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Water Droplet Condensation on Lubricant-Infused Surfaces in a Vacuum Chamber

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Abstract

The infused lubricant on lubricant infused surfaces (LISs) creates the ideal properties for heat transfer condensation due to its chemically homogenous and atomically flat surface. The purpose of this independent study project was to continue the research on lubricant-infused surfaces to find the optimal oil film thickness for condensation. The optimal oil film thickness is determined by its water transfer rate, with reasonable thermal resistance and high droplet mobility to achieve high heat transfer performance. A lot of time was spent designing, building, and testing the vacuum chamber where this experiment will be conducted. The vacuum chamber will take in water vapor from the vapor generator and the vacuum pump will remove any noncondensable gases from the chamber and also decrease the saturation pressure and temperature within the vacuum chamber, causing condensation at lower temperatures. Cooling water will be transferred into the chamber from an external source through the cold plate that will hold the LIS samples, and the condensation on the LIS samples will be observed through the observation window using a camera placed outside of the chamber. We finished all the setup and initial testing, but due to time constraints, the actual experiment itself has been delayed. Next steps include making final modifications on the vacuum chamber and conducting condensation experiments within the vacuum chamber to find the optimal oil film thickness. This experiment will help optimize the conditions for the condensation of water droplets.

Background

This experiment involved the use of lubricant-infused surfaces (LISs) for water droplet condensation purposes. Recently LISs have been studied for its properties especially concerning condensation heat transfer. The infused lubricant creates a chemically homogeneous and atomically flat surface for vapor nucleation and condensation. The extremely low contact angle hysteresis of water droplets on LISs leads to a higher droplet mobility and thereby enhanced droplet condensation heat transfer [1]. In addition to the application in water dropwise condensation, LISs have also been researched for anti-icing, thermal management, and hydrocarbon processing [2]. The lubricant-infused surfaces in this experiment consist of a thin oil layer on top of a clean glass sample coated with Glaco superhydrophobic solutions, as shown in Figure 1.

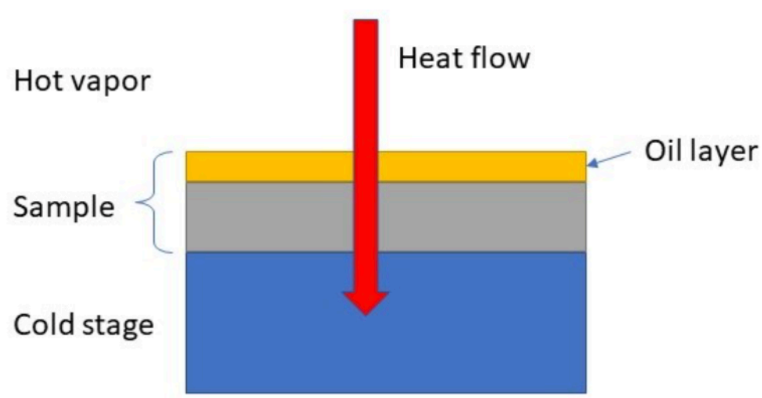

Figure 1. Schematic of Heat Transfer on Lubricant-Infused Surfaces (LISs)

Methods

Overview

In this project, a lot of time was spent designing, building, and testing the vacuum chamber, which is a low-pressure enclosed area. The vacuum chamber system consists of four main parts: vacuum chamber, vacuum pump, vapor generator and chiller. All noncondensable gases are removed by the vacuum pump to achieve more optimized condensation (significantly higher heat transfer rate). The vapor generator stores and heats up water to supply hot water vapor to the main vacuum chamber. The chiller circulates coolant through the cold stage inside the chamber at controllable temperature and flow rate, providing driving force for condensation on LIS samples in the chamber. The condensation process can be observed through the viewpoint of the vacuum chamber. The process for each step will be explained in further detail below.

Vapor generator Preparation

The vapor generator is a cylinder pipe-like chamber wrapped with heater tapes and heat insulation, which equipped with a ConFlat (CF) fitting port on the front for a thermocouple sensor and three CF ports on the top: one of which is sealed and closed, one has a pressure relief valve attached to it, and the other is connected to the vacuum chamber with flexible stainless-steel tubing. The vapor generator stores and heats up water so it will be evaporated into vapor that will go into the main vacuum chamber. A thermocouple sensor is placed inside the vapor generator from the front to measure the temperature of the water stored inside the vapor generator. This thermocouple is part of an Arduino circuit that is connected to a solid-state relay and two heating tapes. The Arduino circuit uses a Proportional-Integral-Derivative (PID) temperature controller to read the current temperature of the water through the thermocouple sensor and relays heat to the heating tapes if the temperature is underneath a certain setpoint inputted by the user. The initial testing setpoint was 90 °C, but later, the temperature setpoint was adjusted to 250 °C. As part of this independent study, I set up and programmed this vapor generator and the PID controller.

The circuit consists of a parallel circuit connecting the two heater tapes that are wrapped around the vapor generator connected to two OTM25 fuses separately to output 1 of the solid-state relay. Output 2 of the solid-state relay is connected to a power outlet. The power outlet is also connected to the node that links one of the heater tapes to its OTM25 fuse. The positive input of the solid-state relay is connected to the digital pin 7 of the Arduino Uno R3 board, while the negative input of the solid-state relay is connected to ground. The Arduino board is connected to the MAX31865 RTD-to-Digital Converter, which will take in the resistance readings from the RTDs and convert them to temperature. The Arduino board is also connected to the computer, which provides input voltage in the circuit and allows the Arduino to download and compile the code used in this experiment. The vapor generator is shown in Figure 2 and components are listed in Table 1.

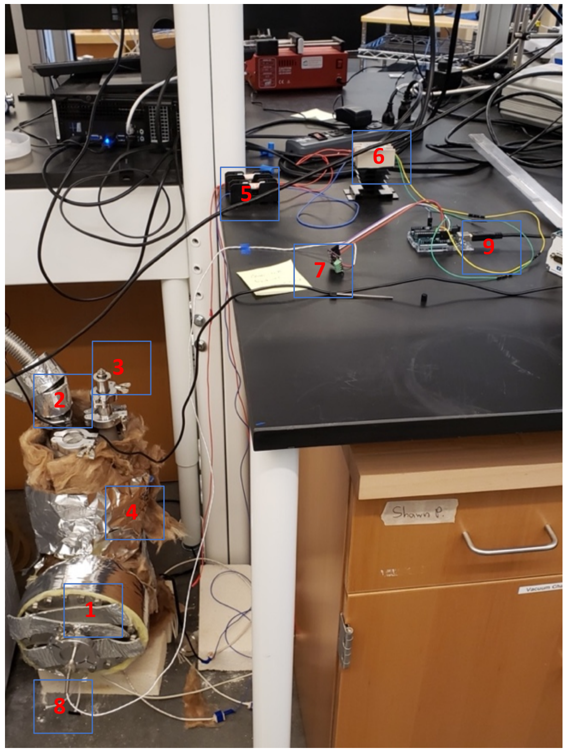

Figure 2. Vapor generator and Arduino Circuit (for numbered items, see Table 1)

Table 1. Equipment Used in Vapor Generator and Arduino Circuit

	Equipment	Description
1	Vapor generator	Stores and heats up distilled water
2	Stainless Steel Flexible Tubing	Connected to vacuum chamber
3	Pressure Relief Valve	
4	Insulation	Two heating tapes wrapped around vapor generator underneath insulation
5	OTM25 fuses	x2
6	Solid state relay	
7	MAX31865 RTD-to-Digital Converter	
8	Thermocouple	
9	Arduino Uno R3 board	Connected to computer

The Arduino code used in this project was an adjusted version of the code for a previous PID temperature sensor. I modified the code from its original use of measuring the temperature readings of three RTD sensors to only measuring the one thermocouple sensor used in this project. In order to use this code for similar experiments, one must change the setpoint values listed throughout the code to the desired temperature value. The thermocouple sensor was calibrated against a thermocouple that is proven to be accurate.

Vacuum Chamber Preparation

The main vacuum chamber intakes water vapor from the evaporation in the vapor generator, and the amount of water vapor taken in can be manipulated using a valve. The pressure pump removes a lot of the gases and vapors from the top of the chamber which decreases the pressure in the chamber, measured using a digital pressure transducer, over time. The vapors are collected in a liquid nitrogen trap, preventing the water vapors from intruding into the mechanical pressure pump and causing the vacuum pump oil to degrade. According to Gay-Lussac's Law, temperature and pressure have a direct relationship. Therefore, the lowering of the pressure inside the vacuum chamber causes the temperature within the vacuum chamber to decrease. This allows the water vapor to condensate by creating saturation conditions. Circulating coolant enters the vacuum chamber by a liquid feedthrough and passes through a cold plate with stainless steel tubing. This allows the heat from the water vapor to transfer from the LIS samples to the cold plate, initiating condensation on the LIS samples. We will place the lubricant infused glass samples on the cold plate where the water vapor will condensate to be observed through a viewpoint. The temperature in the vacuum chamber is measured with three separate RTD sensors near the vacuum chamber walls. The readings from the RTD sensors is recorded through MadgeTech using the MadgeTech OctRTDTempV2, which is an 8 channel RTD temperature data logger. Three different heater tapes generate heat on the different sides of the vacuum chamber to limit the amount of condensation forming on the walls of the vacuum chamber. The heater tapes are connected to each other and a power outlet in series, and the amount of heat generated can be manipulated. Figures 3, 4 and 5 show the different sides of the vacuum chamber, while Figure 6 shows the interior of the vacuum chamber and Table 2 lists the different components.

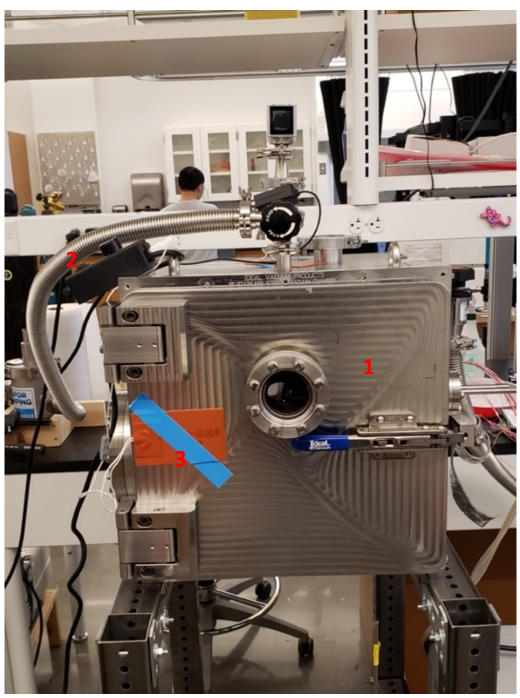

Figure 3. Front of Vacuum Chamber

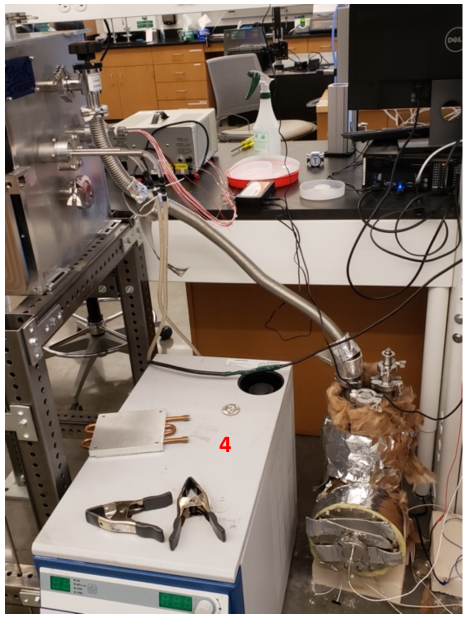

Figure 4. Right Side of Vacuum Chamber, Water Vapor Generator, Vapor generator

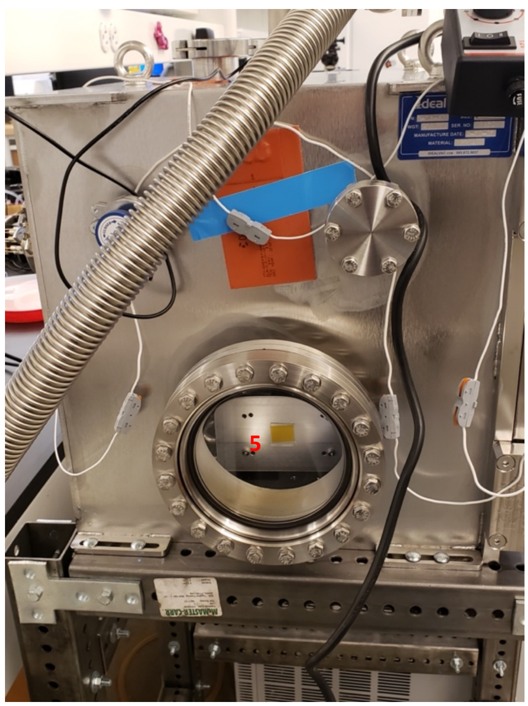

Figure 5. Viewpoint of LIS Samples

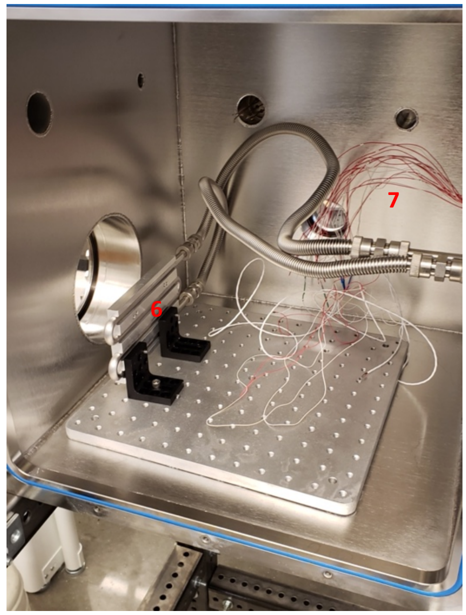

Figure 6. Interior of Vacuum Chamber

Table 2. Equipment used in Vacuum Chamber

	Equipment	Description
1	Vacuum Chamber	Takes in water vapor, removes air and other gases
2	Pressure Pump, Liquid Nitrogen Trap, Pressure Transducer	Removes gases from vacuum chamber and into liquid nitrogen trap, and measures pressure inside vacuum chamber
3	Heater Tape Circuit	x3, connected in series
4	Chiller	For coolant circulation through the cold stage, connected to cold plate with stainless steel flexible tubing
5	LIS glass sample	Seen through viewpoint
6	Cold Plate	Connected to vapor generator, allows heat transfer from LIS
7	RTD	x3, measures temperature inside chamber

Preparation of lubricant-infused surface samples

We used oil lubricant-infused glass samples in this experiment. We used square glass samples that were 1 inch by 1 inch. Each of the glass samples were then cleaned with acetone, propanol, and water, and then dried off with nitrogen gas. We then sprayed the glass samples with Glaco, a commercial superhydrophobic spray, as evenly on the glass samples as possible. We then allowed the solvent to evaporate by placing the samples on a hot plate which was heated at 300 degrees Celsius. Then the Glaco was infused with lubricant oil using spin coating, so that the lubricant spread evenly.

Experimental setup

In this experiment, we conducted water condensation inside the vacuum chamber to find the optimal oil film thickness of LISs to achieve high heat transfer performance. First, a lubricant-infused glass sample is prepared using the methods as explained above, and then placed on the cold plate in the vacuum chamber using conductive double-side tapes. The vapor generator is filled to the lid with distilled water, and the Arduino circuit is activated to heat up the water to around 250 °C. At this point, the pressure knob is opened to allow the water vapor to enter to the vacuum chamber. The chiller is turned on to allow cooling water to flow through the cold plate. The pressure pump is turned on and the liquid nitrogen trap is filled, removing the gases from within the vacuum chamber, decreasing the amount of pressure within the vacuum chamber. Both temperature and pressure inside the chamber are monitored and recorded. The condensation on the LIS glass sample was observed through the viewpoint of the vacuum chamber over time. The optimal oil film thickness will be determined by its water transfer rate with reasonable thermal resistance and high droplet mobility to achieve high heat transfer performance.

Conclusion and Future Work

In this independent study, the vacuum chamber was designed, constructed, and tested with the intention of running condensation on LIS samples inside the vacuum chamber and analyzing the results.

Due to much of this project focusing on the design, construction and testing of the vacuum chamber, the experiment itself was delayed. Some possible next steps are continuing to insulate the vacuum chamber and making other modifications and conducting condensation of the LIS samples inside the vacuum chamber in order to find the optimal oil film thickness for the optimization of condensation.

References

[1] Sett, Soumyadip, et al. “Stable Dropwise Condensation of Ethanol and Hexane on Rationally Designed Ultrascalable Nanostructured Lubricant-Infused Surfaces.” *Nano Letters*, vol. 19, no. 8, 2019, pp. 5287–5296., https://doi.org/10.1021/acs.nanolett.9b01754.

[2] Preston, Daniel J., et al. “Design of Lubricant Infused Surfaces.” *ACS Applied Materials & Interfaces*, vol. 9, no. 48, 2017, pp. 42383–42392., https://doi.org/10.1021/acsami.7b14311.