Michael Hennessy

Project Title: Lifetime of a Microdroplet on a Hot Surface

Faculty Advisor: Dr. Mahsa Ebrahim

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. Data will be collected with four liquids: water, ethanol, isobutanol, and isopropanol. Microscopic droplets of each liquid are dropped onto a heated surface, with the surface temperature ranging from 60 and 150 degrees Celsius. 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.

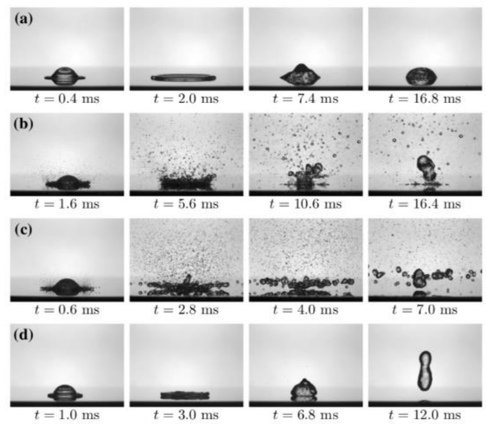

Figure 1 – Hydrodynamics of a macro droplet impact [Breitenbach et al., 2018]

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 Leidenfrost point, Leidenfrost 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).

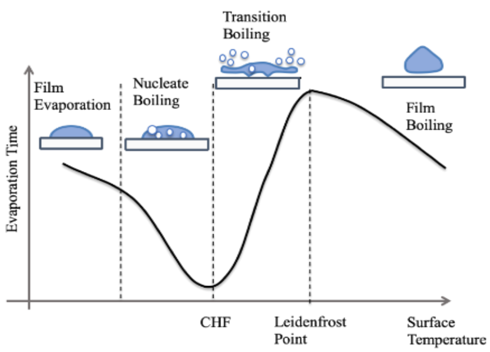

Figure 2 - Heat transfer regimes in droplet evaporation and boiling [Ebrahim 2022]

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.

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 has 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 can be used to adjust the spray rate by knowing the lifetime of each droplet. Creating single microscopic droplets has proven to be challenging. Thus, the goal of one part of the project is to successfully and consistently create a droplet that is one micrometer in size and of correct velocity and diameter.

Our goal is to collect data for four liquid droplets: ethanol, isopropanol, isobutanol, and water. Ethanol droplets have been extensively experimented by the research team during past summers. More experiments should be conducted for isopropanol and isobutanol, so a few weeks will be allotted to create droplets of those two liquids. Creating droplets of water has been attempted but has shown difficulty because of its large surface tension. Thus, more time will be allocated to creating droplets of water because of the lack of data for that liquid. For each liquid, single droplets at different diameters and velocities will be generated for a variety of surface temperatures (for 60 C to 220 C).

The next part of the project is perfecting the heated surface control. The heater in the current apparatus is controlled manually. The goal of this part is to design a control system for the heated surface to automatically modulate the surface temperature. The project was started a few years ago by Dr. Mahsa Ebrahim and four students. Over these few years, multiple 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.

Method

The semester will be used to collect data, complete post-processing, and study the results to form conclusions. A MicroFab jet dispenser with a controller will be used to create droplets of desired characteristics more consistently and efficiently. 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.

Another important factor in droplet generation is the back pressure in the liquid reservoir. The reservoir back pressure must be adjusted to keep the liquid at the nozzle orifice flush. To observe the droplet as it impacts the surface, a high-speed digital camera with a microscopic lens will 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.

Collected data will be saved in Excel throughout the semester to find the ideal impact conditions to maximize surface heat removal. Programs in MATLAB will be created to take all the data from generated Excel files and automatically combine them and then create graphs and tables to formulate results. Lastly, phase diagrams for liquid and impact conditions will be developed, which is necessary for heat transfer application. The ideal impact condition (droplet size, impact velocity, and type of liquid) to maximize the heat dissipation per droplet for a given surface heat can be identified using the developed phase diagram.

Plan for Dissemination

I will present my findings at the Honors Research Symposium in the spring 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. A presentation format is preferred because it will enhance my oral commutation skills. I already planned to present on this project at the Undergraduate Research Symposium from my work in the summer of 2022 with my team of undergraduate researchers, so I will also include this semester's work in the presentation. Lastly, Dr. Mahsa Ebrahim plans to bring students, including myself, to the National Council on Undergraduate Research in April of 2023 at the University of Wisonsin-Eau Claire. Dr. Ebrahim brought a group of students to the same conference in 2022 in Washington, D.C., and plans to attend again. The funds for this trip need not be provided by the Honors Program.

Timeline

Task	**Week Number**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Calibrate and Tinker with the Microdroplet Dispenser														
Record Videos for Isopropanol														
Record Videos for Isobutanol														
Record Videos for Water														
Watch and Gather Data from Post-Processing Videos														
Create Programs to Automate Post-Processing														
Develop Phase Diagrams														
Evaluate Data														
Write-Up Findings														
Prepare for Dissemination														

I will be working the same number of hours (8) each week.

Budget

I am requesting $1,796.48 for the semester. This number is based on working for 14 weeks at 8 hours per week, and making $16.04 per hour, the student worker wage on campus. I have $2,000 to be made through work study, so all the funding can be allocated through 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, 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 Department of Mechanical Engineering.

Calculations for hourly wage:

14 weeks * 8 hours per week * 16.04 dollars per hour = $1,796.48

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