# Lifetime of a Microdroplet on a Hot Surface

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**Purpose:** The purpose of this research is to explore the feasibility of microdroplet spray as a cooling method for electronic components. At the individual component level, conventional electronic cooling methods such as fan airflow and liquid heat sinks may not be as effective as directly spraying components with microscopic amounts of liquid. In the microdroplet cooling process, the heat from an electronic component's surface is transferred into sprayed microdroplets that will in turn evaporate to keep the component's temperature low and at more effective operating level. The effectiveness of microdroplets at transferring heat is a prospective area of interest due to the increasing amounts of processing power that computer processing units can handle and the resulting heat they generate. Research in this field has explored the variety of factors that manipulate microdroplets, such as surface tension and release patterns of a piezoelectric droplet generator.

**Previous Work:** Previous sessions of research on this project have explored how to generate microdroplets 20-70 micrometers in size and built an experimental testing setup for recording and analyzing the cooling effectiveness of these single microdroplets. This session has continued the previous work by focusing on two new challenges: analyzing the factors that manipulate a single microdroplet and building an experimental setup that can test how a microdroplet spray can be manipulated to best cool a heated surface. New equipment for experiments, data acquisition devices, and software had to be learned and helped students develop skills for the experimental procedure. Similar research outside of LMU studied macro-droplet impact on non-heated surfaces, which does not correlate directly with microdroplets because of the physical differences of liquids at a microscopic level versus a macroscopic level. Other research lacks studies of microdroplets on heated surfaces.

## Experimental Setup:

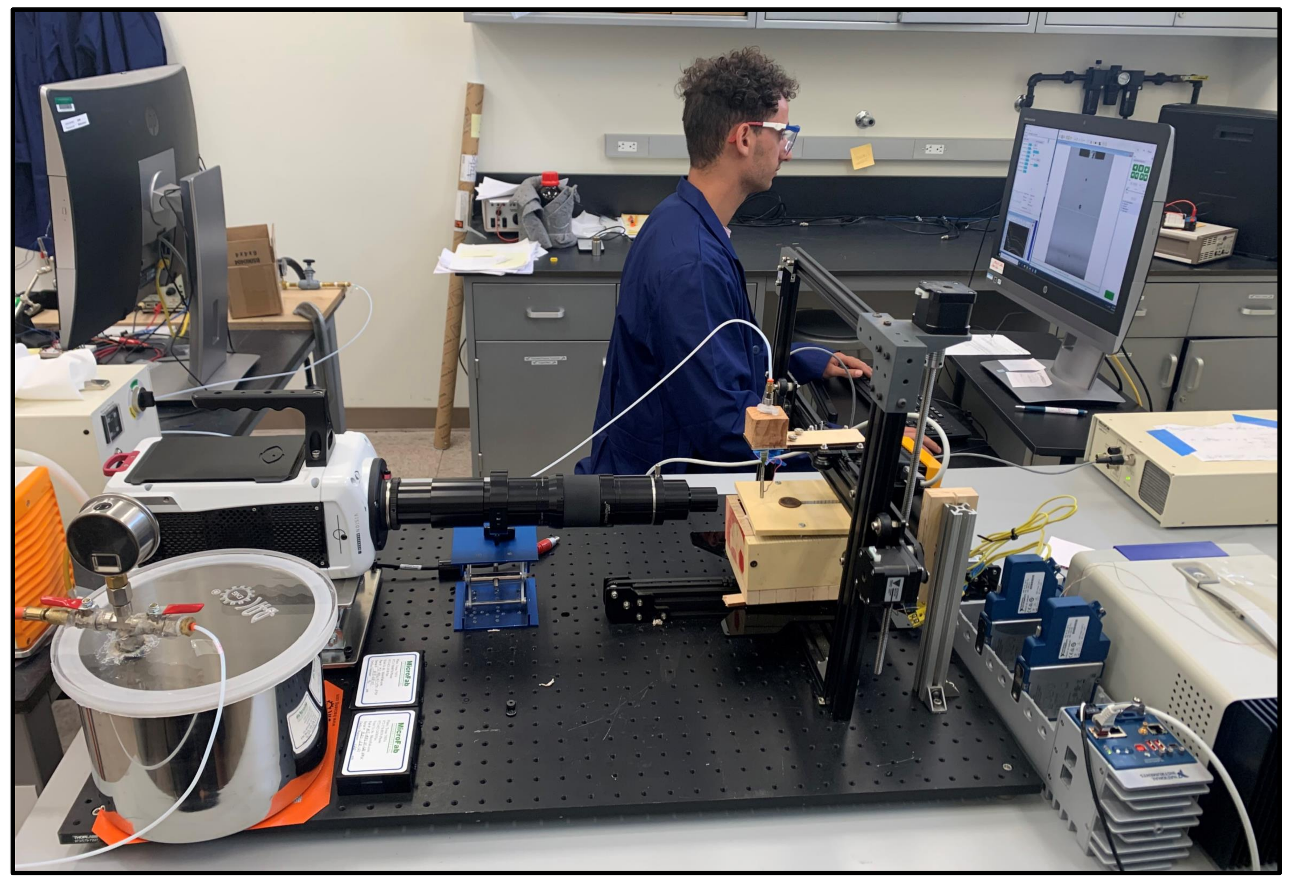


Figure 1 (left): Image of the single-droplet testing setup, including control and DAQ systems, monitored from user's computer.

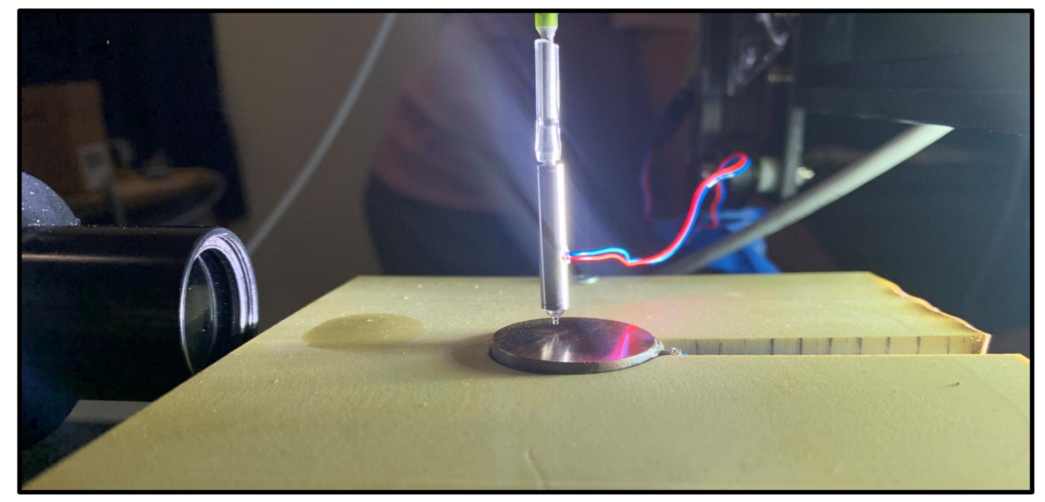


Figure 2 (above): Up close view of the piezoelectric droplet generator above the copper surface and the high-speed camera used to record video of trials.

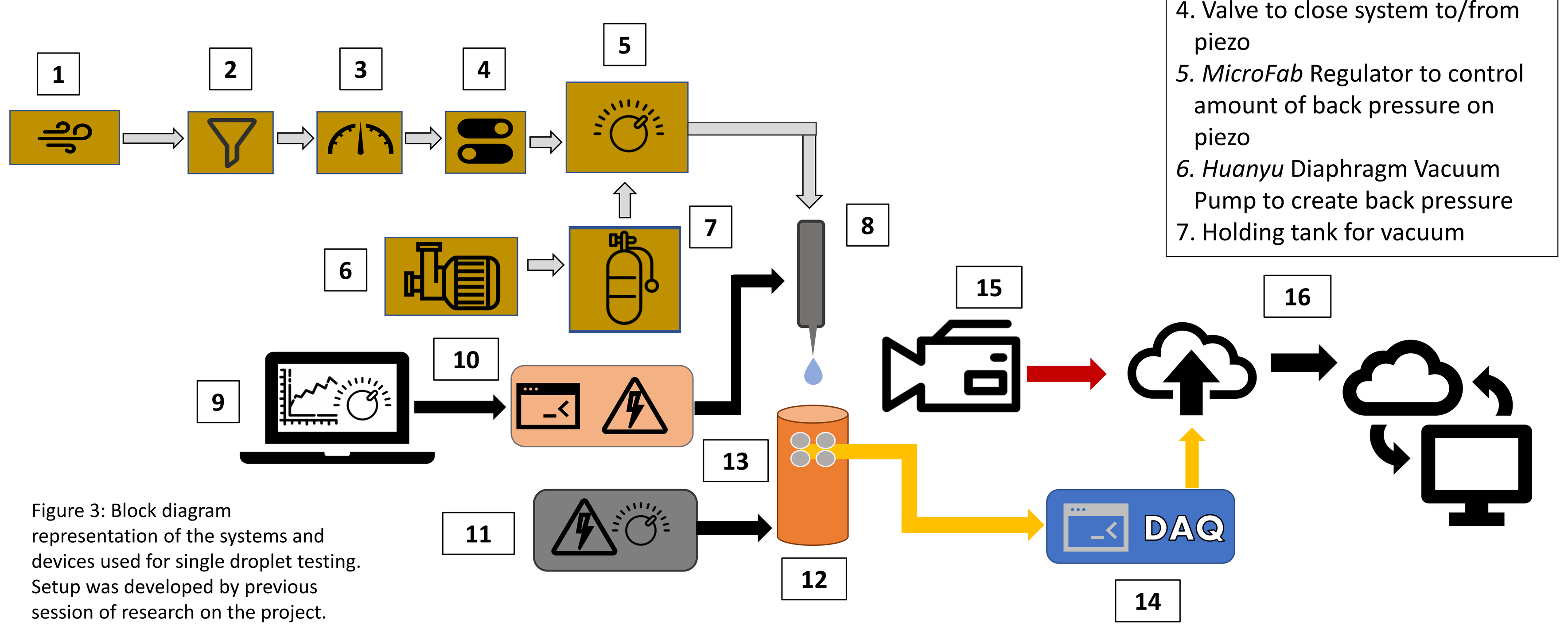



Figure 3: Block diagram representation of the systems and devices used for single droplet testing. Setup was developed by previous session of research on the project.

**Vacuum System:**
1. Connection to compressed air supply of building
2. Air filters to catch particulate matter from supply
3. Pressure regulator and gauge to keep inflow consistent
4. Valve to close system to/from piezo
5. *MicroFab* Regulator to control amount of back pressure on piezo
6. *Huanyu* Diaphragm Vacuum Pump to create back pressure
7. Holding tank for vacuum

**Piezo and Control:**
8. *MicroFab* Piezo Dispenser, 90 and 120 um nozzle sizes
9. Digital Control of piezo dispenser voltage pattern
10. *MicroFab* JetDrive V links control cycle to piezo from computer

**Hot Surface:**
11. *BK Precision* Triple Output Power Supply to send current through copper rod and heat it
12. 1" diameter thickness copper rod to simulate electronic components, holes drilled near surface to insert thermocouples

**Data Acquisition:**
13. 4 thermocouples for overall temperature reading of copper surface
14. *National Instruments* DAQ-9133 reads outputs of thermocouples, records data in Labview
15. *Phantom* Vision Research high speed camera with microscopic lens to collect video recordings of droplets
16. Video and LabVIEW data sent to cloud for tracking and analysis

**Surface Contact Effects:**
Five distinct outcomes were noted when droplets would hit the hot copper surface:
- Puddling, which only occurred when the liquid was exposed to a surface much cooler than its own boiling point.
- Evaporation, that resulted in effective cooling, as the liquid was able to transfer heat from the surface into itself and then dissipate into the surrounding atmosphere.
- Boiling, which had similar results as the evaporation stage. This could be a more effective temperature range for liquids than evaporation, as more liquid is able to change phase and leave the surface quicker.
- Transition boiling, a state between boiling and Leidenfrost. Droplets touch the surface and boil for a short period, then burst into the surrounding area. Less effective than boiling, the droplet only partially changes phase on the surface.
- Leidenfrost, where liquids bounce off the copper surface. This resulted in less effective cooling than the other stages, as there was not enough contact time for the liquid to conduct heat from the source.

**Various Liquids:**
Data collection was attempted using four liquids: ethanol, isobutanol, isopropanol, and water. Most of the successful data came from ethanol, with smaller data sets from isobutanol and isopropanol, and zero successful attempts with water. The mechanical properties of each liquid determine the feasibility of generating droplets using it. The most important properties include saturation temperature, density, surface tension, and viscosity.

Table 1: Mechanical properties of liquids at room temperature used to generate droplets in SI units.

| Liquid | Saturation Temperature (°C) | Density (kg/m³) | Surface Tension (N/m) | Viscosity (P*s) |
|---|---|---|---|---|
| Ethanol | 78.37 | 789 | .022 | .001 |
| Isobutanol | 108 | 802 | .023 | .004 |
| Isopropanol | 82.5 | 786 | .021 | .002 |
| Water | 100 | 998 | .072 | .01 |

## Droplet Phases:

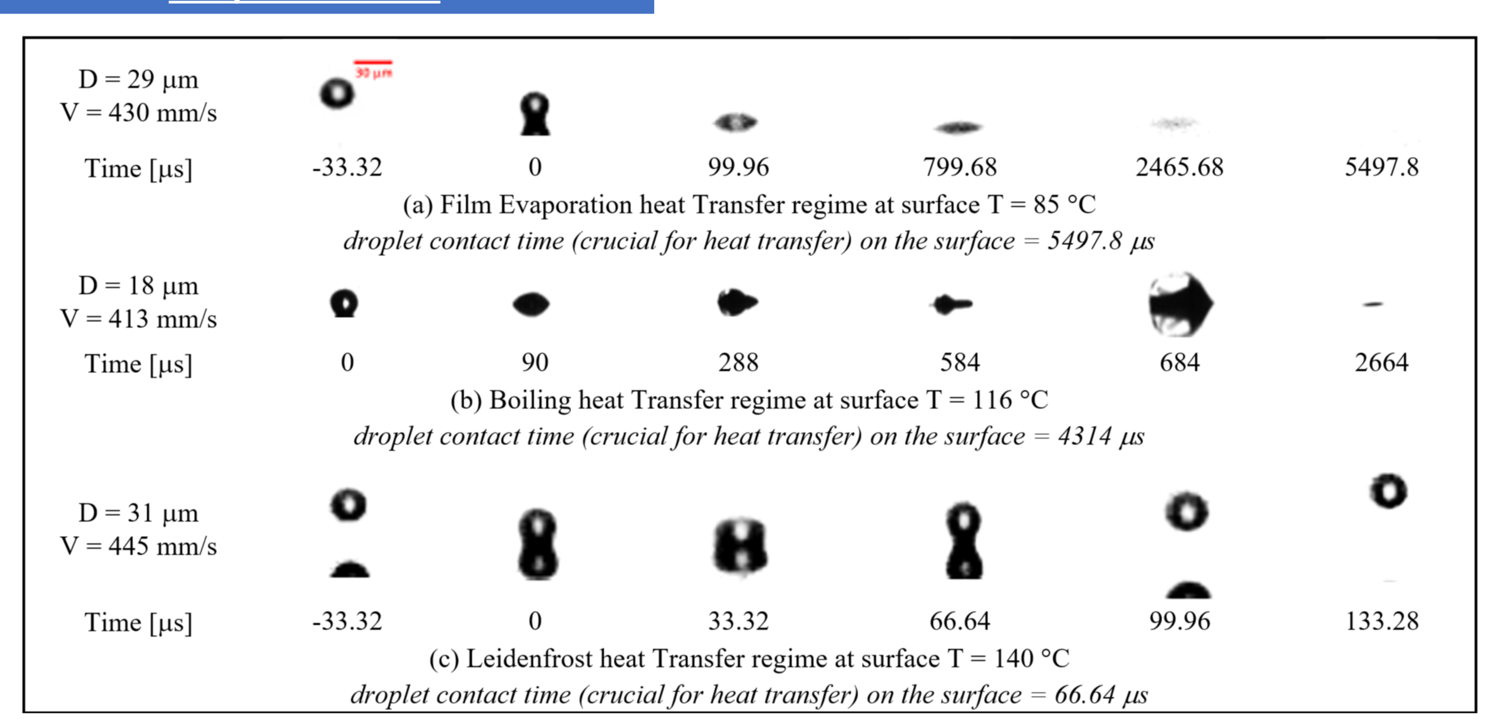



Figure 4: Time elapsed images of an ethanol microdroplet impacting onto a heated surface highlighting how a given microdroplet can result in three distinct regimes (dramatically different lifetimes) based on the surface heat flux.

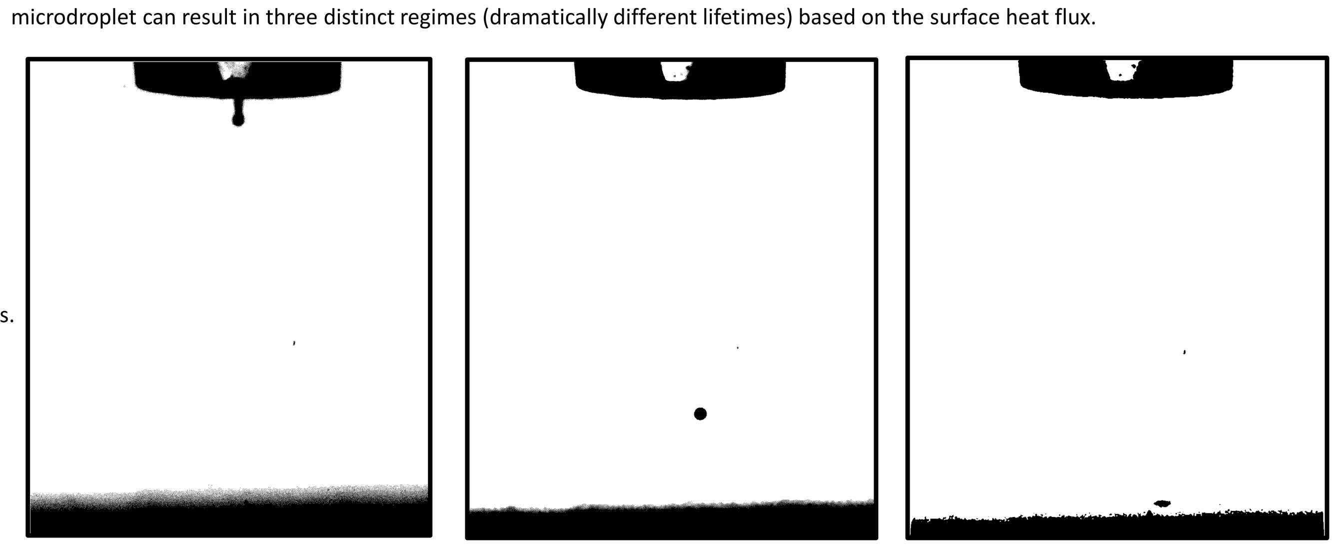


Figure 5: Frames taken from video of the high-speed camera, of an example 90 um droplet. Videos are analyzed through *Phantom Cine Viewer*, where droplet velocity, surface contact time, and diameter are recorded.

## Data Collection Process:

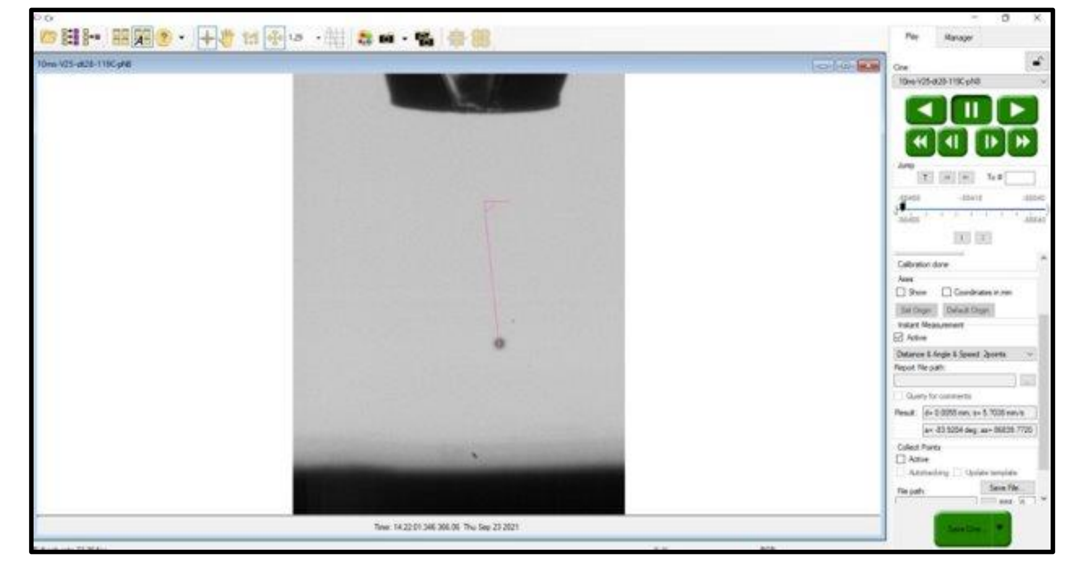


Figure 6: Main page of the Phantom Control Camera (PCC) software used to track the droplets after videos are uploaded. Has the ability to measure diameter and velocity of objects in the frame and give exact frame numbers for shots in the video.

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | Type of Droplet | Ethanol Copper Surface | | Droplet # | Frame # @ detach | Frame # @ Evap | Time (μs) | Frame # @ Surface |
| 2 | # Droplets | 2 | | 1 | -27406 | -27346 | 99.96 | -27349 |
| 3 | Sample Rate (fps) | 30000 | | 2 | -26973 | -26894 | 99.96 | -26897 |
| 4 | Time interval (μs) | 33.32 | | | | | 0 | |
| 5 | Pressure (mmHg) | -10 | | | | | 0 | |
| 6 | Scale (mm/pix) | 0.001874593 | | | | | 0 | |
| 7 | | | | | | | | |
| 8 | | | | | | | | |
| 9 | | | | | | Largest Diameter | Time between | |
| 10 | | | | Diameter (mm) | Velocity (mm/sec) | at Surface (mm) | Droplets (μs) | |
| 11 | Notes (if any): | | | 0.0337 | 280.0123 | 0.0337 | 14427.56 | |
| 12 | 2 Leiden, 1 sat each | | | 0.03 | 297.3997 | 0.0375 | 898740.36 | |

Figure 7: Excel spreadsheet used to input, calculate and track data taken from the microdroplet videos. Data found from each video in the PCC software (figure 6) are inputted into a separate spreadsheet.

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | Temperature of Surface (°C) | Type of Change of State | Average Diameter (mm) | Average Velocity (mm/sec) | Time for Change of State (μs) | Type of Liquid | Reynolds Number | Weber Number |
| 2 | 100 | Evap | 0.0304 | 429.3101 | 15256.0633 | Isobutanol | 2.616730922 | 0.195372002 |
| 3 | 103 | Evap | 0.035267 | 398.6411 | 13085.28 | Isobutanol | 2.818804573 | 0.195424584 |
| 4 | 106 | Evap | 0.033967 | 366.1263 | 12105.9033 | Isobutanol | 2.493460512 | 0.158768952 |
| 5 | 109 | Evap | 0.034933 | 477.8528 | 12550.1567 | Isobutanol | 3.346912788 | 0.278144634 |

Figure 8: Five rows of the spreadsheet with all the data. The data is taken from the spreadsheets as seen in figure 7 and condensed, then put into this spreadsheet with the most important parameters. There are over 400 rows of data in the entire sheet. The graphs below are made using this collection of data.

**Description of Method:**
A piezoelectric microdroplet dispenser of orifice size 90-120 micrometers is used to generate the droplets, whose droplet patterns are manipulated through voltage wave inputs by the user. To maintain a constant pressure and prevent accidental leakage within the nozzle, a negative pressure setup was assembled, (figure 3, parts 1-7), holding the meniscus of the droplet flush with the orifice. A hot electronic surface is simulated by a 1" diameter copper rod, heated via a voltage input ran through it. The temperature is measured through five thermocouples placed inside of the copper surface, and LabVIEW is used to generate a real-time graph of the temperature changes. The microdroplets are then expelled onto this copper surface. Additionally, a high-speed camera is positioned to record the droplets as they impinge the surface.

After the videos are recorded, Phantom Control Camera (PCC, figure 6) software is used to track the droplets. Using the software, the diameter and velocity of each droplet, as well as the frames of when the droplet detaches from the orifice, touches the surface, and leaves the surface completely are inputted into an Excel file (figure 7), along with other minor settings from the software. Using Excel, the time between droplets and time for change of state of the droplets is calculated. After all the droplets are tracked, MATLAB is used to calculate averages of all the variables in each Excel sheet, then moves these averages into a more concise Excel spreadsheet (figure 8) which includes the most important data from every trial. Lastly, the data is manipulated and graphed in MATLAB for further analysis.

See figure three for details of the setup.

## Results:

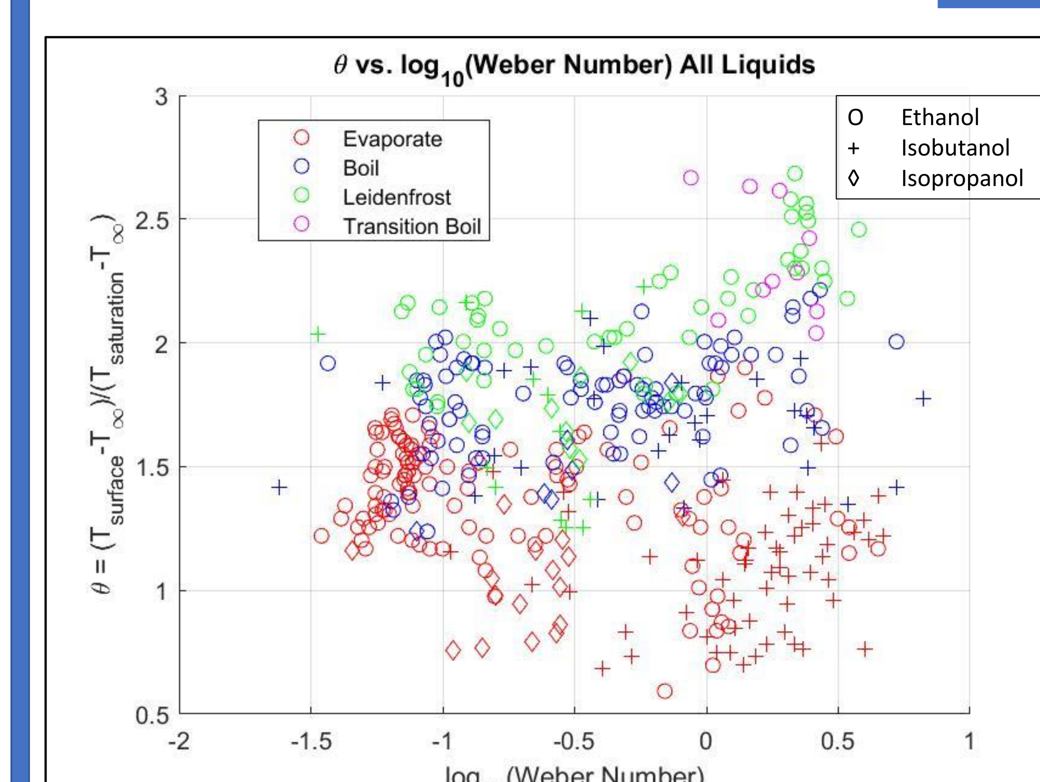
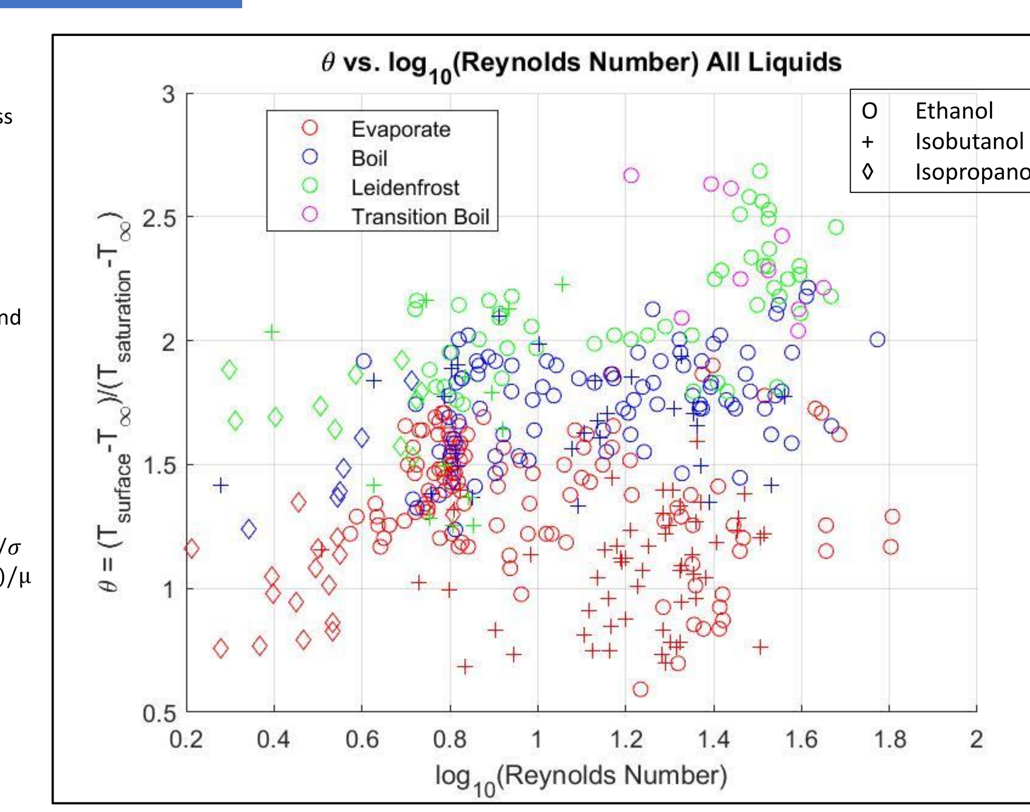



Figure 9 and figure 10: A unitless function of temperature versus the log function of Weber number (left) and Reynolds number (right), which are both common figures in fluid mechanics research, using the data gathered from all liquids and specifying the droplet phase (created with MATLAB).

Legend of variables (SI units):
Weber number = $(\rho \times v^2 \times d)/\sigma$
Reynolds number = $(\rho \times v \times d)/\mu$
$\rho$ = density (kg/m³)
$v$ = velocity (m/s)
$d$ = diameter (m)
$\mu$ = viscosity (P*s)
$\sigma$ = surface tension (N/m)




**Graphical Analysis:**
There are over 400 data points on these plots and a lot to dissect. Firstly, the shapes of the points correlate with the type of liquid used for that piece of data, as shown in the legends on the upper right hand of the graphs, and the color of the data point correlates with the type of phase change the droplet goes through after contacting the surface, as shown in the legends on the top left of the graphs. Moreover, the y-axis on each graph is a unitless depiction of temperature, where $T_\infty$ is room temperature (around 22°C). As for the x-axis, figure 9 graphs the log of Weber number and figure 10 graphs the log of Reynolds number. In research involving fluids, it is considered good practice to use numbers that are unitless. This way, the research is repeatable and may be used by those that adopt various unit systems.

With the current data, no line of best fit has matched the numbers exactly. However, conclusions can still be made. The Leidenfrost effect is delayed with higher Weber and Reynolds numbers. Likewise, the droplets are more likely to undergo Leidenfrost with lower Reynolds and Weber values. Thus, with a higher diameter and velocity, the droplets are more likely to boil at higher temperatures. This information is useful for the purpose of this project because boiling is the ideal heat transfer method, as opposed to the other phases, because it optimizes the amount of heat drawn from the surface. Increasing the likelihood of boiling then increases the magnitude of heat removal.

**Future Goals:**
1. The next objective for single-droplet cooling is to maximize the diameter and velocity of the microdroplets by changing the voltage pattern sent through the nozzle that generates the droplet. This may include changing the magnitude of voltage or other parameters or changing the waveform entirely. Preliminary research indicates that a larger dwell voltage increases droplet velocity, and a larger dwell time (time elapsed of the voltage wave) increases the droplet diameter. However, more testing must occur to optimize these metrics. With higher diameters and velocities, more data will be found with larger Reynolds and Weber numbers, which may fill in holes from the current results.
2. More data may be collected from liquids other than ethanol. More specifically, additional data from isobutanol and isopropanol may be useful, and another attempt at gathering research with water has potential. Initial attempts at water failed because the mechanical properties of water do not fall within the range of liquid parameters of the droplet generator. However, with more attempts and testing, using water is possible. Further, outliers from previous data must be verified as accurate to ensure that no errors were made in tracking or recording them. Revisions of previous data may help to establish or prove patterns in the results.
3. Lastly, a write-up may be started for potential publication. This will include a written method, as well as results and analysis of all the data collected thus far. Despite additional data being collected in the future, there is sufficient data to generate findings now that may prove useful. Further, the method used to carry out this research may also be of use to others carrying out studies involving microdroplet impingement.