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The Effects of Oil Viscosity and Water Vapor Temperature on Droplet Condensation in Lubricant-Infused Surfaces

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Abstract

This experiment is meant to measure the effects of oil viscosity and water vapor temperature on the nucleation rate of droplets on lubricant-infused surfaces. To accomplish this, three different lubricants with a range of viscosities were used. Each lubricant was placed on top on a glass stage with a coating of Glaco, a superhydrophobic surface coating, to create the lubricant-infused surface. The surface was then placed on top of a cold stage in order to cool the sample. Then, hot water vapor was blown over the surface of the sample so that it could condense to form droplets on the surface. After observing the droplet formation, it was found that the droplet nucleation rate increases with increasing water vapor temperature. Also, there is a general trend in the data that as the viscosity of the oil increases, the rate of droplet formation decreases. This trend is not as clear, however, and further experimentation would perhaps be needed to validate this conclusion.

Background

Vapor condensation is widely used in many industries and has a wide variety of applications. Some of these applications include air-conditioning, power generation, and water-harvesting. Filmwise condensation, where the condensate on the surface forms a thick insulating liquid film, is commonly encountered due to the liquid’s tendency to stick most solid surfaces. Another method that is used—and preferred—is that of dropwise condensation. Dropwise condensation occurs when the condensate forms distinct droplets due to a low surface energy of the solid. During dropwise condensation, the heat transfer between the vapor, the droplets, and the surface can be an order of magnitude larger than in filmwise condensation. A so-called *lubricant-infused surface* (LIS) is a surface that stimulates dropwise condensation and maintains stable operating conditions even at high supersaturation. Lubricant-infused surfaces are a promising approach to promote dropwise condensation [1].

A lubricant-infused surface consists of a flat surface—in this experiment a glass stage—coated with a superhydrophobic layer and impregnated with oil or some type of lubricant. The superhydrophobic properties of the initial coating are achieved through the microstructure of the material. Fig. 1, below, shows a microscopic view of the microstructure of Glaco, a widely available superhydrophobic material.

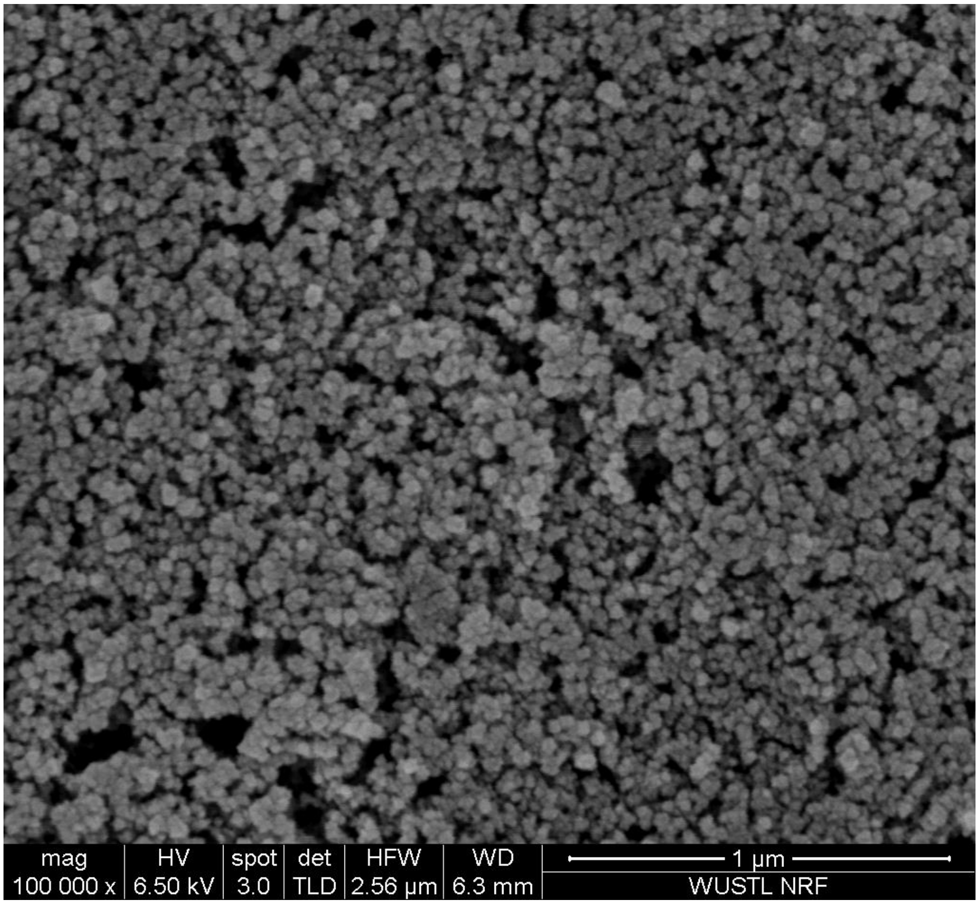

Fig. 1 Glaco microstructure.

By coating a surface with Glaco or some other superhydrophobic coating, water is repelled from the surface. Rather than spreading out and being absorbed into the surface, water that is placed on top of the superhydrophobic surface remains in a compact droplet.

The lubricant that is impregnated into the superhydrophobic coating increases droplet mobility. Droplets on LIS have very high mobility due to a lubricating film between droplets and solid surface. Sometimes, however, the lubricant will entirely encase a particular droplet. When this occurs, the droplet has a lower sliding velocity and increased viscous dissipation. Droplet movement on a lubricant-infused surface is of great importance in ensuring stable operation, and depends strongly on the dynamics of the lubricating oil film. Another phenomenon that can occur is droplet sweeping. This is essential to maintaining nucleation sites, remove condensate, and maintain high heat transfer rates.

There has been a lack of research devoted to droplet mobility on lubricant-infused surfaces on the microscale. The mechanisms that govern microdroplet mobility on LIS is still not well understood. Dr. Weisensee's research group has only recently observed rigorous and random droplet movement on these surfaces. Their hypothesis was that the wetting ridges of neighboring droplets overlap and cause an attractive force, leading to this observed movement. As vapor condensation continues, two distinct regions formed on the surface: oil-concentrated and oil-drained regions. Droplets behaved very differently in these two regions. In oil-concentrated regions, droplets as small as 8 μm become mobile. On the other hand, in oil-drained regions droplets grew much bigger and remained stationary. In this experiment, we mainly investigated the droplet movement and heat transfer in the oil-concentrated regions using the techniques outlined below.

Methods

Preparation of lubricant-infused surface samples:

We used nano-porous aluminum samples in this experiment. We first cleaned the polished Al samples, immersed them in hot DI water to create the nanostructures (boehmite), and then impregnated the samples with lubricant using a spin coating. We used various rotational speeds to change the thickness of the lubricant. The lubricants we used were Krytox GPL 102, GPL 104 and GPL 106. These lubricants were chosen because of their varying viscosities. GPL 102 has a viscosity of around 38 cSt, GPL 104 has a viscosity of around 177 cSt, and GPL 106 has a viscosity of around 882 cSt. This will allow us to measure the effects of viscosity on droplet formation.

Experimental setup:

The condensation apparatus consists of a Linkam PE120 cold stage mounted on the stage of a microscope. The sample is attached to the plate surface with double-sided thermally conductive tape. The cold stage that sits underneath the sample is cooled using ice water. The cold stage will remain at an approximately constant temperature throughout all trials. A flask of water is placed on a heater in order to facilitate the creation of droplets. The water flask is completely sealed. A tube of compressed nitrogen gas is inserted into the heated flask. The nitrogen and water vapor gaseous mixture then exits the flask and blows over the sample. The temperature of the water vapor as it blows over the sample is varied between trials. We measured droplet formation within a water vapor temperature range of approximately 25^{O} C to 55^{O} C. We use a camera coupled to the microscope to measure the droplet condensation on the surface. A diagram of the setup is shown below in Fig. 2.

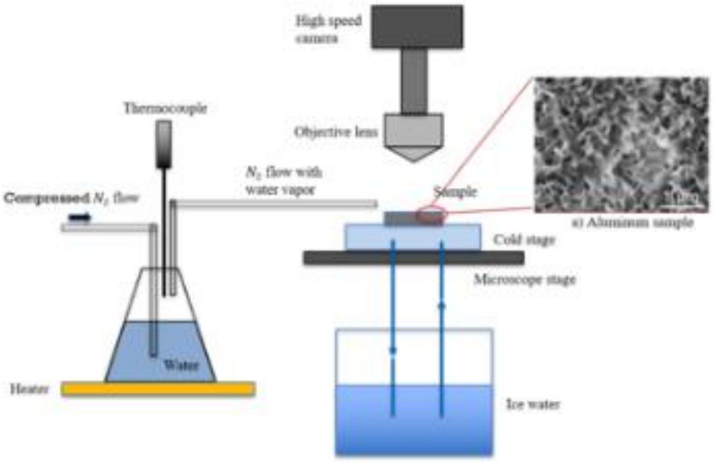

Fig. 2 Schematic of experimental setup [1].

We will analyze the droplet formation using various cameras at various recording speeds (including a high-speed camera).

White light interferometry:

We used white-light interference to measure the lubricant film thickness change during water vapor condensation. We can calculate the change in thickness of the lubricant film by measuring the light that is reflected off of the sample using a monochromatic LED light source and a high-resolution camera. Fig. 3 below shows the principles of this technique.

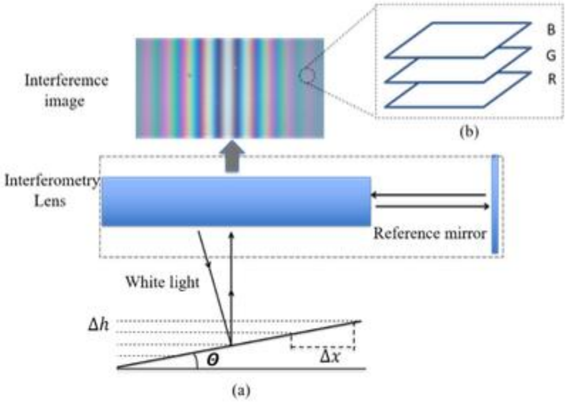

Fig. 3 Principles of white light interferometry.

For each trial, the high-speed camera that was connected to the microscope was initially placed so that the camera captured a particular location on the sample. After collecting around 10 or 20 seconds of video footage at this location, the camera was moved to a different location. This was repeated for four or five different locations for each trial. We repeated this procedure using three different lubricant oils over a range of water vapor temperatures. For each combination of lubricant and temperature, we repeated the experiment several times.

Analysis

After the video footage was collected, we used video software in order to replay and analyze the footage. For each location in each trial, we collected around 10 to 20 seconds of video footage. Because analyzing this much video footage over every trial would be too tedious, we chose three or four random one second intervals of video footage to analyze depending on the length of the video. This greatly reduced the amount of video analysis required. In each one second interval, we counted the number of droplets that formed on the sample. After we had obtained this number, we used the known area of the video camera frame to find the nucleation rate, which is measured in number of droplets per second per square meter.

Results

Our team has not finished collecting all of the data and in the future there are more trials remaining. The data in this section shows the results that the team has collected so far. Fig. 4 shown below shows the nucleation rate for various vapor temperatures and lubricants. Each point on the graph below is found by taking the average of all values at a particular location, and then averaging over all locations for a particular the trial. This value is then averaged over the course of each experiment for a particular combination of vapor temperature and lubricant.

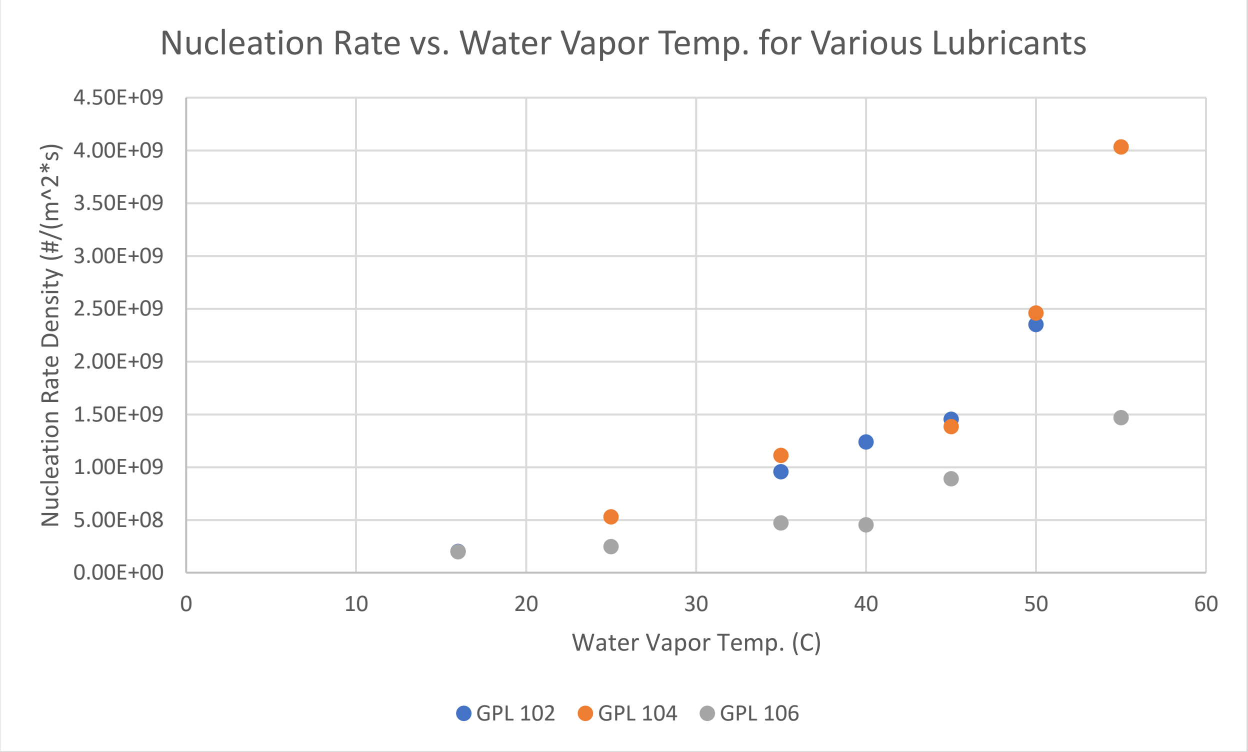

Fig. 4 Nucleation Rate Density Plot

Discussion

The data for all three lubricants shows an upward trend between the vapor temperature and the nucleation rate. This means that higher temperature vapor forms droplets more rapidly than cooler temperature vapor.

The data shows a general trend that as the viscosity of the oil increases, the nucleation rate of droplets decreases. GPL 106 has a lower rate of droplet formation than GPL 102 and GPL 104, while GPL 102 and GPL 104 have an approximately equal rate of droplet formation. GPL 106 has the highest viscosity of the three oils tested and GPL 102 has the lowest. This trend is not as clear as the trend between temperature and nucleation rate, however, due to the overlap between GPL 102 and GPL 104. For certain temperature values, GPL 102 has a lower nucleation rate than GPL 104 and for others it has a higher nucleation rate. These inconsistencies are something that could be investigated in further detail in the future. Also, this experiment has a smaller range of temperature values that were tested for GPL 102 than were tested for the other lubricants. These gaps in the data are an area where future work would be beneficial.

Conclusion

The data in this experiment does show some revealing trends, but these are only preliminary results. Further experimentation remains in order to both validate the data that has already been collected and possibly reveal new trends. For example, the overlap between GPL 102 and GPL 104 is something that could be investigated further. Testing a broader range of oils over a broader range of vapor temperature values would allow us to more accurately quantify the relationship between oil viscosity and nucleation rate. Also, we would ideally collect more data in the future in order to fill the holes in the data for certain temperatures values.

However, this study was greatly important in understanding the dynamics of droplets on LIS and in understanding the mechanisms behind droplet formation. By understanding the mechanisms behind droplet movement, we can improve the heat transfer of these droplets caused from convection, thereby improving the heat transfer coefficient from these surfaces. This could potentially be used in a wide variety of industrial and commercial applications such as power generation, water harvesting, and air conditioning systems, only to name a few. Knowing the relationship between lubricant viscosity and nucleation rate is helpful in choosing a lubricant for

LIS. Also, understanding the relationship between vapor temperature and nucleation rate is critical for the design of systems using LIS.

References

[1] Patricia B. Weisensee, et al, Condensate droplet size distribution on lubricant-infused surfaces, International Journal of Heat and Mass Transfer 109,187–199 (2017)