Using the Leidenfrost Effect to Determine the Concentration of a Solute in a Solution

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ABSTRACT

Water is one of the most important biological molecules to life, which means the cleanliness and purity of drinking water are crucial. When accessing health risks around the globe, the quality of the water in each region often resembles the overall status quo. Polluted water can contain antigens, bacteria, viruses, and toxic pollutants (e.g., metals, metalloids) potentially carcinogenic. The Leidenfrost effect is the phenomenon observed when a liquid drop is released onto a hot surface, usually much greater than the liquid's boiling point, creating a vapor layer due to the instant vaporization of the drop. Since adding solute increases the boiling point of a liquid, the Leidenfrost point of said solution will also increase. The droplets have quantitative lifetimes that can be measured and used as indicators of a solution's relative chemical purity. By maintaining the same temperatures for solutions with different concentrations, the lifetimes of the Leidenfrost droplets will vary. Testing this phenomenon, we added varying concentrations (0.05, 0.10, 0.20, and 0.40 grams solute per liter of solution) of aluminum chloride (AlCl3) to water. Since aluminum chloride is a common water pollutant, this experiment tested whether or not film boiling can determine the relative concentration of aluminum chloride or other common contaminants in water.

INTRODUCTION

Contaminated water is one of the most common sources of disease and illness in countless countries worldwide (*Water Treatment Solutions*). Yearly, five million global casualties originate from unsanitary or polluted drinking water. This water can contain pathogens, toxic elements, and compounds, and trace amounts of other heavy metals, many of which are potentially carcinogenic and some having a moderate LD50 or median lethal dose (some common ones range from 200mg to 1000mg of substance per kilogram of body weight) (Idrees et al., 2018). This experiment observes the film boiling of different "contaminated" solutions of varying concentrations. In the performed tests, differing concentrations of aluminum chloride ($AlCl_3$) were added to water, affecting the time required for each sample to vaporize. We repeated tests for each concentration eight times to determine whether the pollutant concentration would affect the time needed for a film boiling solution to vaporize. This experiment aims to shed light on water pollution through an interesting yet critical approach.

The Leidenfrost effect is when a liquid in close contact with a surface whose temperature is significantly greater than its own vaporizes to create an insulating vapor layer that prevents the liquid from instantly evaporating (*Leidenfrost effect*). This effect is most commonly observed when cooking: a droplet of water falls onto a searing hot pan and boils rapidly (not instantly). The effect is relevant for many instances outside of water and is observable in all types of liquids; for example, this effect can be seen in liquid nitrogen, which sputters across room temperature surfaces.

Once a drop of water is set onto a pan whose temperature is much greater than the liquid's boiling point, the water will not instantly vaporize. Instead, after boiling for a short period, the entirety of the bottom surface is covered with vapor. Then energy is slowly transferred to the liquid above the vapor by radiation and gradual conduction. This phase is called film boiling (Adrian et al., 2013).

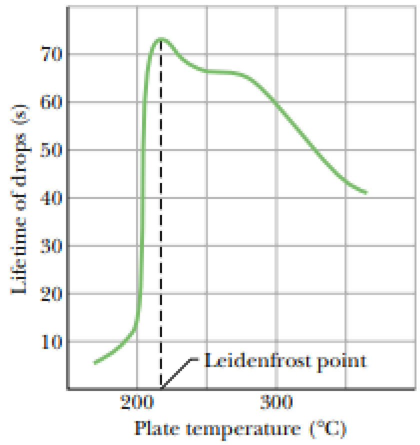

Image 1: Droplet lifetime versus temperature graph that demonstrates the Leidenfrost point of pure water. Source: Jeral Walker, *Cleveland University*

The risk assessment process included analyzing materials and equipment and researching the MSDS sheet for the active harmful chemical, aluminum chloride or AlCl3 (*SAFETY DATA SHEET*, 2010). Equipment and chemicals were handled with gloves, face masks (to prevent inhalation), lab aprons, and safety goggles. A waste disposal contractor in the local area removed the materials.

When a particular solution undergoes film boiling, the amount of time required to vaporize fully is inversely proportional to the concentration of the solute, or pollutant, added into the water; this is because the added solute will disrupt the formation of a "vapor blanket" beneath the droplet, ultimately enabling the droplet of the solution to vaporize in a shorter amount time when compared to a droplet of solution of lower concentration. High heat is required to consider certain variations due to boiling point elevation caused by the added solute.

DATA AND METHODS

The materials used in this project are listed below (without specified order):

Quarter inch diameter copper end caps

Distilled water

Aluminum chloride hexahydrate

Hot plate

Manual volumetric pipettes

Thermocouple

Camera

Glass stirring rod

250mL beakers

Infrared thermometer

A total of 5 solutions were made in 250mL beakers in this experiment with different concentrations of aluminum chloride: 0g/L (control), 0.05g/L, 0.1g/L, 0.2g/L, and 0.4g/L. Each of these solutions were fully dissolved, and they were set to room temperature before use. The hotplate was then set to 215° Celsius with a 5 degree range (210° to 220°), which was measured by the thermocouple and infrared thermometer. The infrared thermocouple was used as the infrared thermometer was inaccurate on the reflective surface. A copper cup was then set onto the plate and heated evenly until it reached the same temperature as the hotplate (measured by the infrared thermometer). A single droplet (measured out by a manual volumetric pipette) was dropped onto the copper cup, and the lifetime of the droplet was measured using a video camera. This step was repeated for each solution: the copper cup was taken off the hotplate to cool, and it was put back on the hotplate for the next trial. Between solutions, a new copper cup was used for testing, so that no cross-contamination took place.

Image 2: Experiment station shown. Left: Copper cap. Right: thermocouple. Both objects are resting on the hot plate.

In order to collect the lifetimes of the droplets of each solution, video cameras were used to record the whole process. Afterwards, the video of the trial was analyzed frame by frame. Doing so allowed the lifetimes of the droplets to be measured to two decimal points.

The only component that changed throughout the processes was the concentration levels of the solution. The hypothesis focuses on how the change of the boiling point elevation was the main factor in the difference in times for the droplet to vaporize. Other factors contribute to the lifetime of the droplet (such as the temperature or the amount of liquid that forms the droplet), but to isolate the change of the concentration levels, those factors stayed constant throughout the entire experiment.

Mass Concentration	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trial 6**	**Trial 7**	**Trial 8**	**Mean**
0.00 g/L	180.20	187.50	170.63	192.40	191.60	174.50	192.60	182.40	184.77
0.05 g/L	25.81	35.99	119.86	225.90	230.70	213.30	177.50	171.30	157.31
0.10 g/L	80.10	44.74	36.47	28.80	94.11	225.76	49.60	56.30	60.22
0.20 g/L	83.40	74.30	86.70	168.20	46.70	86.30	66.70	55.90	75.55
0.40 g/L	170.10	86.30	65.30	75.50	31.40	42.80	33.60	125.50	71.50

Table 1: Note: "mean" stands for the average of the middle 50% of data points. Blue colored numbers represent the greatest mean time while red colored numbers represent the lowest mean time.

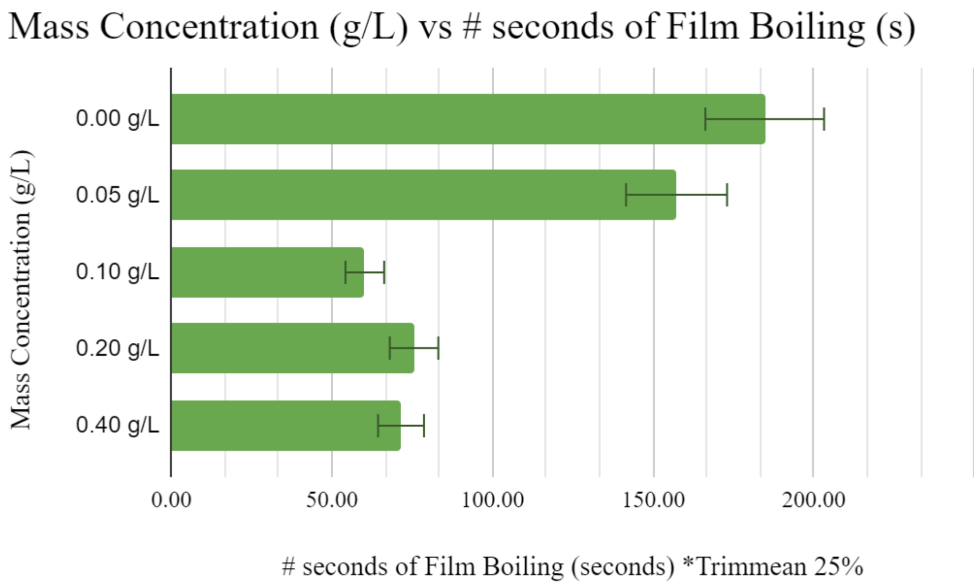

Figure 1: Bar graph of the data set using trimmed mean of middle 50% for seconds of film boiling.

Mass Concentration	0.00 g/L	0.05 g/L	0.10 g/L	0.20 g/L	0.40 g/L
Trial 1	180.20	25.81	80.10	83.40	170.10
Trial 2	187.50	35.99	44.74	74.30	86.30
Trial 3	170.63	119.86	36.47	86.70	65.30
Trial 4	192.40	225.90	28.80	168.20	75.50
Trial 5	191.60	230.70	94.11	46.70	31.40
Trial 6	174.50	213.30	225.76	86.30	42.80
Trial 7	192.60	177.50	49.60	66.70	33.60
Trial 8	182.40	171.30	56.30	55.90	125.50

Table 2: Data numbers are in seconds. Red numbers represent the trial with the least amount of time recorded and blue numbers represent the trial with the greatest amount of time recorded. All colored numbers (red, blue, and green) are excluded from trimmed mean calculations.

Mass Concentration	Trimmean	St Dev	Mean	Median	Range
0.00 g/L	184.77	8.46	183.98	184.95	21.97
0.05 g/L	157.31	81.78	150.05	174.40	204.89
0.10 g/L	60.22	63.94	76.99	52.95	196.96
0.20 g/L	75.55	37.18	83.53	78.85	121.50
0.40 g/L	71.50	48.33	78.81	70.40	138.70

Table 3: Data table with common statistical functions. Red colored numbers represent a trimmed mean that is smaller than the mean while blue colored numbers represent a trimmed mean that is greater than the mean. (25% excluded extremes in mean)

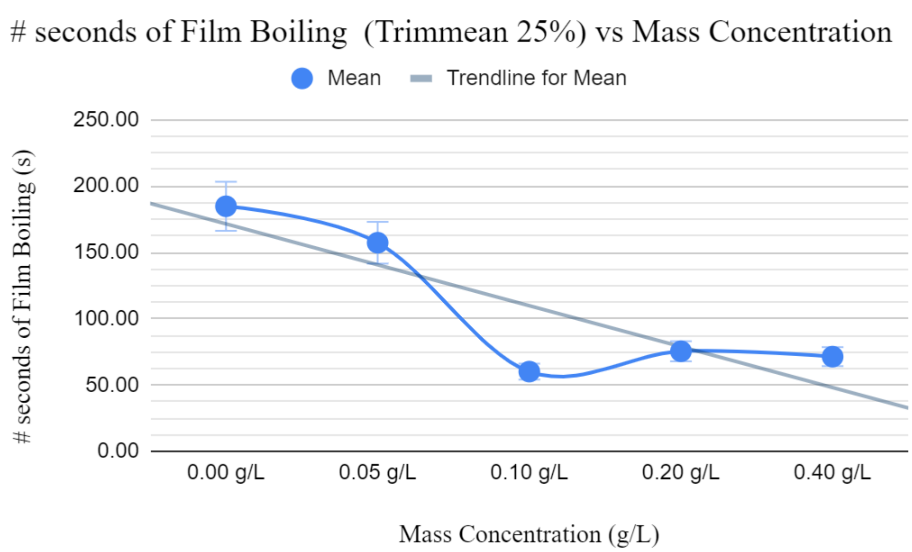

Figure 2: Downward trend that shows an inverse relationship between film boiling time and mass concentration of solution. The blue “mean” is a calculation of the average of the middle 50% of the data points to exclude outliers.

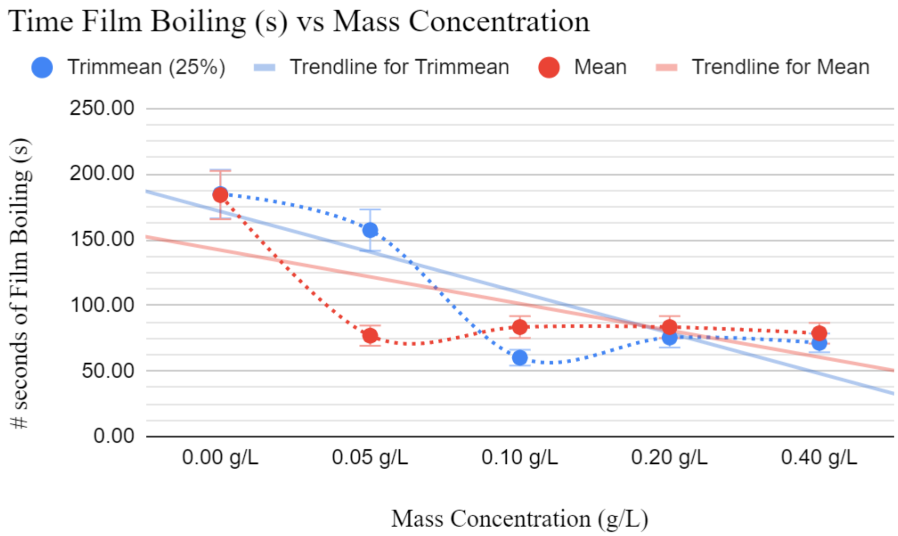

Figure 3: Graph of the trimmed mean (middle 50%) and mean in seconds, with their lines of best fit, set against the mass concentration of solution.

Using both the mean and median of these data sets, there is a general downward trend as the mass concentration increases. Since the trimmed mean excludes the upper and lower extremes (takes the middle 50% of points), the central four points are considered. Doing so achieves more accurate averages and thus returns a more accurate line of best fit for the data points.

The main observation noted was a drastic color change of the copper cups used in the experiment. There were multiple color stages, changing from the bronze color to a metallic pink color, then to a metallic purple, which further changed to gold, silver, and grey. During all these tests, we kept the surface of the hotplate at 215±5 degrees Celsius. However, these color changes affected whether the droplet in the cup would create the Leidenfrost effect or boil. For example, the droplets had nearly perfect Leidenfrost conditions when they were dropped into the copper cups in their first stage, bronze color. When droplets were dropped into the cups in their second to third stage, metallic pink and metallic purple, they sputtered violently, and small droplets of the solution flew out of the cup. However, they still maintained the Leidenfrost shape, but their lifetimes were lower than those of the droplets in the first stage of the cups. Finally, once the cups were in their fourth stage or later, any color past the gold color, the droplets instantly vaporized once making contact with the cap. This changing of color is due to the oxidation of the copper cups. Since the color of cuprous oxide, Copper(I) oxide, is red, it is likely that the copper cup, whose composition wasn't entirely copper, had partially oxidized (*Copper(1+) oxidocopper*, 2006). Since cupric oxide, Copper(II) oxide, is black, the last stage of the copper cups was likely oxidizing into cupric oxide (*Copper(II) oxide*, 2005).

Image 3: Color differences between copper caps. The newest cap is on the right while most used is on the left. Caps in between follow the gradient order.

Other observations include those about the Leidenfrost droplets themselves. As mentioned above, the droplets were considered "perfect" if they didn't sputter and had long lifetimes. If the droplets sputtered and had violent reactions with the heat, they were not considered perfect, and they had shorter lifetimes. Finally, if the droplet was dropped in the cup and instantly vaporized, the data was considered unusable due to the negligible lifespans of the droplets.

RESULTS

After removing two extreme outliers from each data set, the mean and trimmed mean of each set shows a general downward trend. The data reaffirms the previously proposed hypothesis. By analyzing the collected data, as the concentration of the solution increases from 0 to 0.05 to 0.1 to 0.2 to 0.4, in g of solute/L of solution, the average lifetime of the droplet generally decreases, from 184.77 to 157.31 to 60.22 to 75.55 to 71.50 seconds respectively. Since the plotted data does not fully correspond with the line of best fit, some sources of error were probably present, skewing the results of some trials. However, the general trend proves that as the concentration of the solute increases, the lifetime of the film boiling droplet decreases.

CONCLUSIONS AND FUTURE WORK

Many variables contributed to the results of this experiment, from changes in boiling point to slight variations in temperature. However, many trials were tested to limit the effect of these variables. Overall, the tests proved an inverse relationship between the concentration of solute and the time it takes for a droplet of solution to vaporize. The solution with 0g/L took the longest time and maintained film boiling for the longest period with an average of 183.98 seconds and a trimmed mean of 184.77 seconds. As the mass concentration of solute increased, the time to completely vaporize decreased: with averages of 150.045 seconds for 0.05g/L, 76.985 seconds for 0.1g/L, 83.525 seconds for 0.2g/L, and 78.813 seconds for 0.4g/L (#g of solute/L of solution). This data shows a trend that supports the hypothesis of the time to fully vaporize and concentration of solute is inversely proportional with one another; this means that a solution with pure water will take a longer time to completely film boil while a solution with high concentrations of pollutants, or solute, will take a shorter amount of time to completely vaporize.

There were multiple sources of error in this experiment, including material defects with the copper cups, temperature variations on the hotplate, and environmental factors, including temperature and humidity. Reducing these sources of error would be a primary goal if this experiment was repeated, along with an increase in the number of trials for more consistency. For additional future work, more chemicals and solutes can be tested to achieve a wider range of results, allowing for both more consistency and a wider scope of testing analysis.

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