Mechanical Engineering and Materials Science Independent Study

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12-13-2019

Droplet Condensation and Actuation via Surface Acoustic Waves on Lubricant Infused Surfaces

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December 2019

Abstract

Both lubricant-infused surfaces and surface acoustic waves have been studied for their applicability to the field of microfluidics. However, combining the use of the two technologies has not been thoroughly explored. Specifically, this research aims to build off of the work done with single droplets last semester to characterize the way surface acoustic waves cause condensed droplets to behave over a range of wave frequencies and amplitudes, as well as droplet sizes, for possible heat transfer applications. From this study, it is clear that there are four distinct modes of droplet actuation for a given frequency, depending on their size. Large droplets (high diameter) actuate freely, while a range of smaller droplets will not move at all. Droplets that are smaller still will start to move again to a point, while the smallest droplets observed did not move, but did evaporate more quickly when exposed to surface acoustic waves. The exact mechanisms driving this behavior are not currently understood, but still this research shows promise, as further developing an understanding of these phases of droplet movement could allow for greater control in microfluidic applications.

Introduction

This experiment involved the use of lubricant-infused surfaces (LIS) and surface acoustic wave (SAW) generating interdigital transducers (IDTs) for droplet manipulation purposes. Lubricant-infused surfaces consist of two main components: a porous underlayer of hydrophobic material (such as glaco, a polymer spray used to repel water from windshields), and a surface layer of oil [1]. The atomically flat surface provided by LIS allows for the placement and smooth movement of water droplets on the surface, as shown in Figure 1.

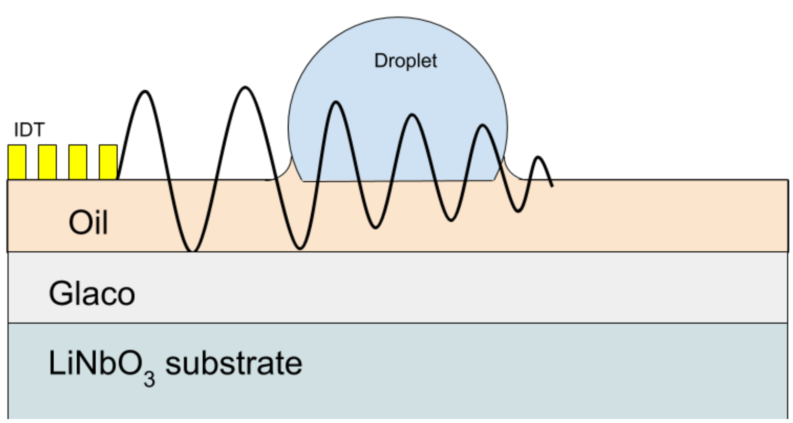

Figure 1: Schematic of a water droplet subject to surface acoustic waves on LIS. The sample consists of a layer of glaco deposited on a piezoelectric substrate, with a layer of oil infused. The droplet sits on top of the oil, affording a useful balance between contact area and low contact angle hysteresis and thus reducing the force needed from the IDT.

By condensing and then expelling droplets from the surface, the rate of heat transfer between the surface and the surrounding vapor can be increased. Because of their robustness, LIS have applications in industry and lab environments for controlled heat transfer, including using LIS to protect surfaces from unwanted biocontamination and fouling in heat exchangers [2].

SAW interdigital transducers are electrical devices used to generate surface acoustic waves of desired frequencies on piezoelectric substrates. Each IDT consists of a series of interspersed metal strips, the spacing of which determines the frequency of the surface acoustic wave generated. Many types exist for different applications, but for this research chirped IDTs were selected. Because of a differential spacing between fingers, they allow for operation over a broad range of frequencies rather than just one. As shown in Figure 1, the waves generated by an IDT propagate along the substrate perpendicular to the direction of the fingers. This directionality affords greater control over the effects of the waves.

When a surface acoustic wave encounters a droplet, the wave diffracts into the droplet, imparting its energy and momentum into the droplet [3]. A certain minimum force will have to be overcome in order to move the droplet. Otherwise the wave will simply induce acoustic streaming within the droplet without actually moving it. This minimum required force increases with the droplet radius and sine of the contact angle, and also depends on the wettability of the droplet.

Procedure

Before any data could be collected, a lubricant-infused surface first needed to be fabricated on a piezoelectric $LiNbO_3$ substrate with a SAW IDT already fabricated on it. The fabrication of IDTs is a complicated process involving multiple days of work, and is not the main area of study for this project. As such, IDTs for this project have been supplied by a PHD student in Dr. Meacham's lab, Minyang Cui, who has been fabricating them along with IDTs for his own research to be efficient.

Once the IDT has been fabricated, I cleaned the sample using isopropyl alcohol and water. Then an even coat of glaco (a commercially available water repellant) was applied to the surface and allowed to dry. Once completely dry, the surface was spin coated with Krytox 104 oil (a medium viscosity industrial grade oil) for 60 seconds at 2000 RPM, thus creating a uniform oil layer on the $LiNbO_3$ substrate.

For the lower magnification images (1X-5X), an Edgertronic SC1 high-speed camera with a 1x Nikon macro lens was fixed above the stage to record the effects of the SAW on the droplets. For the higher magnification images (5X-50X), a Photron Mini high-speed camera was used with microscope lenses of various magnifications to record slow motion videos. In both cases, the camera was calibrated by taking a picture of a syringe of known diameter once it was focused, allowing the size of one pixel in the shot to be calculated later on.

The substrate containing the IDT and LIS was then placed on a cold plate on a level stage. The cold plate was held at a constant 0℃ by circulating ice water through it. A hot plate was used to heat a beaker of deionized water and produce steam, which was then blown over the sample with a gentle stream of inert nitrogen gas. The water vapor was condensed onto the substrate in this way, producing an even spread of droplets on the lubricant infused surface. The IDT was then supplied with power from a function generator connected to an AC signal amplifier. This setup is shown in Figure 2 below.

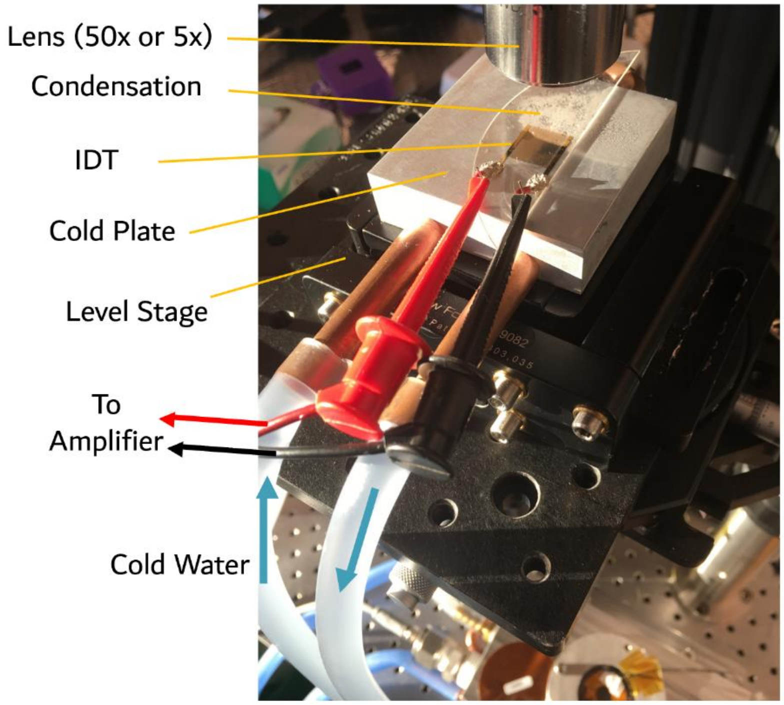

Figure 2: Experimental setup: The stage was leveled before conducting any experiments, to ensure that the effects of gravity would be negligible.

Trials were conducted with droplets ranging in size from 1mm to 0.05mm, using lenses of progressively higher magnifications to get a closer look at the smaller droplets. After the data was collected, the images were processed in a MATLAB script that counted each droplet, its location, and its radius for every 125 frames in the video.

Results

With a 1X lens, droplets around 1mm in diameter would begin to actuate at frequencies between 8 and 9 MHz. As the droplets moved, they would coalesce into larger droplets, which moved at slower speeds. Shown below in Figure 3 is an example of the clearing capability of the IDT, actuating at 8.5MHz with an amplitude from the function generator of 200mV peak to peak. It clears the droplets a distance of about 8mm.

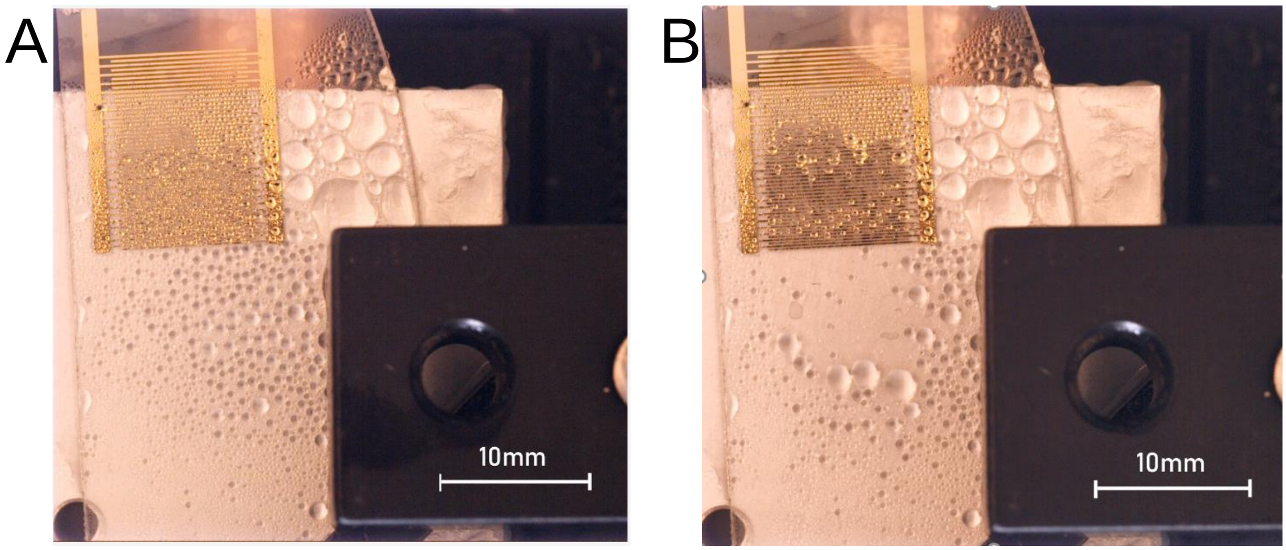

Figure 3: Shown in A are the droplets before actuation, and in B the effects of the 8.5MHz wave.

After running numerous trials at this droplet scale and magnification, I studied smaller droplets under a 5X microscope lens. In the trial shown below in Figure 4, droplets smaller than 0.25mm in diameter were condensed on the LIS. Then a droplet with about a 1mm diameter was deposited on the surface with a 30-gauge syringe. The IDT was then supplied an 8.5MHz frequency at 250mV peak to peak from the function generator. The large droplet moved quickly, but the smaller droplets around it were impeded and moved much more slowly. The oil on top of the substrate was displaced by the smaller droplets. As these droplets coalesced with the large droplet, the oil they displaced did not settle evenly. Rather, it began to stream in the direction of the SAW actuation.

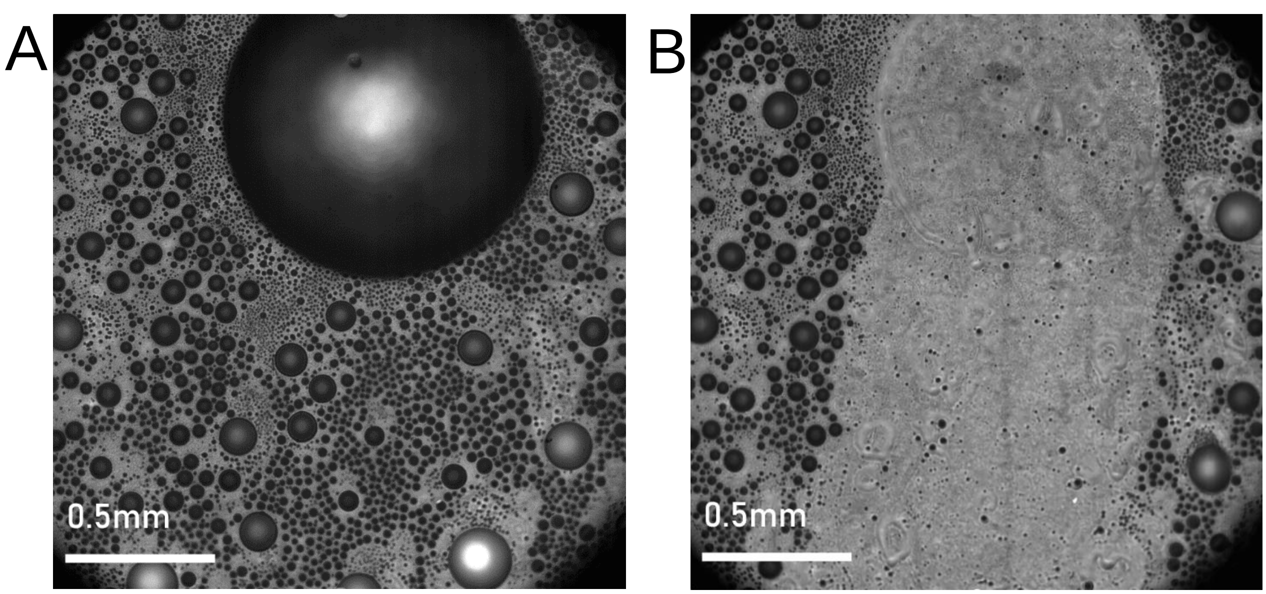

Figure 4: Shown in A are the droplets before actuation, and in B the effects of the 8.5MHz wave. Note the streaming of the oil menisci.

More trials were conducted at 50X magnification, to get a look at droplets in the size range of 0.1 to droplets at micrometer scales. In the trial shown in Figure 5, droplets between 0.1 and 0.03mm were condensed, then actuated with an 8.5MHz 250mV peak to peak signal. The droplets are able to actuate, and the area is cleared. At this scale the oil streaming is even more visible, as well as small defects in the surface, possible due to repeated droplet condensing.

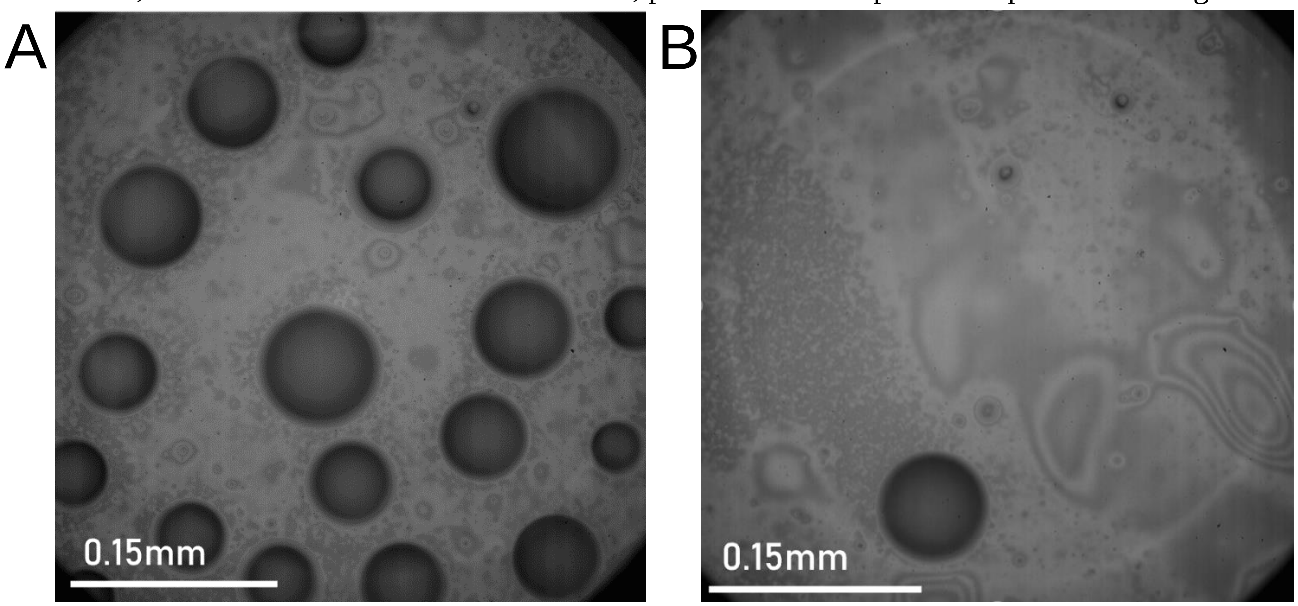

Figure 5: Shown in A are the droplets before actuation, and in B the effects of the 8.5MHz wave. The light circle is a lens defect, not a part of the actual surface. Note the streaming of the oil in the direction of droplet actuation.

Another interesting phenomenon was observed at 50X magnification, this time to do with droplets at the micrometer scale. At this size, the droplets didn’t move from the locations where they condensed, but they did appear to evaporate more quickly than droplets of the same size without the actuation.

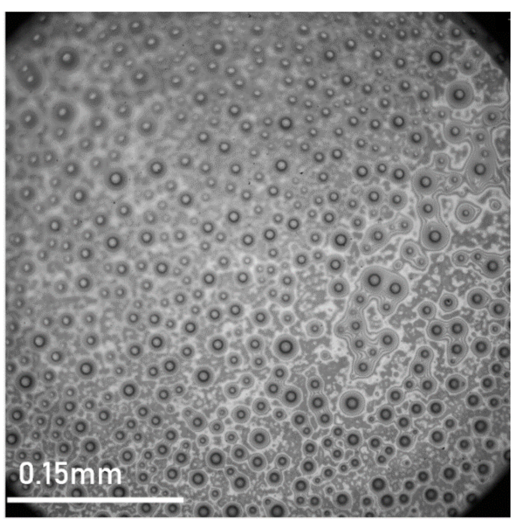

Figure 5: Shown in A are the droplets before actuation, and in B the effects of the 8.5MHz wave. These droplets evaporated quickly.

Analysis

There is quite a lot going on in each of these videos, with far too many droplets to be counted by hand. Because of this, MATLAB was used to identify each droplet in a given frame and record data about their sizes and locations. This data was exported into a Microsoft Excel spreadsheet, from which the data could be processed analyzed. The first area we tackled using this method was the droplet evaporation noticed at the smallest scale described above, because the droplets were not moving, and thus could be more easily analyzed. The MATLAB program reads in a single frame, then uses the built in imFindCircles() method to locate droplets within a certain size range. This is done for every relevant size range, and then the next frame is processed. Shown below in Figure 6 is a single frame with circles drawn to show the droplets that MATLAB was able to find for one of the evaporation trials. As you can see, the droplet detection isn’t perfect, but it is able to measure the vast majority of droplets in the frame.

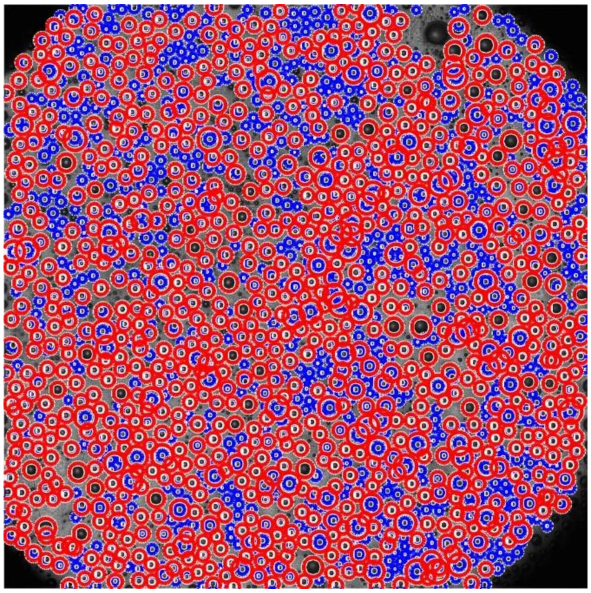

Figure 6: Each color of circle corresponds to a different size range the program searched for.

Graphs were produced showing the number of droplets in a frame versus the timestamp of the frame for trials with and without SAW actuation. Shown in Figure 7 are the results of this analysis. The rising droplet count region represents the condensation of the droplets, followed by a steady decline in droplet count and then a sharp decrease as the droplets evaporate. The trial without any SAW actuation took 46 seconds to evaporate from a starting average droplet diameter of 6um, while the trial with an 8MHz SAW took only 20s from the same starting droplet diameter.

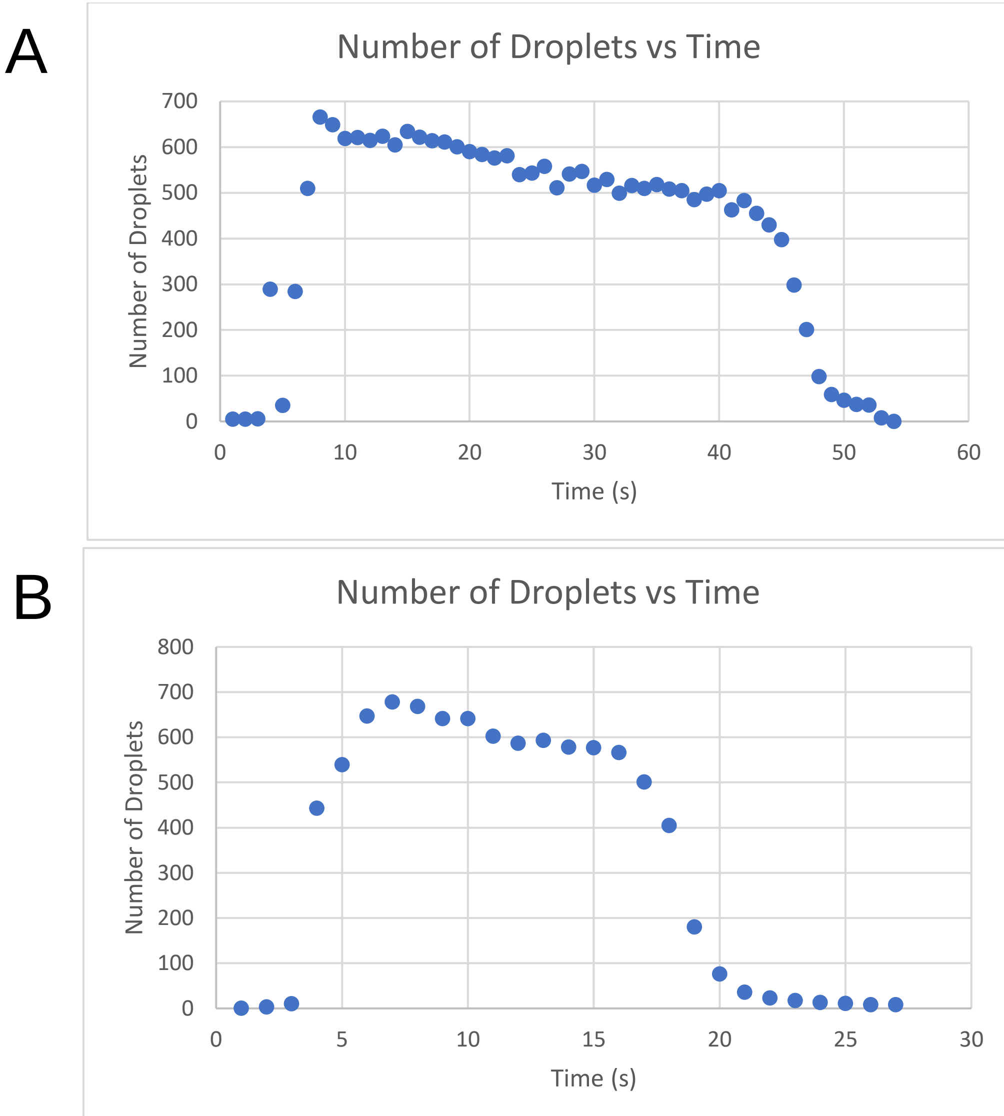

Figure 7: A shows a trial without SAW actuation, and B shows the same plot but for a trial with an 8MHz SAW.

Modeling the behavior of the more complicated videos is an ongoing effort. Figuring out how to accurately track moving droplets to make sense of what is going on in a quantitative way is a much more challenging computational problem than dealing with static droplets as shown above.

Discussion

From the results shown above, it seems that there are four main modes of droplet behavior for a given frequency, depending on the droplet size. The first of these modes is the acoustic streaming that was observed at the lowest magnification. A proposed explanation for this is that the droplet diameter was simply large enough that the droplet had enough contact area for the SAW to diffract into it, thus overcoming the pinning force described in the introduction to this paper.

The second observed behavior is that droplets within a certain diameter range did not move, as observed in the studies with a 5x microscope lens. This is likely due to the smaller droplets having a smaller radius as well as a contact angle that exceeds 90 degrees. Because the small droplets weigh less, they sit with a much higher contact angle, which decreases their contact area and makes them more difficult to move.

The third mode of droplet motion observed is that droplets that were yet smaller began to actuate again. The exact reasons for this are unclear, but it could have something to do with the streaming of the oil noted above. Perhaps when the droplets get below a certain maximum size, viscous interactions with the streaming oil begin to affect their movement more intensely. It could be that the oil streams enough to carry them like a tiny, slow moving river. It could also be that these droplets are so small that the meniscus of oil around them makes up a significant amount of the area they are contacting the oil, allowing the SAW to leak more efficiently into the droplet. Whatever the exact reasons, it is likely that the effects of the oil are what cause droplets in this size range to begin to move again.

The fourth observed behavior was most noticeable with very small droplets. They did not move from the locations where they were condensed. This is likely because they first condensed with a very high contact angle and did not have a very high contact area, making it difficult for the SAW to leak into these droplets. However, they did evaporate significantly faster in the presence of a SAW. There are two proposed reasons for this. First, the IDT heats the substrate on which it is fabricated, and will heat it up more with prolonged use. It is possible that this heat was simply transferred directly to the droplets, causing them to evaporate faster. However, the sample was on a cold plate, which may have counteracted this effect. A second cause of the increased evaporation speed could be that the SAW, while not leaking enough to move the droplet, was leaking enough to cause it to stream internally. This internal streaming could have created a convection current inside the droplets that increased their rate of heat transfer with the air, causing the faster evaporation. This experiment needs to be repeated under an infrared camera to get a thermal image to get a better picture of what is happening.

Conclusion

In short, it is clear that the behavior a droplet experiences when exposed to a surface acoustic wave on a lubricant infused surface depends significantly on the size of the droplet for a given SAW frequency. More work is needed to verify the proposed modes of droplet behavior, as well as to explain the causes of the phenomena observed. Specifically, more work needs to be done on image processing to quantify the behavior of large numbers of moving droplets. Different IDT designs, different thicknesses and viscosities of oil, and different droplet materials should also be tested.

References

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