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Project Title: Lifetime of a Microdroplet on a Hot Surface

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Abstract

The purpose of this research is to understand fluid mechanics and heat transfer to enhance spray cooling, one of the most efficient cooling techniques, for high heat flux applications like metal forming and electronic cooling. Without the fundamental knowledge of fluid mechanics in these applications, spray cooling can be ineffective because of dry-out, or excessive liquid accumulation, occurring at low and high spray rates, respectively. In electronics like computer chips, these errors can cause crucial and expensive failures. From previous iterations of this project, data has been collected with three liquids: ethanol, isobutanol, and isopropanol. Microscopic droplets of each liquid are dropped onto a heated surface. The droplets' diameter and velocity upon hitting the surface are varied and recorded. Droplets' resident time (the time it takes the droplet to fully evaporate); whether by boiling, evaporating, or Leidenfrost; is tracked. After the data is reviewed and studied, the results will show what temperature of surface, diameter of droplet, and velocity of droplet cools a surface most effectively and efficiently. It is hypothesized that a high velocity boiling regime will be most effective.

Keywords: fluid mechanics, heat transfer, spray cooling

Project Details

Background Information

When a single droplet of a liquid impacts a dry surface, it goes through four phases: spreading, receding, splash, and re-bound (figure 1). The droplet's kinetic energy upon impact converts to surface tension energy and forces the drop to spread. When the kinetic energy reaches zero, the droplet is at maximum diameter. The diameter then starts to shrink as the droplet comes together from the surface tension energy. For maximum heat removal in spray cooling, the spreading phase must be extended, the receding phase must be minimized, and splash or bounce must be avoided.

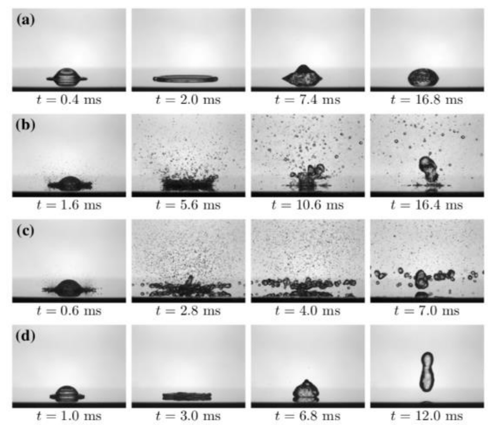

Figure 1: Hydrodynamics of a macro droplet impact [Breitenbach et al., 2018]

After impact of the surface, the droplet will evaporate when the surface temperature is below the saturation temperature of the liquid (figure 2). When the surface temperature is higher than the saturation temperature, nucleate boiling occurs, and when the surface temperature is above the Critical Heat Flux (CHF), transition boiling occurs. Likewise, when the temperature reaches above the Leidenfrost point, Leidenfrost (film boiling) will occur. Transition boiling and film boiling should be avoided due to the reduced heat transfer rate. All four of these regimes have been studied extensively for macro-meter size (~1-3 mm) droplets (Liang and Mudawar, 2017; Breitenbach et al., 2018).

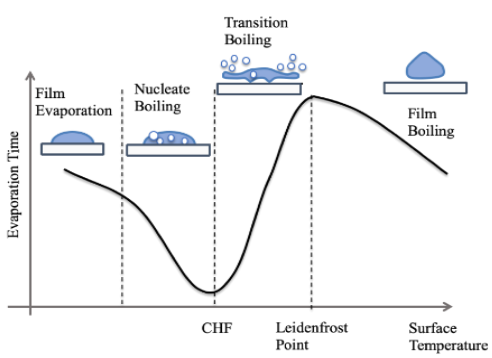

Figure 2: Heat transfer regimes in droplet evaporation and boiling [Ebrahim 2022]

There are many studies on droplet impact on dry unheated surfaces, wet unheated surfaces, dry heated surfaces at varying temperatures, and wet heated surfaces at varying temperatures, but they use macro-droplets, rather than microdroplets (Liang and Mudawar, 2017; Breitenbach *et al*., 2018). The findings from these studies have not been correlated successfully to microdroplets because they are based on the impact velocity and do not include the physical differences between macro-droplets and microdroplets or the effects of droplet's liquid properties (Castanet et al., 2015; Ebrahim et al., 2017; Liang and Mudawar, 2017; Breitenbach et al., 2018).

The few studies that look at the impact of one microdroplet either use unheated surfaces or surfaces heated to above the Leidenfrost point (Ko and Chung, 1996; Visser et al., 2012; Van Dam and Le Clerc, 2004). Likewise, experiments have been conducted with streams of consecutive microdroplets on a heated surface at high frequencies (Zhang et al., 2015; Soriano et al., 2014; Black and Sellers, 2008). None of these studies used a single droplet with a heated surface under the Leidenfrost temperature.

This project was started a few years ago by Dr. Mahsa Ebrahim and four students. Over these few years, many students have helped Dr. Ebrahim with the research. During the 2022 Summer Undergraduate Research Program (SURP), Kennedy Necoechea, David Kandah, Tyler Keen, Hannah Agbyani, Connor Powers, and I worked together to collect data and continue the design and build of the parts. In the fall of 2022, I continued this work, making sufficient progress in data collection and analysis. Despite this progress, there are still holes to fill in for the research to be completed.

Purpose

Spray cooling is a common heat removal technique. However, it can be ineffective when the spray rates are too high or too low, which can cause damage to expensive parts, especially computer chips. Without the fundamental knowledge of fluid mechanics, it is a much higher likelihood for spray cooling to be ineffective. The goal of this research is to find the heat transfer and fluid mechanics for high heat flux applications like metal forming and electronic cooling.

This project is focused on learning the mechanics of a single micrometer-sized droplet, rather than studying millimeter-sized droplets, which have been studied in the past. Specifically, the properties of millimeter-sized droplets and micrometer-sized droplets are not the same. It is better to first focus on a single microdroplet to understand its fundamental physics rather than studying the chaotic spray. This work can then be extended to study the impact of a consecutive droplet and finally to a whole spray case. For instance, the knowledge gained from single droplets, e.g., the resident time, can be used to adjust the spray rate by knowing the lifetime of each droplet.

Thus far, data from over 350 droplets has been collected for three liquids: ethanol, isobutanol, and isopropanol, with ethanol receiving the most data. There is near-sufficient data to begin writing up results. Prior to writing, previous data must be double-checked for potential errors. For example, the data circled in figure (3) contains an outlier, where Leidenfrost occurred in a droplet that was expected to evaporate. The video and spreadsheet for this droplet will be found from the archives and verified that the collected information is correct. If so, more data from this temperature and Reynolds number will be collected.

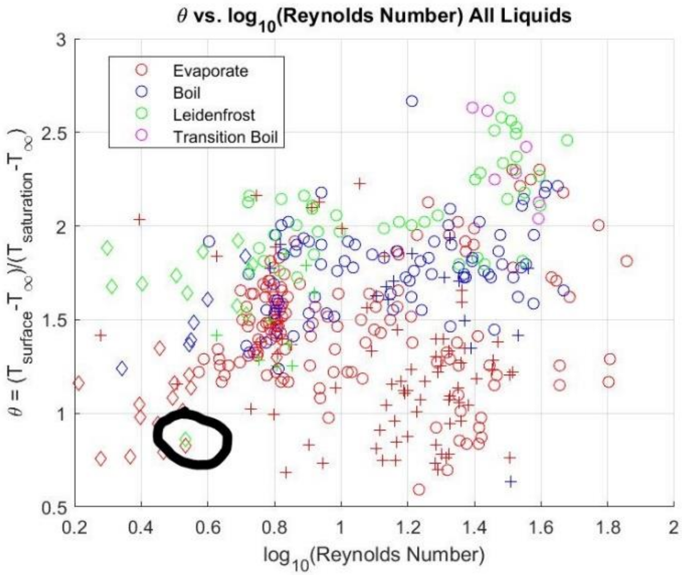

Figure 3: Scatter plot of previously collected data with an outlier circled.

Further, small portions of data with irregularly large and small Weber and Reynolds numbers must be generated to fill the gap in the literature and cover a broader range of influential parameters such as liquid properties, droplet diameter, and impact velocity. Weber (We) and Reynolds (Re) numbers are both common displays of mechanical properties of liquids and used extensively for analysis:

$$We = (\rho \times v^2 \times d)/\sigma \tag{1}$$

$$Re = (\rho \times v \times d)/\mu \tag{2}$$

where ρ is density, v is velocity, d is diameter, σ is surface tension, and μ is viscosity. We and Re numbers are unitless, so data can be compared between all liquids and different impact conditions regardless of the units of measurements. From these equations, We and Re numbers can be manipulated for a particular liquid by changing the velocity and diameter of the droplets. Thus, these two variables are used to generate droplets of different values. Increasing or decreasing either velocity or diameter may produce droplets of extreme We and Re values. The experimental apparatus has failed to generate water microdroplets due to the high surface tension of water. Studying water is essential since it is the most commonly used liquid in spray cooling. To simulate the heat transfer regimes of water microdroplets using other liquids, the Re and We numbers of the substitute liquid must match the corresponding values of a theoretical water microdroplet. Water microdroplets will produce higher We and Re numbers because of the high density of water. Thus, microdroplets with higher We and Re numbers must be generated and studied to expand the experimental data and develop a comprehensive regime map. As mentioned above, producing larger microdroplets at higher impact velocities can increase the Re and We numbers.

Essential to every research project, writing-up results for the purpose of publication, which is this semester's focus, allows for others to use the results for their own products, education, and other research. Moreover, it allows others to understand how an experiment has been done and emulate the method with other purposes.

Method

The semester will be used to double-check for errors in previous data-processing, cover research gaps and potential experimental errors from previous data, and begin writing up the results and method for publication. A MicroFab jet dispenser with a controller is used to create droplets of desired characteristics. The dispenser consists of a piezo tube encapsulating a capillary tube nozzle. The controller allows the creation of droplets of different sizes and speeds by adjusting the voltage pulse. Thus, the voltage pulse characteristics such as its amplitude and frequency must be modulated and refined for each impact condition to create the desired droplet size and speed. Based on previous observation, the dwell voltage of the pulse correlates with velocity of the droplet, and the dwell time correlates with the droplet diameter. Since extreme velocities and diameters is desired, these numbers will be adjusted to exaggerated levels.

To observe the droplet as it impacts the surface, a high-speed digital camera with a microscopic lens is utilized. Though it takes a significant amount of time to look through so many frames from a single droplet's impact, the camera's extreme frame rate has proven useful to collect precise data and observations regarding the evaporation time and hydrodynamics of the droplet's impact. The videos are produced and processed to measure droplet diameter and velocity through Phantom Camera Control's (PCC) software. All previous videos have been saved, so videos from outliers in the data collection will be verified to ensure that errors were not made while tracking them.

All collected data is saved in Excel. Programs in MATLAB have been created to combine all the data from Excel files and then create graphs and tables to formulate results. The graphs are the main form of analysis. After completing the data collection, the write-up consists of two main parts: results and discussion and experimental procedure. The experimental procedure can be written simultaneously as collecting new data. Both tasks will take substantial time to perfect and do not plan to be entirely completed by the end of the spring semester of 2023. However, much progress will be made toward future publication.

Plan for Dissemination

I will present my findings at the Honors Research Symposium in the spring of 2023 as well as the Undergraduate Research Symposium if the times do not overlap. If the times overlap, then I will present at the Honors Research Symposium and not at the Undergraduate Research Symposium. The form of presentation will either be a poster or a PowerPoint, whichever fits the requirements and time limit of the event best. I already planned to present on this project at these events from my work in the summer and fall of 2022, so I will also include this semester's work in the presentations. Lastly, I will attend the National Council on Undergraduate Research in April of 2023 at the University of Wisonsin-Eau Claire. The funds for this trip need not be provided by the Honors Program. All three of these events occur prior to the end date of my timeline, but most of my work will be finished by the time of these events. Thus, the last few weeks of my research will not be presented. However, these last weeks will be used for writing purposes which will go towards dissemination of a different manner - ideally, publication.

Timeline

Table 1: Timeline of research for spring 2023.

Task	Week Number														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Analyze Data to Identify Potential Experimental Errors															
Skim Previous Videos for Errors															
Generate Limited Number of High Velocity Droplets															
Generate Limited Number of Low Velocity Droplets															
Watch and Gather Data from Post-Processing Videos															
Evaluate Recent Data															
Plan for Dissemination															
Write-Up Results															
Write-Up Detailed Method															

I will be working the same number of hours (3) each week.

Budget

I am requesting $721.80 for the semester. This number is based on working for 15 weeks at 3 hours per week, and making $16.04 per hour, the student worker wage on campus. The 15 weeks include most weeks in the semester, including Easter break, excluding spring break and finals week. In the 2022-2023 academic year, I had $2,000 to be made through work study, and $1,796.48 of that was allocated in the fall semester, leaving $203.52 for the spring semester. Thus, $518.28 must be allocated outside of work study. This money will solely support my time spent doing the research. Outside of the funds given for time spent doing the research, all additional costs will be covered by Dr. Mahsa Ebrahim or the Mechanical Engineering Department, including all equipment and supplies needed to complete the project. Costs for dissemination at the National Council on Undergraduate Research (NCUR) will also be provided by the Department of Mechanical Engineering.

Calculations for hourly wage:

15 weeks * 3 hours per week * 16.04 dollars per hour = $721.80

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