behavior of droplets in chambers with varying *w/d* ratios. In order to understand how the chambers changed the flow, all of the droplets in the experiments are made from the same materials and are close to the same size. In future experiments, I could look to understand how different parameters of the droplet's makeup could affect their motion.

5.1 Changing Surface Tension/ Energy

The first parameter I could change would be the surface tension and its effects. In order for the droplets to move through tight openings, they must deform. Once the droplets are not pushed upwards hard enough to balance the surface tension keeping them circular, they will no longer pass through the tight opening. Surface tension can be measured using the Dropometer (dropletlab.com), which analyzes the shape of a droplet coming out of a syringe to determine the surface tension of that droplet. There are a few ways to change the surface tension of the droplets while keeping a consistent *w/d* ratio. One would be to change the surfactant. Different surfactants will allow the droplets to deform to different degrees for the same upward pressure.

Another way to change the effect of surface tension and deformation is to change the size of the droplets. Changing the size of the droplets affects both the surface energy and the gravitational energy. For quasi-2D droplets, the surface energy is proportional to d^2. The gravitational energy, *U* pushing up quasi-2D droplets is measures as

$$U \sim \rho * d^2 * g * h$$

with also increases as d^2, but since the droplets are moving upwards, there is an extra factor of *d* for the height, *h*, so the gravitational energy increases in total as d^3. This means that as the droplets get bigger, the energy benefit from flowing upwards increases faster than that for maintaining a circular shape, so larger droplets deform more easily. It would be interesting to understand how the size of the droplets affects the minimum *w/d* ratio that would allow for flow of droplets.

5.2 Changing Upward Force

Another way to manipulate the forces would be to try and increase or decrease the buoyancy force. The buoyancy force is measured as the weight of the displaced liquid. For each droplet, the upward buoyancy, *B,* is measured as

$$B \sim \rho_s * d^2 * g$$

with the ρ_s being the density of the surfactant solution, but the downward force, *F*, on each droplet due to gravity is

$$F \sim \rho_o * d^2 * g$$

with ρ_o being the density of the oil inside the droplet. This means that the net upward force is measured as

$$F_{net} \sim (\rho_s - \rho_o) * d^2 * g.$$

In order to change the net force acting on the droplets without changing the size, we can change the density of either the surfactant solution or the oil. If the difference was increased, the upward force would be larger, causing the droplets to fit through a smaller opening. If the difference was decreased, the droplets would not have as much upward force and would not be able to deform through small openings.

In some cases, it is also possible to change the effective gravitational force. Experiments have already been completed with chambers that can be held at varying tilt angles (10). At fully vertical, the gravitational constant, *g,* is about 9.8 m/s, and at fully horizontal, it is 0. In between, the force, g_{eff}, which is the force down the chamber, changes as

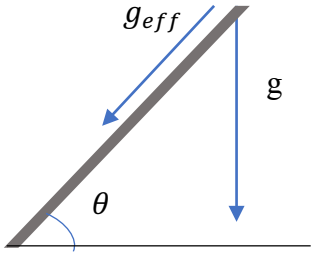

Figure 19 Side view of a chamber with a tilt angle of θ.

$$g_{eff} = \frac{g}{\sin(\theta)}$$

with θ being the tilt angle as seen in figure 19. Using a tilt in the microscope, it is possible to reduce the gravitational constant and therefor decrease the upward force.

5.3 Conclusion

In this experiment, I look at the effects of the environment of the droplets on their motion, but all of these possible changes would allow us to understand something new about what causes the droplets to flow and deform. By changing different parameters and even materials, we can learn new information about particle flow. This information can be applied to better understand different types of flow that may be more complex or difficult to study.

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