PRELIMINARY STUDY ON THE FILM BOILING BEHAVIOR OF WATER AND SODIUM CARBONATE SOLUTIONS DROPLETS ON A STAINLESS-STEEL SURFACE

V.M.V. CRUZ[1], E. JIN[2]

[1] Centro Universitário do Leste de Minas Gerais, Departamento de Engenharia Química
[2] University of Toronto, Department of Chemical Engineering and Applied Chemistry
E-mail para contato: vitor.machadovianacruz@mail.utoronto.ca

RESUMO – Film boiling is a critical phenomenon in vapor explosion backed by many studies in literature; however, film boiling behavior is not studied in the context of sodium salt solutions and its behavior in different parameters. Experiments were conducted by dropping a droplet with different sodium carbonate (Na_2CO_3) concentrations on a hot surface and the measurement of the time of vaporization. This research aimed to investigate the effect of two different parameters, the variation in salt concentration and temperature, on film boiling behavior. The method used provided an understanding of the phenomenon, as well as comparative boiling curves based on the droplet lifetime using image analysis. The salt addition developed a thinner unstable film during boiling in high temperatures, as the salt lowers the vapor pressure of water, it reduced the repulsive forces between the hot surface and the droplet, and increasing the rate of heat transfer.

1. INTRODUCTION

The production of vapor bubbles is called nucleate boiling because the formation and growth of the bubbles depend on crevices serving as nucleating sites. As the surface temperature increases, the heat flux to the liquid increases. If the surface become hotter, the boiling enters a new phase called the transition regime (Incropera *et al.*, 2011).

After the transition regime, each increase in the pan's temperature reduces the rate at which energy is transferred to the liquid. In the transition, the bottom of the pan is starts to be covered by a layer of vapor. As the vapor conducts less heat than liquid water, the hotter the pan becomes, the less likely that the hot surface will be in direct contact with the water, and a film boiling regime is formed (Walker, 1996).

Film boiling causes a lot of problems in a variety of process, being harmful to a heat exchanger, for instance, whose purpose is to transfer energy. The presented work, aims to develop and establish an apparatus to observe and generate data on the boiling behavior, as well as building boiling curves with a variation in two parameters, the water temperature and sodium salt solution concentration. As a preliminary work, and with the future work focused on the smelt-water interaction in the kraft recovery boiler dissolving tanks in the pulp and paper industry.

2. PROBLEM DESCRIPTION AND METHODOLOGY

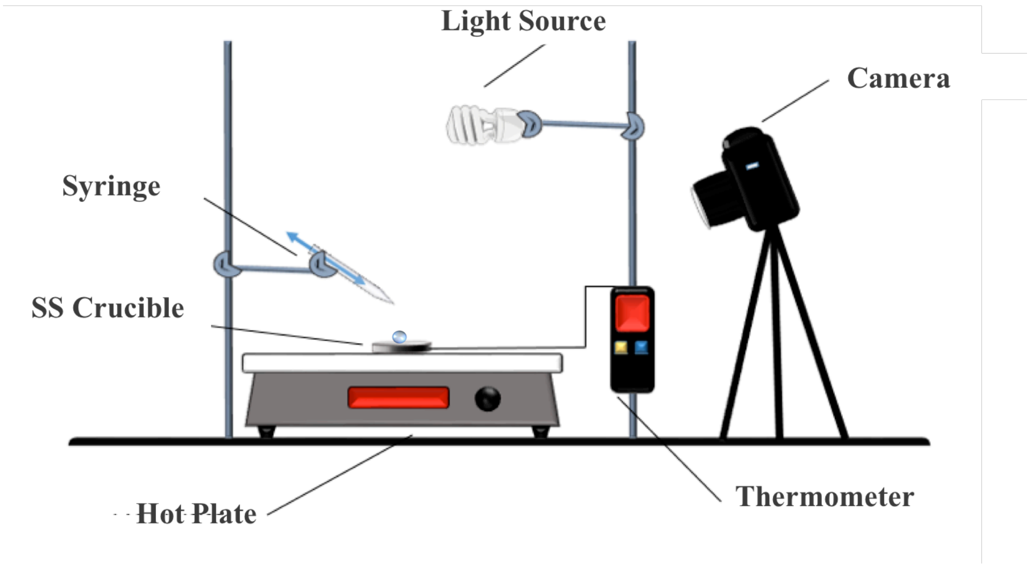
The formation and behavior of the film boiling depends on a series of variables, and the temperature plays an important role, once these liquid-liquid or liquid-solid interactions are between components with a large difference in temperature. Due to this difference, the film boiling is formed, and as a result, an extremely and violent interaction can take place during the transition boiling before the film boiling is achieved.

The study of this phenomenon is very important for a better understanding of a variety of process, for instance, the pulp and paper industry. The film boiling is not a desirable phenomenon in most of the process, since the vapor film formed between the two components prevents the desired heat transfer flow to take place. To better understand the vapor film formation and show the possible causes of its formation and violent course, a study to investigate the formation and effect of salt concentration, and temperature on film boiling stability on metal hot surface was carried out and an experimental apparatus was established.

2.1. Experimental Apparatus

To investigate the object of study, the film boiling phenomenon, an apparatus was designed, and it was built in the "Pulp and Paper - Chemical Recovery Laboratory" at the University of Toronto, Canada. As shown in the Figure 1, the apparatus consists of a syringe that generates liquid droplets with and average diameter of 0,291 cm and 0,0140 cm^3 in volume. The hot plate is the heat source, which heats up the stainless-steel crucible (SS Crucible) positioned at the center of the plate.

Figure 1 – Schematic of the Experimental Apparatus for Liquid-Hot Surface Interaction.



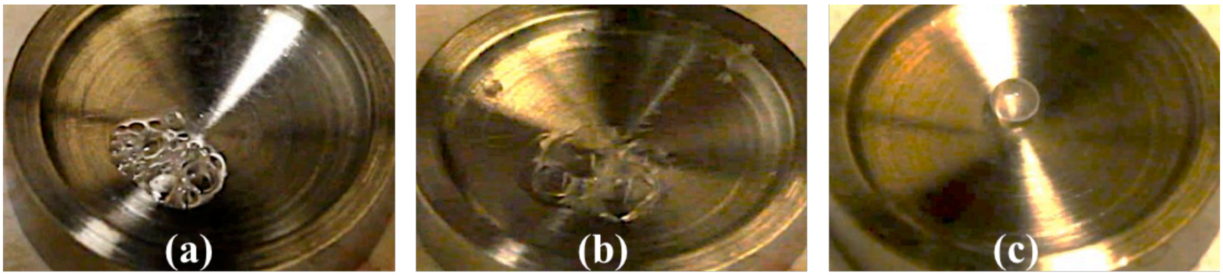
The exact temperature on the surface of the SS Crucible surface was measured by a thermocouple wire connected between the center of the stainless-steel crucible and the thermometer. To record each trial, a setup of a camera (Canon EOS T5i) and a light source (Light Bulb) was used.

2.2. Data Acquisition and Analysis

In this study, the film boiling phenomenon characteristics investigated were the boiling time, which also represents the rate of heat transfer along the boiling, and the film boiling stability of a single droplet onto the hot metal surface at different parameters. The main parameters used were the hot metal surface temperature variation from 100 to 550 °C; water droplet temperatures variation in 25, 50, 75 and 90 °C; droplets concentrations of 5 g/L and 50 g/L and saturated – 500 g/L at 30 °C – sodium carbonate (Na_2CO_3) solutions.

For every trial a single droplet generated by the syringe were dropped onto the hot surface of the stainless-steel crucible, and, in each run, a video was shot and processed using the Visualdub® video editing software to observe and obtain the boiling time and stability. The boiling time were calculated frame by frame by the time the droplet entered in contact with the hot metal surface until its complete boiling. To observe the stability, the droplet behavior was divided into three types of boiling: Nucleate boiling, transition boiling and film boiling as shown in Figure 2.

Figure 2 – Droplet Regime: (a) Nucleate Boiling, (b) Transition Boiling, and (c) Film Boiling.



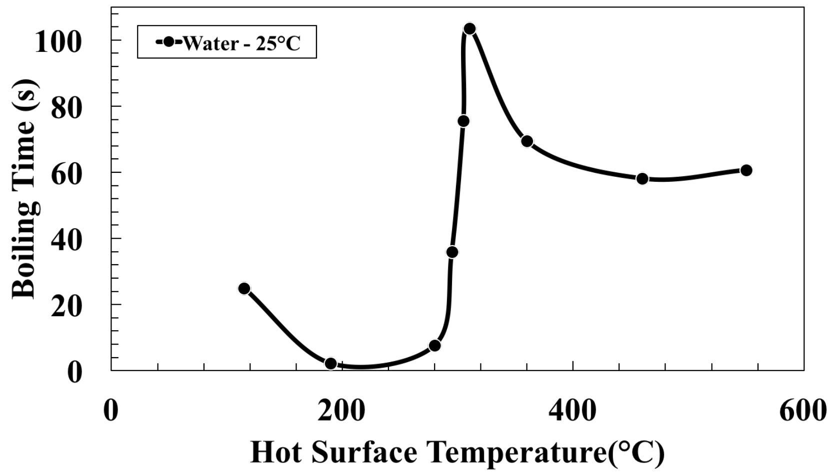
After all the substantial video and data analysis have been obtained, the boiling time showed to be the main correlation to observe how the droplet boils in terms of time and stability. A water boiling curve, using water droplets at room temperature (25 °C), was constructed and used as a blank pattern for comparison with the data processed, in relation to the droplets vaporization time, for every variation of parameter.

3. RESULTS AND DISCUSSION

The water boiling curve showed in Figure 3, was built using the apparatus established in section 2. The curve clearly states the desired boiling regimes, as the first third of the curve (up to 275 °C) is the nucleate boiling, the second third of the curve (up to 350 °C) until the Leindenfrost point (critical point) is the transition boiling and the third part of the graph (After 350 °C), after the critical point is the film boiling region.

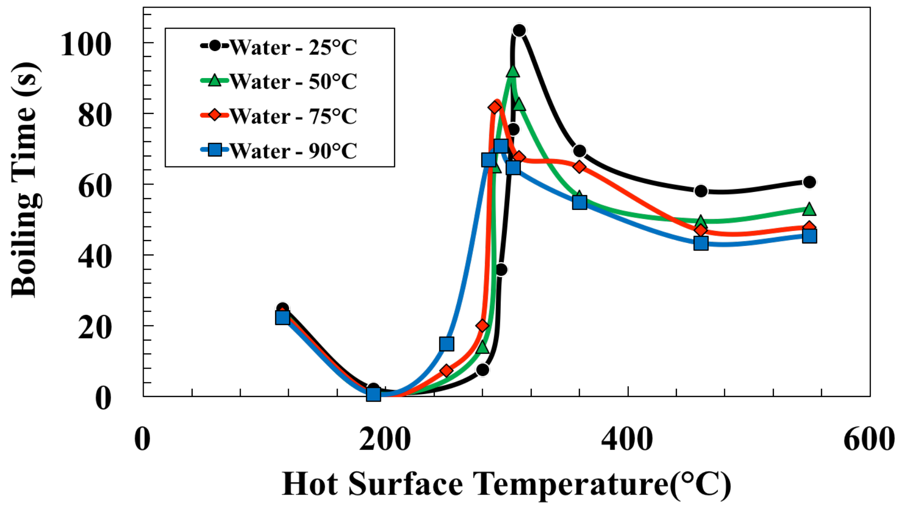
According to Bernardini and Mudawar (1999), Walker (1996), and Incropera *et al.* (2011) studies when plotting the boiling data in terms of time and hot surface temperature, the boiling curve was very similar, where the found boiling curve was also divided into the three boiling regimes (Nucleate, transition and film boiling). The surface temperatures and the boiling regimes areas, also agrees with the data presented in the literature.

Figure 3 – Water Boiling Curve: Blank Water Boiling Curve.



The curve was built to establish a blank pattern to follow, so that the curves based on the water droplets temperatures and sodium carbonate solutions droplets could be built, and compared with the water droplets curve, and observe how the phenomenon change its behavior by adding Na_2CO_3. The first variation in parameters was the water temperature, which the boiling was studied for four different temperatures, 25 °C, 50 °C, 75 °C and 90 °C. The found boiling curves for the variation in water temperature is presented in Figure 4.

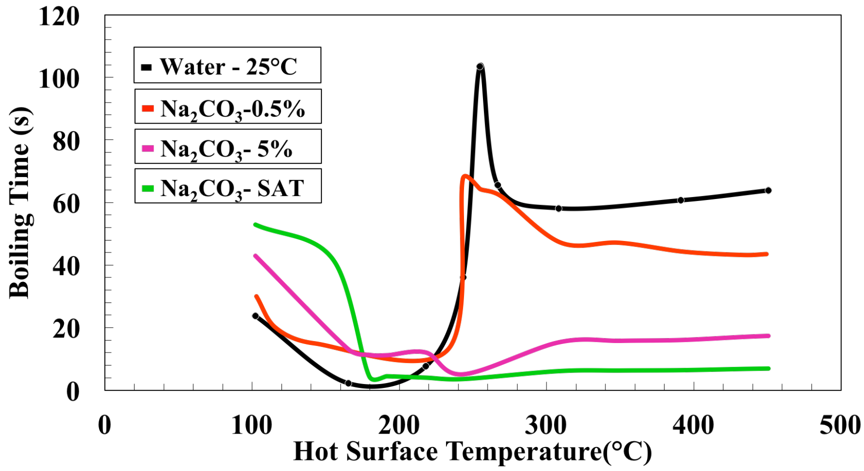
Figure 4 – Water Boiling Curve: Different Temperatures.



All the curves showed a pattern during the first temperature point (115 °C) of the nucleate boiling regime, as water at 90 °C (22.33 ± 0.3 s) was the first to boil, followed by 75 °C (23.5 ± 0.7 s), 50 °C (23.8 ± 0.4 s), 25 °C (25.0 ± 0.8 s). The Leidenfrost point was decreased as the temperature increased. Although, the film boiling time had also decreased with the increase in the temperature, the film boiling behavior was more stable compared with water at lower temperatures, with less "splashing" and "bouncing" on the crucible (hot surface). There is not a lot of studies on boiling small droplets of salt solutions, considering this, it is important to study the impact of salts concentrations on the boiling curve path of droplets on a hot metal plate. In Figure 5 are presented the results for the boiling curves of 5 g/L, 50 g/L and saturated sodium carbonate (Na_2CO_3) solutions at 25 °C. The water temperature doesn't play a very significant change in water boiling curve.

The biggest change, comparing with water (25 °C), in the boiling curve for Na_2CO_3 solutions (at 25 °C) was noticed to be the saturated solution, followed by the 50 g/L solution and the 5 g/L solution. Noticeably, the salt content had increased the nucleate boiling time, once the heat transfer was high and the salt concentration had an impact increasing the droplet boiling point. At surface temperature of 115 °C (nucleate boiling region) it took 53.2 ± 0.6 s for the saturated, 42.4 ± 0.7 s for the 50 g/L and 30.2 ± 0.3 s to the 5 g/L sodium carbonate droplets to boil.

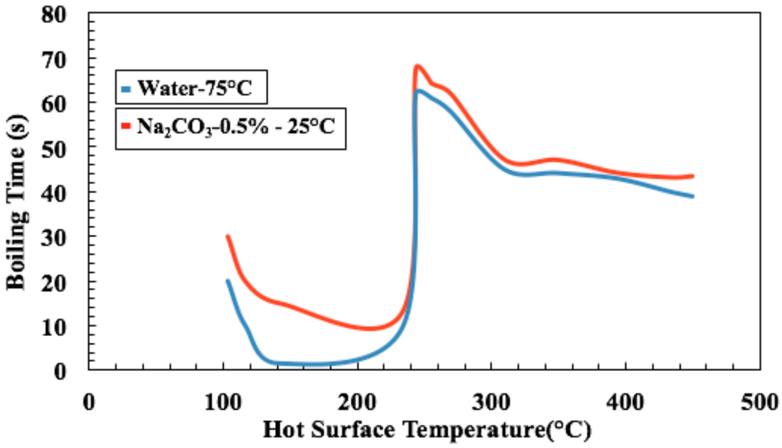
Figure 5 - Boiling Curve: Water (25 °C) versus 5 g/L, 50 g/L and Saturated Na_2CO_3 (25 °C).



The 5 g/L transition boiling region was the least affected by the salt content, but almost no transition boiling region was observed to the Na_2CO_3 saturated, and 50 g/L solution, as the sodium salt content decreased the water vapor pressure and increased the heat flux, which was high enough not form the vapor film and prevent the film boiling phenomenon. A similar behavior to the 5 g/L curve was reported by Walker (1996), where tap water (rich in salts and minerals) droplets boiling curve generated a graph with a flatter peak, probably due to the suspended particles of impurities in the droplets, that breached the vapor layer, conducting heat into the drops. The 5 g/L film boiling time was 47.20 ± 0.2 s at 310 °C, 44.27 ± 0.4 s at 390 °C and 43.5 ± 0.6 s 450 °C. Although the graph shows results for the boiling of 50 g/L and saturated sodium carbonate solutions at high temperatures, no film boiling was observed.

Comparing the boiling curve results in Figure 6, for the salt solutions droplets and for the water droplets at different temperatures, was noticed that the curve for water at 75 °C had a very similar behavior as the Na_2CO_3 5 g/L solution. However, there might not be any scientific significant behind it, and more data points at different temperature and concentration are needed to build and to prove the correlated data. More studies are needed to have a better understanding in the applicability of the study of this phenomenon.

Figure 6 – Boiling Curve: Water (75 °C) versus 5 g/L Na_2CO_3 (25 °C).



5. CONCLUSION

The increase in water temperature, also made the boiling time for the nucleate region go up, dropped the Leidenfrost point and decreased the film boiling time. As for the sodium carbonate solutions, the salt proved to have a significant increase in the time of boiling at nucleate region, but not only decreased the Leidenfrost point, but also the film boiling time for 5 g/L solutions, and no film boiling for higher concentrations, and it was established a correlation between the effect of the salt concentration with the water temperature.

Future work has already been done, and the data is being processed. The goal is to study more the variation of other parameters, for instance droplet velocity, different sodium salt contents, and variation in the sodium salt solution droplets temperatures. The study of this phenomenon is also important for the pulp and paper industry to have a better understanding of the smelt-water interaction in the recovery boiler, which will be the main subject of study of future articles.

6. ACKNOWLEDGMENTS

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