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Integration of Boiling Experiments in the Undergraduate Heat Transfer Laboratory

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Abstract

This paper presents three boiling experiments that can be integrated in the undergraduate heat transfer laboratory. The objective of these experiments is to enhance the understanding of boiling process by undergraduate mechanical engineering students. These experiments expose the students to several important concepts in boiling, such as subcooled boiling, modes of pool boiling, and Leidenfrost Phenomenon. The experimental setup and apparatus required to carry out these experiments is simple. It includes a metallic plate such as brass, stainless steel or aluminum, a heating source such as a Hot Plate, thermocouples, a stopwatch, a liquid dropper, and a camera. These equipments are inexpensive and available in almost all undergraduate heat transfer laboratories.

I. Introduction

Boiling and condensing processes play an important role in a large number of practical engineering applications, such as the production of electrical power from vapor cycles, production of refrigeration, and the design of petrochemical processes (such as the refining of petroleum and the manufacture of chemicals). Boiling and condensing are vapor-liquid phase change processes where fluid motion is involved. Due to this fact, boiling and condensing are classified as convective mechanisms. However, there are major differences between these mechanisms and single phase convective heat transfer. This is because there are significant differences between the various fluid properties in the two phases, such as conductivity, specific heat, and density. Also, there is a consumption or release of latent heat h_{fg} which influences the heat transfer rates greatly during phase change.

Both boiling and evaporation are liquid-to-vapor phase change processes, but there are major differences between the two. Evaporation process occurs at the liquid-vapor interface when the vapor pressure p_v is less than the saturation pressure p_{sat} of the liquid at a given temperature. And evaporation does not involve bubble formation or bubble motion. Examples of evaporation are the evaporation of sweat to cool the human body and the drying of fruits and cloths. On the other hand, boiling occurs at the solid-liquid interface when the temperature of the surface is maintained at a temperature T_s that exceeds the saturation temperature T_{sat} corresponding to the pressure of the liquid that is in contact with the surface. The boiling process is characterized by the rapid formation of vapor bubbles at the solid-liquid interface. When the vapor bubbles reach a certain size they start to detach from the surface and attempt to rise to the free surface of the liquid. Bubbles are formed, during the boiling process, as a result of the surface tension σ at the liquid-vapor interface due to the attraction force on molecules at the interface toward the liquid phase.

Boiling is classified as pool boiling or flow boiling (forced convection boiling) depending on the absence or presence of fluid motion, respectively. In the case of pool boiling, the fluid is stationary, and its motion near the surface is due to natural convection and to the motion of the bubbles caused by their growth and detachment. Whereas, in flow boiling, the fluid is set in motion by external means such as a pump, as well as by natural convection and the motion of the bubbles. In addition, boiling is classified as subcooled boiling or saturated boiling, depending on the liquid temperature. Boiling is referred to as subcooled when the temperature of the liquid is below the saturated temperature T_{sat} (i.e., the liquid is subcooled) and it is considered saturated when the temperature of the liquid is equal to the saturated temperature T_{sat} (i.e., the liquid is saturated). It should be noted that the three experiments presented in this paper examine pool boiling under subcooled conditions.

Depending on the value of the excess temperature ΔT_e which represents the excess of the surface temperature above the saturation temperature of the liquid ($\Delta T_e = T_s - T_{sat}$), pool boiling takes different forms. These forms or regimes are natural convection boiling, nucleate boiling, transition boiling, and film boiling. One of the three experiments suggested in this paper is to observe the different mechanisms of pool boiling in these different regimes. In another experiment, the total evaporation time of droplets of water deposited on a hot surface will be measured at different surface temperatures. The trends will be compared with the boiling curve (see section B). In the third experiment, the Leidenfrost point, where the heat flux reaches a minimum, will be determined for different liquids.

The objective of this paper is to develop laboratory experiments to enhance the learning of basic boiling concepts by undergraduate mechanical engineering students. The equipments required to achieve this goal are inexpensive and available in almost all undergraduate heat transfer laboratories.

II. Experimental Setup and Equipment

The experimental apparatus is relatively simple and inexpensive. A brass plate (140 mm long, 76 mm wide and 12.7 mm thick) is placed horizontally on a Scientific Hot Plate. The brass plate can be heated and maintained at a constant temperature by adjusting the Scientific Hot Plate to the appropriate heating level. The temperature of the brass plate is measured by a thermocouple. The measuring junction of the thermocouple is inserted from the side of the brass plate into a small hole and it reaches the center of the plate. The output of the thermocouple is read using an Omega Microprocessor Thermometer. A depression in the form of a shallow spherical cap (35 mm in diameter and 3.4 mm deep) has been machined into the brass plate in order to provide a seat onto which droplets of liquid could be deposited for observation. A camera was used to take pictures of the different boiling forms and regimes. A stopwatch was also used to measure the time that the liquid droplet would take to evaporate. All observations and measurements were made only after the system had reached steady state conditions.

III. The Experiments

A. Observations of the Different Regimes in Pool Boiling of Subcooled Liquid

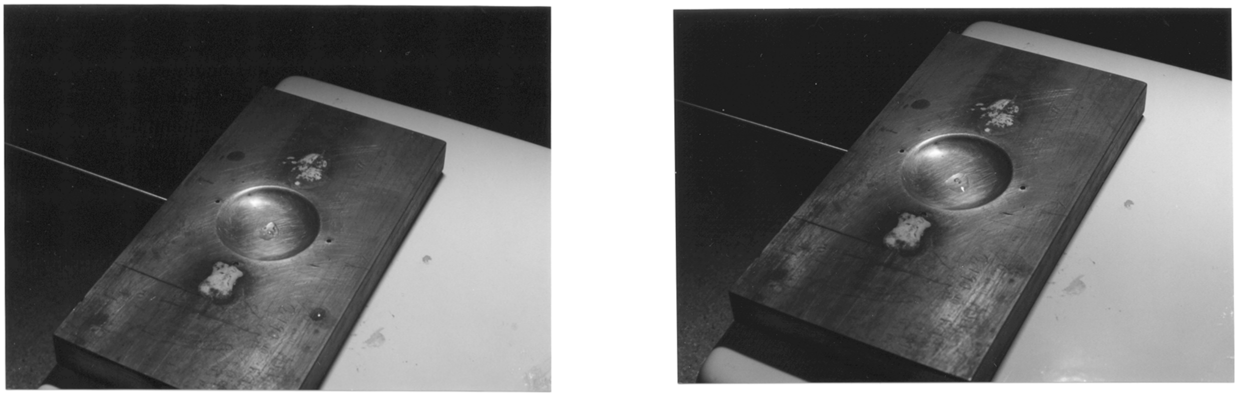
The objective of this experiment was to observe the different behaviors associated with the different regimes of pool boiling (i.e., natural convection boiling, nucleate boiling, transition boiling, and film boiling) of a droplet of subcooled water on a brass plate that is heated to a temperature that exceeds the saturated temperature of water.

The horizontal brass plate is heated to the desired temperature T_s by adjusting the electrical energy input to the Scientific Hot Plate. When steady state is reached, a droplet of deionized water at room temperature is placed in the grove on the heated brass plate using a liquid dropper. The behavior of the water droplet during the boiling process is observed carefully and recorded. Also, a picture of the droplet during the boiling process can be taken for the record. This procedure is repeated several times, by readjusting the electrical energy input to the Scientific Hot Plate, to cover all the regimes of pool boiling. It should be noted that the temperature of the brass plate T_s dropped about 1 to 1.5^{o}C after the water droplet is deposited on the surface. This is because of the heat transfer (the heat loss) from the surface of the heated brass plate to the water droplet during the evaporation of the droplet. But once the evaporation of the water droplet is completed, the temperature of the plate T_s increases to the original temperature value.

It was observed that the water droplet assumed completely different shapes during the boiling process in each regime and the time of evaporation was different from one regime to another and within the regime itself. The results were carefully analyzed and grouped into seven different zones of behavior that are summarized in Table 1. The reason for arranging these observation in seven zones and not four, the number of the different regimes in pool boiling (natural convection boiling, nucleate boiling, transition boiling, and film boiling) is that the characteristics sometimes are different within one regime. Zones I and II correspond to natural convection boiling and nucleate boiling, respectively. Zone III is the neighborhood where minimum evaporation time of the liquid droplet is attained and at which there is maximum heat flux q_s (i.e., maximum heat transfer rate from the heated surface to the liquid droplet). The transition boiling regime is divided into three zones (zones IV, V, and VI). This is because the behavior of the evaporation of the liquid droplet was not exactly the same throughout the transition regime as Table 1 illustrates. And finally, zone VII corresponds to the film boiling regime. Figures 1, 2, 3, and 4 present pictures of the droplet behavior during the different regimes of pool boiling. The pictures (a) and (b) in Fig. 1 show the pool boiling process of a subcooled water droplet in the natural convection boiling regime at $\Delta T_e = 7^{o}C$. Figure 2 shows the pool boiling process of a subcooled water droplet in the nucleate boiling regime at $\Delta T_e = 16^{o}C$. The transition boiling at $\Delta T_e = 120^{o}C$ and film boiling at $\Delta T_e = 161^{o}C$ are shown in Figs. 3 and 4, respectively. The description of the behavior of the water droplet during the boiling process shown in these pictures is summarized in Table 1.

Table 1 Characteristic Zones and their Descriptions.

Observed Zones	Excess Temperature Range (ºC)	Observed Behavior
I	$0 < \Delta T_e < 10$	Many small bubbles form instantly at the base. Two main features are observed here: 1) a single bubble remains by itself for a short while; and 2) after this single bubble disappears, there is a period when no bubbles can be seen in the drop at all. Finally, the drop shrinks until it disappears.
II	$10 < \Delta T_e < 44$	Many bubbles form at the base of the drop. The drop spreads out, swells up and breaks up into two or more patches. The bubbles disappear. Thereafter, individual patches shrink in size continuously until they disappear. Increases in temperature appear to speed up the processes described in this zone.
III	$44 < \Delta T_e < 50$	The drop breaks up very quickly and its evaporation is so rapid that it seems instantaneous.
IV	$50 < \Delta T_e < 70$	The drop breaks up so quickly that it starts to shatter into small droplets. Evaporation is very rapid. Shattering becomes even more evident at higher temperatures.
V	$70 < \Delta T_e < 120$	The drop shatters instantly into crystallized balls that are well defined. One of the balls is typically larger than the rest. The balls jump from one spot to another repeatedly (like pop corn). The large ball gets larger with increasing temperatures and the smaller balls become fewer and fewer. At still higher temperatures, however, the large ball, once formed, breaks up into smaller balls whose sizes vary with the temperature.
VI	$120 < \Delta T_e < 130$	One single ball is formed. It takes it a while to evaporate. However, just before it evaporates completely, it would shatter into tiny balls.
VII	$130 < \Delta T_e < 200$	One single ball is formed. It takes it a while to evaporate. The ball gets smaller and smaller until it evaporates completely. No shattering is observed at all.



(a)

(b)

Fig. 1 Natural Convection Boiling Regime

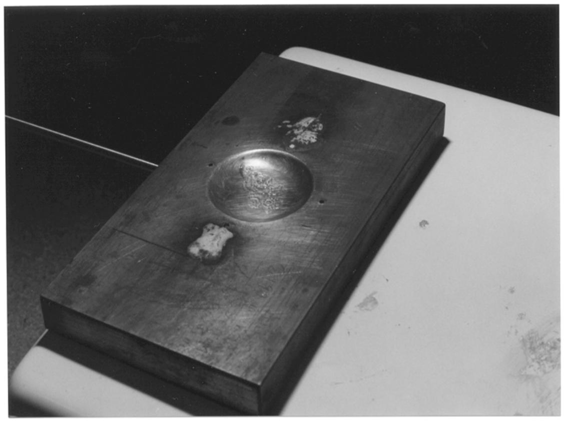


Fig. 2 Nucleate Boiling Regime

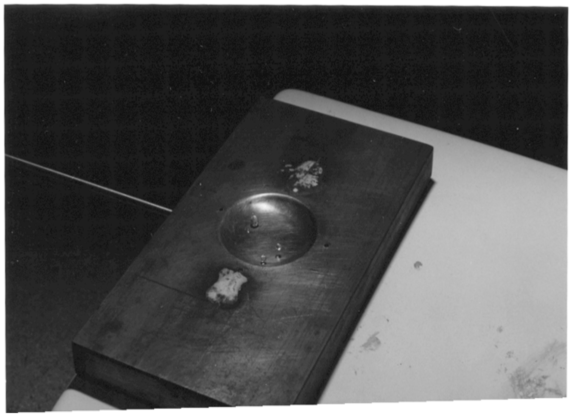


Fig. 3 Transition Boiling Regime

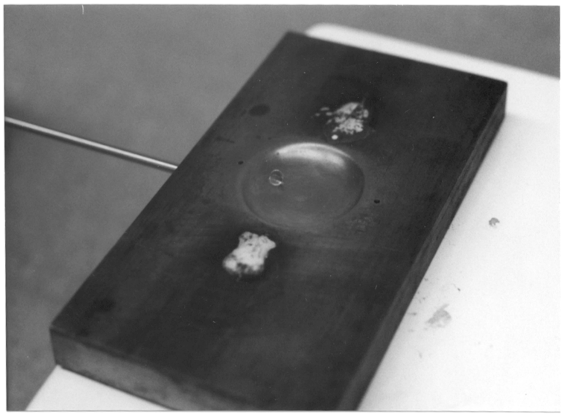


Fig. 4 Film Boiling Regime

B. Measurements of Total Evaporation Time of a Droplet of Subcooled Water in Pool Boiling

The objective of this experiment was to experimentally determine the total evaporation time of a droplet of deionized water in the different pool boiling regimes. The mass of the individual droplet was measured to be m = 32 mg. This value represents the average of 10 different measurements using a Denver Instrument M-310 digital scale. The repeatability of the mass measurements was determined to be within 2.5 mg (7.8%).

The experimental procedure for this experiment is relatively simple. The horizontal brass plate is heated to the desired temperature by the Scientific Hot Plate. Once steady state condition is reached, the water droplet is then deposited onto the heated plate using a liquid dropper. The total evaporation time (i.e., the time elapsed from the instant at which the water droplet is deposited on the heated plate to the instant at which the droplet is evaporated completely) was measured using a stopwatch. Each measurement was repeated 5 times and then an average of the total evaporation times was calculated. The repeatability of the time measurements was determined to be within 9%. It should be noted that the measurements of the total evaporation time were carried out for three regimes only: the natural convection boiling regime, nucleate boiling regime, and film boiling regime. It was not possible to measure the total evaporation time of the droplet in the transition boiling regime. This is because the ball that formed during the transition boiling shatters to smaller balls and some of these balls jump off the heated brass plate. The transition boiling regime is also known as the unstable boiling or partial film boiling regime. In this boiling regime, an unstable condition exists in which the process oscillates between nucleate boiling and film boiling.

The variation of the total evaporation time with the excess temperature ΔT_e in the natural convection and nucleate boiling regimes is illustrated in Fig. 5. The figure clearly shows that the total evaporation time in these two regimes decreases as the excess temperature ΔT_e increases. This is because in these two regimes the heat flux q_s increases with increasing excess temperature ΔT_e (i.e., the rate of heat transfer from the heated plate to the water droplet increases as the surface temperature T_s increases) as the general boiling curve in reference [1] shows. The measured results of the total evaporation time in these two regimes agree favorably with the results reported by Cumo, et al. [2].

Figure 6 shows the effect of the excess temperature ΔT_e on the total evaporation time in the film boiling regime. It can be seen from the figure that the total evaporation time decreases as the excess temperature ΔT_e increases. Again, this is because in the film boiling regime, the heat flux q_s increases as the excess temperature increases (i.e., the rate of heat transferred from the hot surface increases as the surface temperature T_s increases in this regime) as the general boiling curve in reference [1] shows. In the film boiling regime, the heat flux q_s increases with increasing excess temperature ΔT_e as a result of heat exchange between the heated plate and the liquid droplet through the vapor film due to radiation, which becomes significant at high temperatures ($\Delta T_e \geq 150^oC$). These measured results of the total evaporation time in the film boiling regime agree favorably with the results reported by Cumo, et al. [2] in this regime.

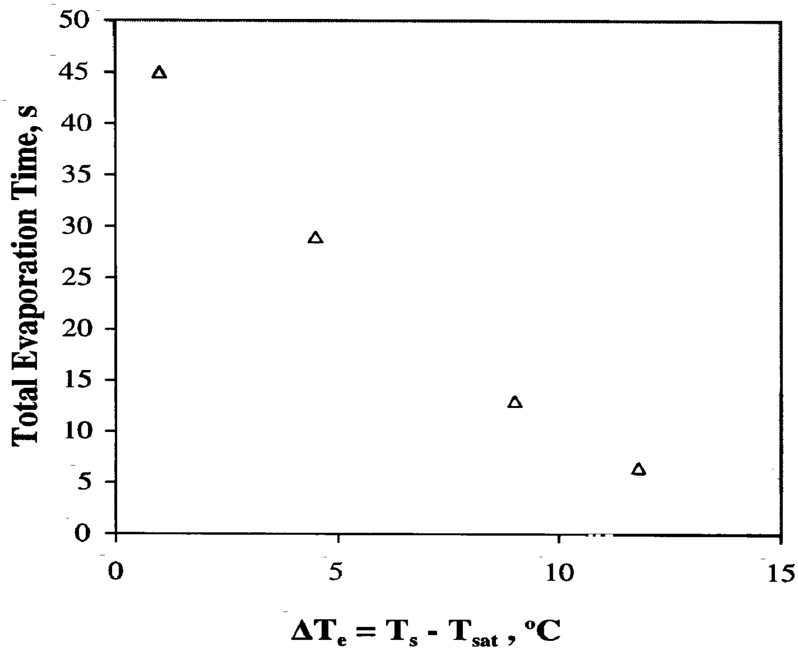


Fig. 5 Total evaporation time vs. excess temperature in natural convection and nucleate boiling regimes.

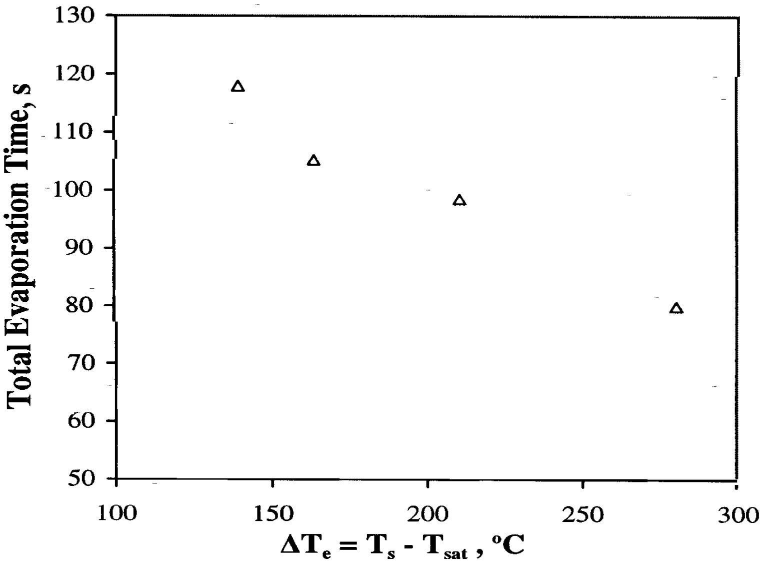


Fig. 6 Total evaporation time vs. excess temperature in film boiling regime.

C. The Leidenfrost Phenomenon: Film Boiling of Liquid Droplets on a Flat Plate

The film boiling of small droplets of liquid on a heated surface is commonly known as the Leidenfrost Phenomenon after J. G. Leidenfrost who first studied the process in 1756. The objective of this experiment is to determine the Leidenfrost point, defined as the excess temperature at which the droplet evaporation time is greatest, for different liquids, such as water, ethanol, benzene. It was reported by Gottfried et al. [3] that the Leidenfrost point is well defined for organic liquids (ethanol and benzene) and it is at excess temperature ΔT_e of 100 - 105ºC , while for water it varies between excess temperatures ΔT_e of 150ºC and 210ºC. This is because for water the Leidenfrost point depends on the surface and the method of depositing the droplet on the surface. They also reported that the Leidenfrost point is independent of droplet size. However, the experimental study of Cumo, et al. [2] indicate that the Leidenfrost point for water droplet on a hot plate is about an excess temperature ΔT_e of 140ºC. And in our experimental study, the Leidenfrost point for a dionized water droplet on a heated brass plate was observed to be about an excess temperature ΔT_e of 130ºC. The boiling process of liquid droplets on a hot surface was extensively examined in the past (see for example, Wachters et al. [4] and Wachters and Westerling [5], Wachters and van Andel [6]).

In this experiment, the students will try to determine Leidenfrost point for droplets of water and a couple of organic liquids on a hot horizontal plate, and then compare their results with those of reported in the literature. Also, they will examine the fact that the Leidenfrost point is independent of the droplet size.

IV. Impact of the Project

The three boiling experiments discussed above were introduced to the students of the undergraduate heat transfer laboratory (ME 322) in spring 2000. Upon the completion of these experiments, the students were asked to submit some feedback regarding the integration of these experiments into the undergraduate heat transfer laboratory. Almost all of the students favorably agreed that the inclusion of these three boiling experiments will widen the scope of the undergraduate heat transfer laboratory. They also have indicated that these experiments have enhanced their understanding of the boiling phenomenon.

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