SURFACE TENSION DRIVEN FLOW OF MICRO PARTICLES

by

Lorin Baird

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Lorin Baird

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Date	Stephen Turcotte, Advisor
Date	David Oliphant, Senior Thesis Coordinator
Date	Richard Hatt, Committee Member
Date	Stephen Turcotte, Chair

ABSTRACT

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Naturally-occurring-surface-tension-induced flow could result in the generation of electricity when magnetic micro particles are suspened in rotating fluids. A water droplet sandwiched between glass slides is a potential setup for this system. Sulfate micro particles suspended in distilled water trace flow patterns in the droplet. Film thickness, temperature gradient strength, surfactant levels, particle size, and water droplet size are all parameters that affect the geometry and rotation of micro eddies in the water droplet. Surfactants reduce the speed of the micro particles on the edge. Greater temperature gradients result in faster flow on the edge. A greater distance between the glass slides results in a wider edge flow. The results in this paper are not a general model for micro eddies in liquid droplets because surfactant levels are different for every experiment. A receding evaporating edge is a problem for sustained micro eddies.

ACKNOWLEDGMENTS

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Chapter 1

Problem and Purpose of the Research

A non driven fluid rotation was observed at the air water interface by Dr. Li Tan and his graduate student Ziguang Chen while they were studying particle packing with micrometer sized sulfate micro spheres. A micro sphere, shown in Figure 1.1, was observed to rotate for half an hour near the air water interface. Although their understanding of these micrometer sized eddies was limited, they wanted to generate electricity by replacing the sulfate spheres with micro magnets. The changing magnetic field of rotating magnetic micro spheres could create a current in coiled wires. A fundamental understanding of the edge flow that causes these micro sized eddies is important to get controlled and lasting rotations.

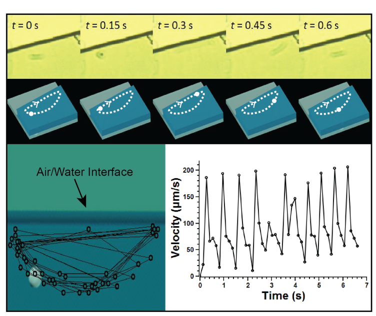

Figure 1.1 A naturally occurring fluid rotation observed near the air water interface.

1.1 Electricity Generation

Electricity generated from magnetic particles rotating in a micro eddy could be used to power small electronics such as biomedical devices. This electricity is important because it is environmentally friendly. The components of this potential generator are air, water, glass, wire, and magnetic micro particles. The micro eddy shown in Figure 1.1 is naturally occurring in that nothing is used to drive the edge or bulk flow.

1.2 Particle depositions

An idea suggested by a previous article [1] suggests using micro heaters to control flow and deposition patterns. While micro heaters were not used to control the flow, a heat gradient was used to control the direction and speed of the edge flow. The micro eddies could be used to control particle depositions on the micro and possibly nano scale. A proper application of a heat gradient will drive the particles to cooler areas. The strength of the heat gradient controls how fast the particles are moving. A cold area could also be set up to control where the particles are deposited.

Chapter 2

Literature Review

2.1 Marangoni flow

The Marangoni effect is a flow caused by a surface tension gradient. The effect was named after Marangoni number are named after Carlo Giuseppe Matteo Marangoni who first studied it in his doctorate thesis in 1865. Tears of wine, a Marangoni effect, was studied 10 years earlier by Thompson. Tears of wine is a chemical concentration gradient or a surface tension gradient caused by evaporation that drives wine up the sides of the glass. The alcohol evaporates from the wine and it falls back into the bulk [2].

Bubbles on the surface of a liquid can be driven by the surface tension gradient flow. A recent study on Marangoni heat transfer experimented with Marangoni convection and its effect on bubbles near the surface [3]. The two main causes of surface tension gradients are temperature and chemical gradients such as the ones mentioned above.

Figure 2.1 shows the direction of the flow in a temperature gradient. Water molecules on the surface are pulled to the areas of higher surface tension or the colder areas. This mass and heat transfer mechanism results in an amplified disturbance over time [4].

Surfactants are molecules that find it energetically favorable to be on the surface of a liquid because of their structure. Surfactants suppress Marangoni flow because they reduce surface tension. The strength of Marangoni flow is given by the Marangoni number which can be calculated a number of ways. The most common one is a dimensionless number that was established by Pearson [4]. A higher Marangoni number means edge flow from surface tension gradients will be much faster. A small Marangoni numbers mean slower edge flow. A number less than the critical Marangoni number will have no edge flow.

Marangoni flow is mostly studied in thin films, liquid droplets on a substrate, and computer simulations. It is mostly an effect that is present on the smaller scales because convection currents dominate on larger scales.

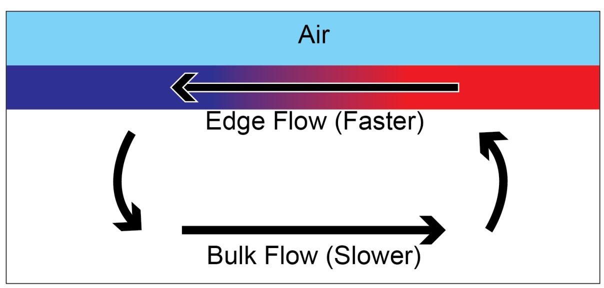

Figure 2.1 An illustration showing the edge and bulk flow from the Marangoni effect.

2.1.1 Water droplets

Flow patterns have been simulated with computers and observed experimentally. Flow patterns, and stagnation points are usually studied and observed using fluorescent particles in liquid droplets on a substrate [5].

2.1.2 Particle deposition

It is important to consider Marangoni flow on the smaller scale for things like printing, and the deposition of colloid materials on a substrate. Coffee ring depositions have been reversed when there are strong Marangoni flows. It has also been suggested that micro heaters or radiative heat transfer could be used to manipulate the flow field and deposition patterns [1]. By controlling evaporation rates, nano crystals can be made from surface tension gradients. Hexagonal nano crystals can be self assembled by controlling temperature gradients through evaporation rates [4]. Other shapes and structures are observed to form from the Marangoni effect as well [6].

2.1.3 Surfactants

The theoretical Marangoni number for distilled water that is free from surfactants is 1000. But, when there are contaminants with a concentration as low as 300 molecules per micrometer squared, the Marangoni number is reduced more than 100 times to approximately 8 [1]. Marangoni flow is not only restricted to water. Other liquids such as octane can be used. Sometimes these liquids are better for stronger Marangoni flow because they are easier to keep free from surfactants. The Marangoni number for octane is 45800. In an octane droplet $4.7\mu m$ diameter fluorescent particles had a measured velocity of 7.2 $\frac{mm}{s}$ [1]. These particles were the same size as the fluorescent particles that I was using, but they had velocities about 50x greater than my fastest edge flow.

I mainly used distilled water droplets that were very difficult to keep free from surfactants. These water droplets have a very low Marangoni number and it is even lower when the water droplet is contaminated by surfactants.

2.1.4 Fluid mechanics

Water molecules in the bulk repel because of close packing and have less energy. Energy is greatest at the surface because molecules are missing half of their neighbors. The surface is the place where there is the greatest amount of energy [7].

Chapter 3

Methods

3.1 Instruments

Fluorescent sulfate micro spheres suspended in distilled water were placed between a clean class slide and cover glass. The resulting bulk and edge flow was observed using a Meiji ML8500 series microscope. Pictures and video were taken through the microscope using a Moticam 2000 2.0 MP that was attached to the microscope. Motic Images Plus 2.0 ML was used to take length measurements from the pictures.

An Ungar #6966C Heat gun was used to heat up one end of the slide to get a temperature gradient. Parafilm “M” is a thin film that was wrapped around the glass slide to get different sandwich thicknesses. Silica micro spheres were used to measure the edge thickness but not velocity because they were too small for the camera to track individual particles. See Figure 3.1 for a picture of the microscope, camera and computer used to collect data. The following is a list of equipment used:

- Corning glass slides pre-cleaned 3”x1” .96 to 1.06 mm thick 0215 Glass.
- Fisherbrand Microscope Cover Glass 12-54-B 22x22-2: U.

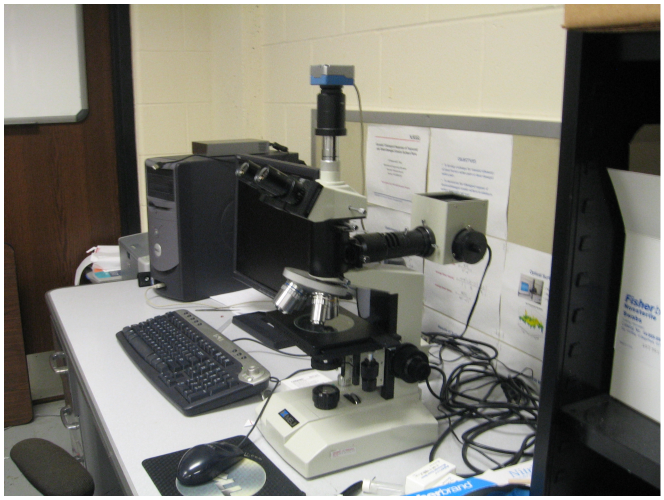

Figure 3.1 The experimental setup included the microscope, camera, and computer for data processing.

- Fluo Spheres Sulfate Micro spheres 4.2 μm diameter, red fluorescent.
- Silica Micro spheres 1+/-0.05 μm SiOxide -Polysciences.com.

3.2 Procedure

Micro particles are a colloid solution suspended in distilled water as seen in Figure 3.2. These particles must be refrigerated and protected from light to prevent them from being ruined.

A syringe injects the micro particle solution from the bottle onto the microscope slide. A whole drop should not be used because the water will have some initial angular momentum. To do this, no drop should hang from the syringe. Push the liquid to the edge of the hole in the syringe and touch it onto the glass slide. The cohesion of the water onto the glass will transfer some micro particle solution onto the slide. With a smaller drop, the whole system's evolution is observable. Put cover glass on top of the droplet. This will usually spread it out.

Observe the tracer particles in the whole droplet to confirm that there is little or

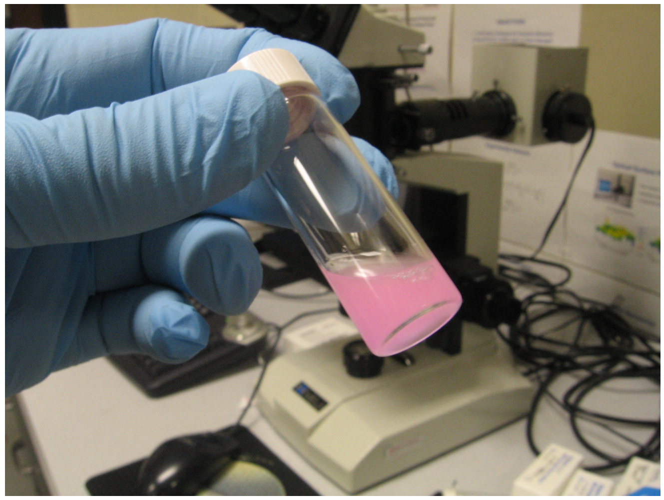

Figure 3.2 Fluorescent sulfate spheres trace the edge and bulk flow.

no bulk movement. Scan the edges of the droplet for edge flow and micro eddies. A typical water droplet that is not driven with a heat gun usually has around 10 micro eddies along the edge after 20 minutes. Take video or pictures with the camera of edge flow, recording its position on the droplet and the current direction of the heat gradient. Motic Images Plus software can make linear or curved measurements of distance. This will be used later to calculate velocity.

Use the heat gun to heat one side of the glass slide to get an induced heat gradient. The room temperature in the lab is 20 degrees Celsius. Thermometers are placed on both sides of the glass slide to measure the temperature gradient.

Limitations include camera resolution on the smaller particles, uncertainty in exact temperatures, and purity of liquids from surfactants.

3.2.1 Data analysis

A Matlab program adapted from "Measuring and Quantifying Dynamic Visual Signals in Jumping Spiders" was used to measure edge flow velocity [8]. This is done by measuring the edge of a micro eddy and the time it takes a tracer particle to travel along the edge. The time for the particle to travel the distance previously measured is given from the number of frames and the frame rate of the camera. (See Appendix A for more details).

Chapter 4

Results and Observations

4.1 Droplet size

The edge flow is observed to be amplified over time in a system where the heat gun is not used to create a temperature gradient. When larger droplets are used, there is a lot of initial movement in the bulk and on the edge. This is undesirable because it is hard to differentiate between the initial movement of the water droplet and the Marangoni effect. When a smaller droplet is used, there is no initial movement in the bulk or the edge. Sporadic movement starts at the edges in the smaller droplet after a few minutes. This back and forth movement doesn't take the particles on the edge far from their initial positions. After 20 minutes all the particles are flowing in the same direction.

4.2 Surfactant effects on the edge flow

Two different surfactants introduced into the water droplet reduced or eliminated edge flow.

Adding oil results in a receding edge but no edge flow. Micro particles are carried toward the bulk by the receding edge. They are not forced along the edge.

A low concentration of ammonium C12-15 pareth sulfate slows the edge flow, but does not stop it. Figure 4.1 shows the particles being carried toward the bulk in a direction normal to the edge. At 10 minutes the edge flow velocity is about 3 micrometers per second. At 20 minutes the initial disturbance is amplified to 10 micrometers per second. At 40 minutes the edge flow velocity drops to less than 5 micrometers per second. At 60 minutes there is no movement and the edge has stopped receding.

When the water droplet is accidentally contaminated with surfactants, there is little or no edge flow observed. If the surfactants have reduced the Marangoni number to less the critical level there will be no edge flow, even when a heat gun is used to create a strong temperature gradient.

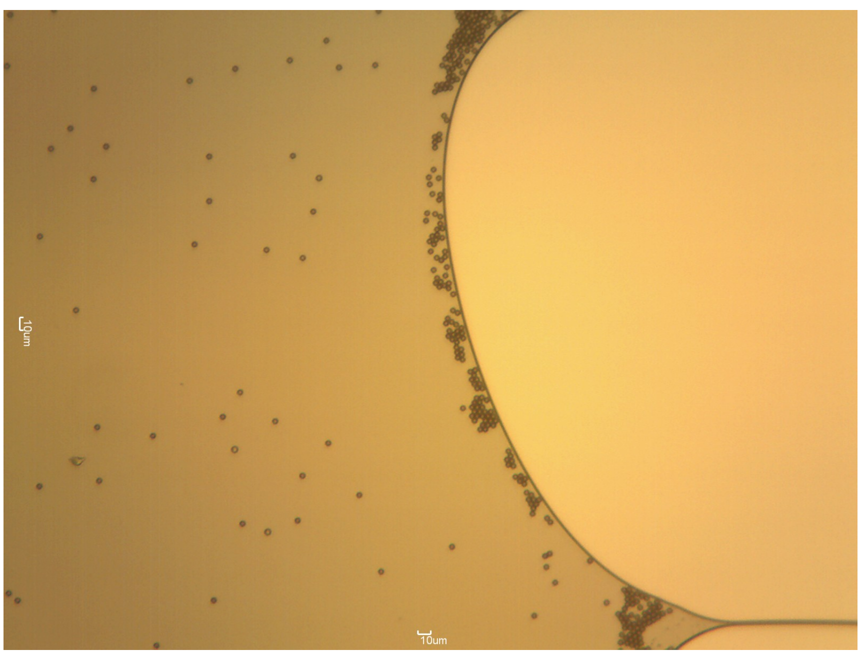

Figure 4.1 A water droplet with ammonium C12-15 pareth sulfate added has no edge flow.

4.3 Induced heat gradient

Heated and cooled lumps of clay do not create a sufficient temperature gradient to influence the direction of flow. The hot lump of clay, heated in an oven at 55°C, is placed directly on one side of the glass slide. The cold lump, cooled in a freezer to 0°C, is placed on the glass slide opposite the hot clay. In this setup the tracer particles near the edge flow from cold to hot. This is in conflict with the current literature on the Marangoni which says that edge flow should be in the direction of higher surface tension, hot to cold.

When a heat gun raises the temperature of one side of the glass slide, a temperature gradient is created that is large enough to get the particles moving in the direction predicted by the literature. This result suggests that the heated and cooled lumps of clay do not produce a strong enough temperature gradient or that they relax to room temperature too quickly.

Figure 4.2 shows the particle velocity in the edge flow against the strength of the temperature gradient in the heat gun experiments. The velocities in the figure are taken from a micro eddy as it cools. The velocity of $20\frac{\mu m}{s}$ at a temperature gradient of $\frac{0^\circ}{m}$ is caused by uneven evaporation in the water droplet and can not be measured with the thermometers on the glass slide.

A stronger heat gradient results in faster edge flow. The relationship appears to be linear over the temperature range. It should be remembered that my experiments are not a general model because the Marangoni number changes drastically with contaminants. One experiment had a Marangoni number below the critical Marangoni number because heating with the heat gun did not produce any edge flow.

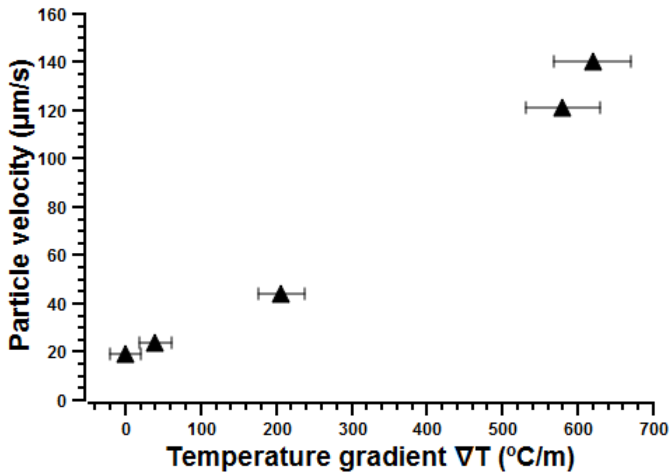

Figure 4.2 Particle velocity in the edge flow plotted against temperature gradient strength shows a linear relationship.

4.4 Receding edge

The initial small droplet system has no receding edge. Uneven evaporation and the amplified Marangoni effect start to cool one area on the drop rather than many points. The coolest and most active evaporation point results in a receding edge. The center of the receding edge is where the particles flow to and accumulate. The side of the drop opposite of this receding edge will not recede.

The evaporating and receding edge causes the temperature gradients, but it would also disrupt the micro eddies. The duration of a micro eddy is mainly determined by the disruption of the receding edge.

4.5 Sandwich thickness

Edge flow width is linearly proportional to sandwich thickness as seen in Figure 4.4. The edge flow width has some implications for micro eddy creation. If the edge flow is too thin, then the micro spheres cannot be moved by it. If the edge flow is too wide, then naturally occurring obstacles do not force particles back into the bulk rotation.

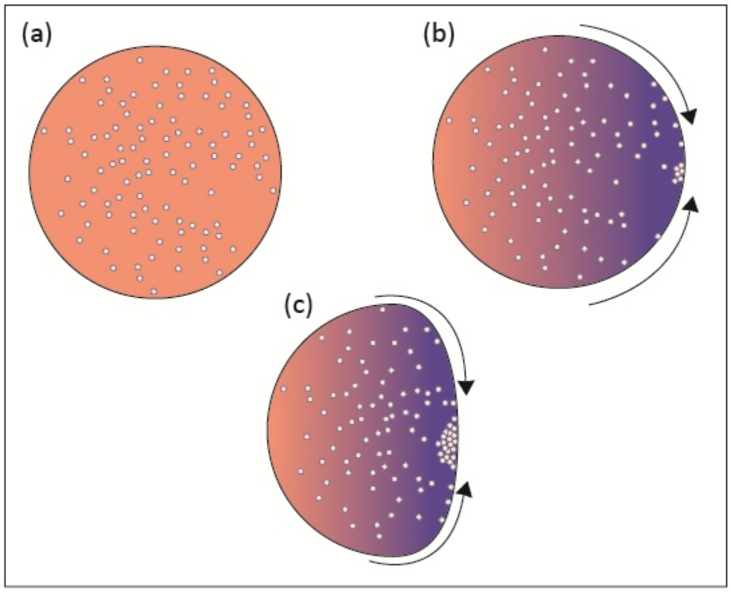

Figure 4.3 (a) Initial water droplet with uniform temperature. (b) Uneven evaporation results in the Marangoni effect which is amplified over time. Water on the surface flows to the colder area. (c) Stagnation points and particle buildup occur where there is no temperature gradient.

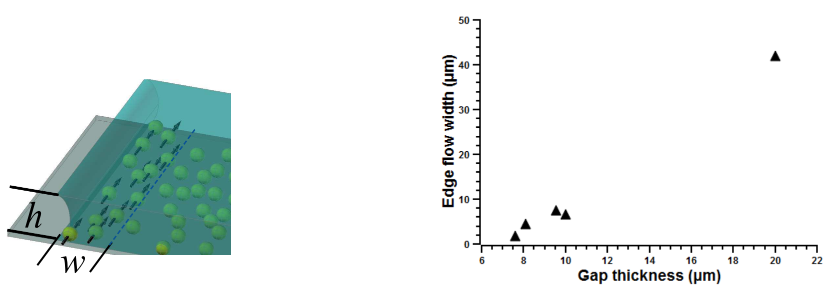

Figure 4.4 A schematic showing how the edge glow width compares to the gap thickness.

4.6 Liquid type and particle size

Particle rotations are still observed when ethanol is used in placed of water. This is the only other liquid used besides water.

The size of the micro/nano particles determined if they would be caught in the edge flow. Bigger particles could not be carried by the edge flow in one experiment either because the edge flow was not wide or powerful enough (See Figure 4.5).

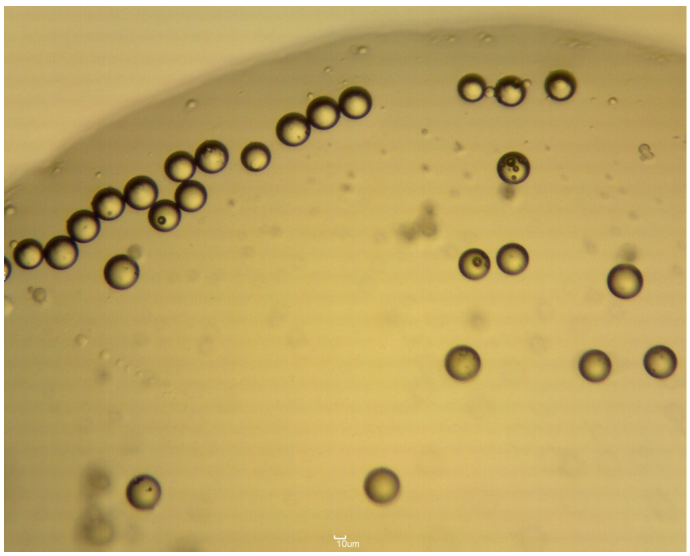

Figure 4.5 Edge flow in this water droplet was not strong or wide enough to carry these $30\mu m$ diameter particles.

Chapter 5

Discussion of the Results

5.1 Edge flow is caused by surface tension gradients

Surfactants and temperature gradients are the two main parameters to test to see if the edge flow is a Marangoni effect. For a temperature gradient, an equation for the surface tension of distilled water (N/m) for temperatures 0°-374°C is

$$\sigma = -0.0002 * T + .0778 \tag{5.1}$$

Where $\sigma$is surface tension in (N/m) and T is temperature in Celsius [9]. Higher temperatures are areas of lower surface tension. Water molecules are pulled along the surface to areas of higher surface tension, or the colder areas.

Edge flow is observed in the directioin of the colder areas when a temperature gradient is forced with a heat gun. The direction of the flow can easily be manipulated with the heat gun knowing that the edge flow will go in the direction of the colder. Heating up the slide to higher temperatures will also result in stronger temperature gradients and faster edge flow.

Naturally occurring temperature gradients also cause edge flow. Evaporation cools down one side of the droplet, and this is where the particles will flow to. The opposite side of the drop was the hotter side. Because there is no gradient on the hot or the cool sides, there are always two stagnation points the drop. There is only edge flow where there is a temperature gradient.

One possibility for the mechanism behind edge flow is the receding edge. One way to test this is to add surfactants to the drop. There is still a receding edge, but surface tension is drastically reduced. When oil was added to the droplet, there was still a receding edge but the particles were just pushed into the bulk instead of carried along the edge. When ammonium pareth sulfate was added to the droplet there was still a receding edge and some edge flow. The reduction in surface tension resulted in edge flow that was 2-14 times slower than a water droplet without surfactants added.

5.2 Description of the micro eddies

When micro particles are near the air and water boundary they are carried with the water molecules to the areas of higher surface tension. When there are no obstacles, the particles will flow along the edge to the area of highest surface tension (See Figure 5.1 part (a) and (b)). If the micro particles meet the obstruction, they are forced away from the edge. Three things can happen when a micro particle is forced away from the edge: it can go around it, back into the bulk, or is can be forced into a rotation as in Figure 5.1 part (c).

As the water on the edge moves to higher surface tension areas, it is replaced by the water in the bulk as seen in Figure 5.2. The water in the bulk is warmer than the cold spot where the water is evaporating and the initial temperature gradient is amplified over time.

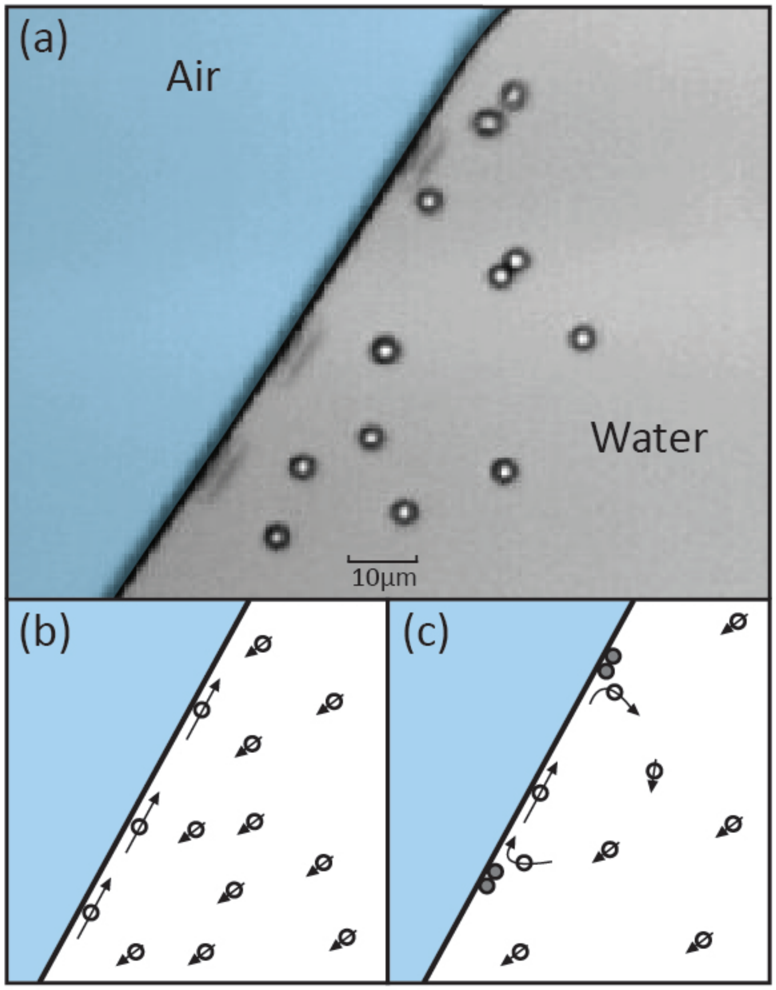

Figure 5.1 (a) A picture of unobstructed edge flow from the Marangoni effect. (b) A schematic showing bulk and edge flow from the Marangoni effect. (c) A schematic showing the geometry that leads to micro eddies. Grey circles are immobile

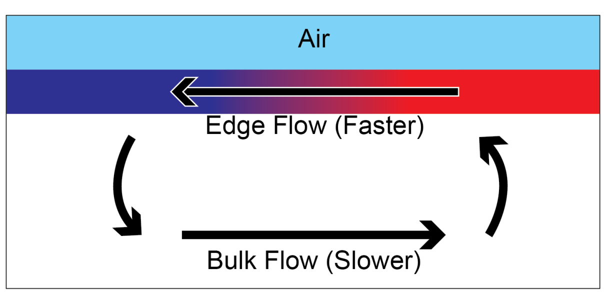

Figure 5.2 An illustration showing the edge and bulk flow from the Marangoni effect.

5.3 Conclusion

The direction, speed, and width of the edge flow can be controlled by varying the strength of a temperature gradient, sandwich gap thickness, and surfactant levels. Some obstacles to make the micro eddy mechanism into an electrical generator include: the short duration of fluid rotations (longest observed rotation is 30 minutes), the solubility of water makes it difficult to keep free from surfactants, and the receding edge caused by evaporation water disrupts the micro eddies.

To overcome the obstacles of the receding edge and the short duration of micro eddies, the water in the droplet will need to be replenished. A future work would possibly include a mechanism to replace the water that evaporates. A liquid that is easier to keep free from surfactants could be used for faster edge flow.

Controlling micro eddies and edge flow for particle deposition could be done using micro heaters, coolers, or focused light. Many particles could be transported to cooler areas on a substrate. The number of particles and their speed, which influences particle packing, can be controlled using the parameters discussed above.

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Appendix A

1. When taking videos under microscope, take a picture as well. Measure the length of the particle path with the software for the microscope.
2. Convert the .avi video file to a Matlab file with the program “aviConverter”
3. Run the Matlab video in the “LinearVelocity” program.
4. Count the number of frames that it takes the particle to travel the path length. Frame number is displayed in Matlab’s output window. Keep pressing space bar to advance frames.
5. Time can be calculated from the number of frames per second, and the number of frames it took to travel the length.
6. Now you can calculate velocity of a particle. Time comes from the number of frames. Distance comes from the measured length from the microscope software.

AVI converter

```
clear all
    % Put the avi file name here
    % Make sure you have the right number of frames
    % If you run it with a number that is too high, it will tell you how many
    % frames the video is.
    filename='after'; frames=[1:86];
    fout='matlab';
```

% Put the file path where the video is located here with a '\' at the end

% Example: [C:\Users\Videos\,filename,'.avi']...

mov = aviread (...

['C:\Users\Lorin\Documents\NANO\Digital lab notebook\Videos\Heat Gun 2\',file-name,'.avi'],...

frames);

% Put the file path of the place you want your matlab video to be

filename=[filename,fout];

save (['C:\Users\Lorin\Documents\NANO\Digital lab notebook\Videos\Heat Gun 2\',...

filename,'.mat'])

Linear Velocity Program

clear all

figure(1)

clf

set(gcf,'doublebuffer','on');

% Put the name of the video file with 'matlab' at the end

% Example: filename='your videomatlab';xRange = [1:1600]; yRange = [1:1200];

% Make sure the dimensions to your video are the right size in xRange and

% yRange

filename='aftermatlab';xRange = [1:1600]; yRange = [1:1200];

% Make sure the path to the video file is here with a '\' at the end.

% Example: load(['C:\Users\Videos\',filename,'.mat']);

load(['C:\Users\Lorin\Documents\NANO\Digital lab notebook\Videos\Heat Gun

```
2\',filename,'.mat']);
    [nX,nY,junk] = size(mov(1).cdata) ;
    [junk,nT] = size(mov);
    rfactor = .5;
    frameNumber=0;
    clear vol
    %=====================================
    tstep = 1;
    count = 1;
    for i=1:tstep:nT
    im = mov(i).cdata(yRange,xRange,:);
    im = imresize(rgb2gray(im),rfactor,'bicubic');
    imagesc(im);
    colormap(gray)
    drawnow
    vol(:,:,count) = double(im) ;
    pause;
    frameNumber=frameNumber+1
    count=count+1;
    end
```