Integration of boiling experiments in the undergraduate heat transfer laboratory

Hosni I. Abu-Mulaweh (corresponding author) and Josué Njock Libii
Engineering Department, Indiana University–Purdue University Fort Wayne, Fort Wayne, IN 46805, USA
E-mail: mulaweh@engr.ipfw.edu

Abstract This paper presents two boiling experiments that can be integrated in the undergraduate heat transfer laboratory. The objective of these experiments is to enhance the understanding of the boiling process by undergraduate mechanical engineering students. These experiments expose students to several important concepts in boiling, such as subcooled boiling, modes of pool boiling, and the Leidenfrost phenomenon. The experimental set-up required to carry out these experiments is simple. It includes metallic plates such as brass, stainless steel or aluminium, a heating source such as a heating pad, thermocouples, a stopwatch, a liquid dropper, and a camera. The equipment is inexpensive and available in almost all undergraduate heat transfer laboratories.

Keywords experiments; boiling; Leidenfrost phenomenon; heat transfer laboratory

Boiling and condensing processes play an important role in a large number of practical engineering applications, such as the production of electrical power from vapour cycles, refrigeration, and the design of petrochemical processes (such as the refining of petroleum and the manufacture of chemicals). Boiling and condensing are vapour–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-vapour phase change processes, but there are major differences between the two. Evaporation occurs at the liquid–vapour interface when the vapour 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 vapour bubbles at the solid–liquid interface. When the vapour 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–vapour interface due to the attraction force on molecules at the interface to 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 (free) convection and to the motion of the bubbles caused by their growth and detachment. 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 T_{sat} (i.e., the liquid is saturated). It should be noted that the two 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 two experiments suggested in this paper is to observe the different mechanisms of pool boiling in these different regimes. In the second 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 general boiling curve shown in Fig. 1.

The boiling process of liquid droplets on a hot surface was extensively examined in the past (see for example, Gottfried *et al.* [1], Wachters *et al.* [2] and Wachters and Westerling [3], Wachters and van Andel [4], Cumo *et al.* [5], and the references cited therein). The objective of this paper is to develop laboratory experiments to enhance the learning of basic boiling concepts by undergraduate mechanical engineering students. The equipment required is inexpensive and available in almost all undergraduate heat transfer laboratories.

Experimental set-up and equipment

The experimental apparatus is relatively simple, as shown in Fig. 2. Three heated brass plates are utilized in order to reduce the time required to complete the experiments and make it possible for the students to finish running the experiment within the allocated laboratory period. The heated brass plates are made of three composite layers that are held together by screws. The upper layer is a brass plate (10 cm in diameter and 1.27 cm thick). The middle layer consists of a heating pad that can be controlled for electrical energy input. The bottom layer of the heated plates is a brass plate 0.64 cm thick serving as backing and support for the heated plate structure. The brass plate can be heated and maintained at a constant temperature by adjusting and controlling the level of electrical energy input to the heating pad. This is accomplished using variable-voltage transformers. 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 centre of the plate. The output of the thermocouple is read using an Omega

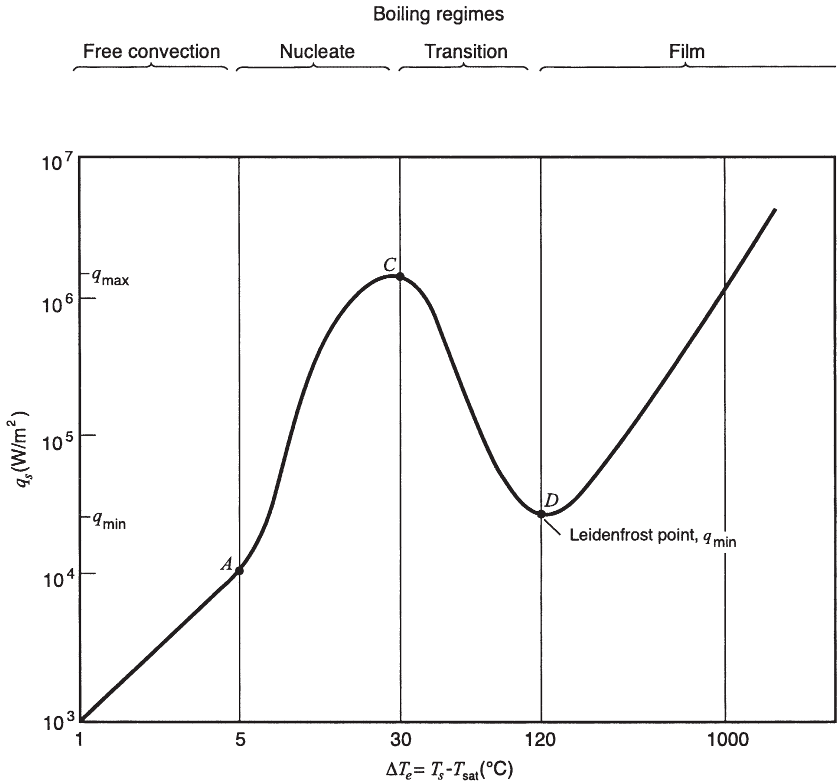

Fig. 1 *General boiling curve.*

Fig. 2 *Experimental set-up.*

microprocessor thermometer. A depression in the form of a shallow spherical cap (45 mm in diameter and 3.5 mm deep) has been machined into the upper brass plate in order to provide a seat onto which droplets of liquid can be deposited for observation. A digital camera is used to take pictures of the different boiling forms and regimes. A stopwatch is used to measure the total time that the liquid droplet takes to evaporate. The mass of the individual water droplet is measured using a Denver Instrument M-310 digital scale. All observations and measurements are made only after the system has reached steady-state conditions.

The experiments

Observations of the different regimes in pool boiling of subcooled liquid

The objective of this experiment was to observe the different behaviours 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 plates are heated to the desired temperatures, T_s, by adjusting the electrical energy input to the heating pads using the variable-voltage transformers. When steady state is reached, a droplet of deionized water at room temperature is placed in the grove on the heated brass plates using a liquid dropper. The behaviour 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, after adjusting the electrical energy input to the heating pads, to cover all the regimes of pool boiling. It should be noted that the temperature of the brass plate, T_s, drops about 1–1.5 °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 its original value.

It was observed that the water droplet assumed completely different shapes during the subcooled boiling process in each regime and the total time of evaporation varied with the excess temperature from one regime to another and within the regime itself. The results were carefully analysed and grouped into seven different zones of behaviour, which are summarized in Table 1. The reason for arranging these observations in seven zones and not four, the number of the different regimes in saturated pool boiling (i.e., natural convection boiling, nucleate boiling, transition boiling, and film boiling), is that the characteristics sometimes are different within the same regime. Zones I and II correspond to natural convection boiling and nucleate boiling, respectively. Zone III is where the 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 (i.e., zones IV, V, and VI). This is because the behaviour of the evaporation of the liquid droplet was not exactly the same throughout the transition regime, as Table 1 illustrates. Finally, zone VII corresponds to the film boiling regime.

TABLE 1 *Characteristic zones and their descriptions*

Observed zones	Excess temperature range (°C)	Observed behaviour
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 popcorn). 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.

Figs. 3–6 present pictures of the droplet behaviour during the different regimes of pool boiling. Fig. 3 shows the pool boiling process of a subcooled water droplet in the natural convection boiling regime at $\Delta T_e = 6\,°C$. In this pool boiling regime there is insufficient vapour in contact with the liquid phase to cause boiling at the saturation temperature. The figure clearly shows that in this regime many small bubbles form instantly at the base. More characteristics of the behaviour of pool boiling during this regime is given in Table 1. Fig. 4 shows the pool boiling process of a subcooled water droplet in the nucleate boiling regime at $\Delta T_e = 27\,°C$. In this pool boiling regime heat transfer rates and convection coefficients are high and associated with small values of the excess temperature. That is why it is desirable to operate engineering devices in the nucleate boiling regime. As can be seen from the figure, the water droplet is spread out and swollen up. More details on the behaviour of the droplet during this pool boiling regime are given in Table 1. The transi-

Fig. 3 *Natural convection boiling regime.*

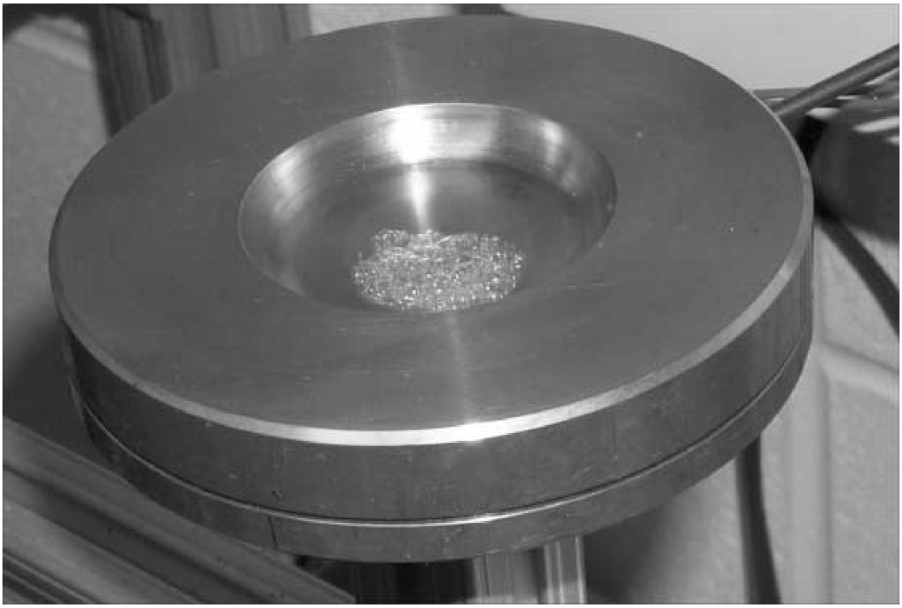

Fig. 4 *Nucleate boiling regime.*

tion boiling at $\Delta T_e = 118\,^\circ\mathrm{C}$ is illustrated in Fig. 5. Transition boiling is referred to as unstable film boiling or partial film boiling. In this pool boiling regime the water droplet shatters instantly into crystallized balls that are well defined. As the figure clearly shows, one of the balls is typically larger than the rest. The balls jump from

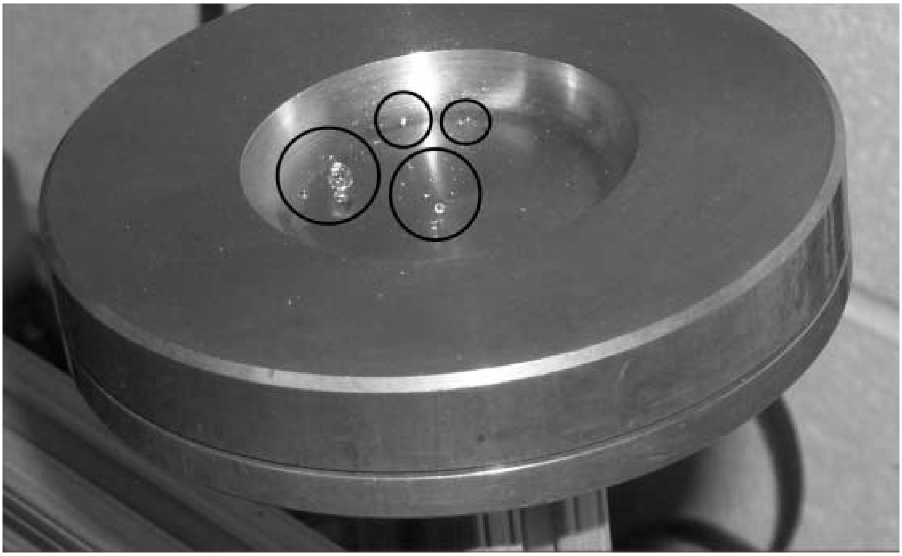

Fig. 5 *Transition boiling regime.*

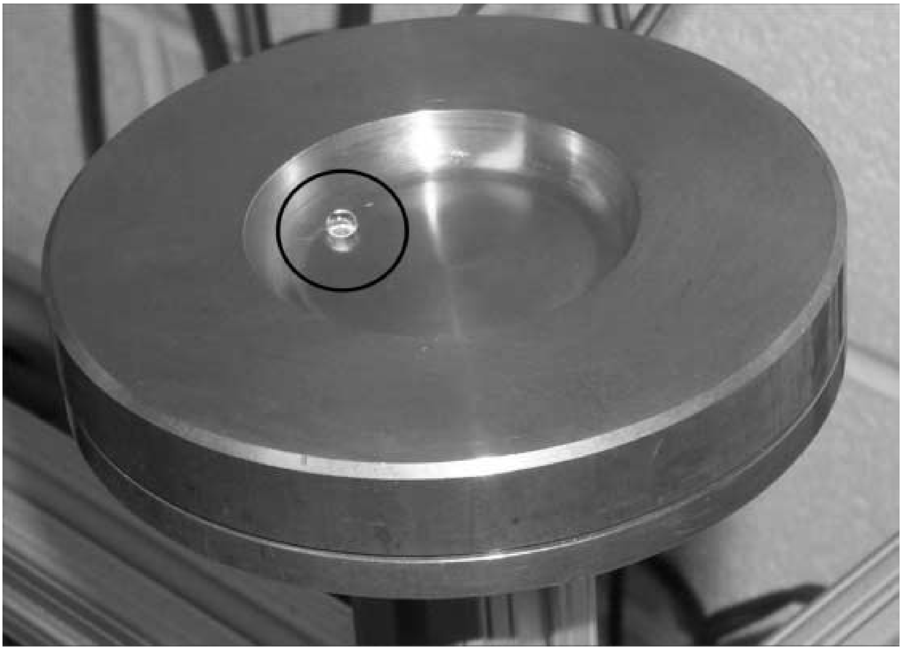

Fig. 6 *Film boiling regime.*

one spot to another repeatedly. For more details on the behaviour of droplet during this regime see Table 1. Film boiling at $\Delta T_e = 140\,^\circ\text{C}$ is shown in Fig. 6. In this boiling regime heat transfer from the surface to the liquid occurs by conduction through the vapour film that is formed between the surface and the liquid. This is known as the Leidenfrost phenomenon. The figure clearly shows that one single ball is formed and no shattering is observed. The ball gets smaller and smaller until it completely boils away. In this regime, the water droplet supported by the vapour film slowly boils away as it moves about the hot plate. As the plate temperature is increased, radiation through the vapour film becomes significant and the heat flux increases with increasing excess temperature.

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 32 mg. This value represents the average of 10 different measurements using the 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 plates are heated to the desired temperatures by adjusting the electrical energy input to the heating pads. Once a 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 has completely evaporated) was measured using a stopwatch. Each measurement was repeated five 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 into 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. 7. 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 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 (Fig. 1) shows. The measured results of the total evaporation time in these two regimes agree favourably with the results reported by Cumo *et al.* [5].

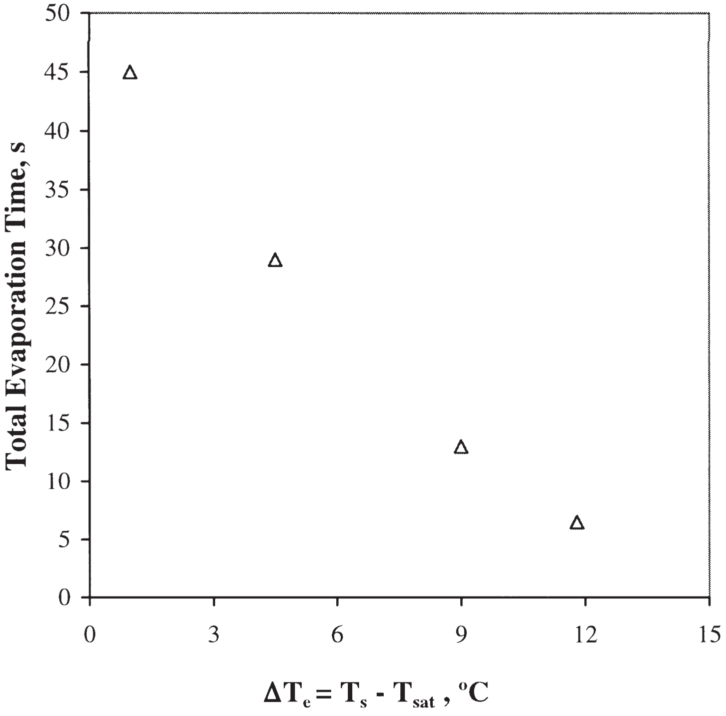

Fig. 7 *Effect of excess temperature on the total evaporation time in the natural convection and nucleate boiling regimes.*

Fig. 8 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 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 shows. In the film boiling regime, the q_s increases with increasing ΔT_e as a result of heat exchange between the heated plate and the liquid droplet through the vapour film due to radiation, which becomes significant at high temperatures ($\Delta T_e \geq 150\,°C$). These measured results of the total evaporation time in the film boiling regime agree favourably with the results reported by Cumo *et al.* [5] in this regime. As can seen from Figs. 7 and 8, the evaporation times in the case of film boiling regime (Fig. 8) are considerably longer than those in the natural convection and nucleate boiling regimes (Fig. 7). This is because in the case of film boiling a vapour layer is formed between the film and the crystallized ball. This layer acts as an insulator (the thermal conductivity of the vapour is much less than that of the liquid), hence reducing the heat flux from the plate to the liquid ball.

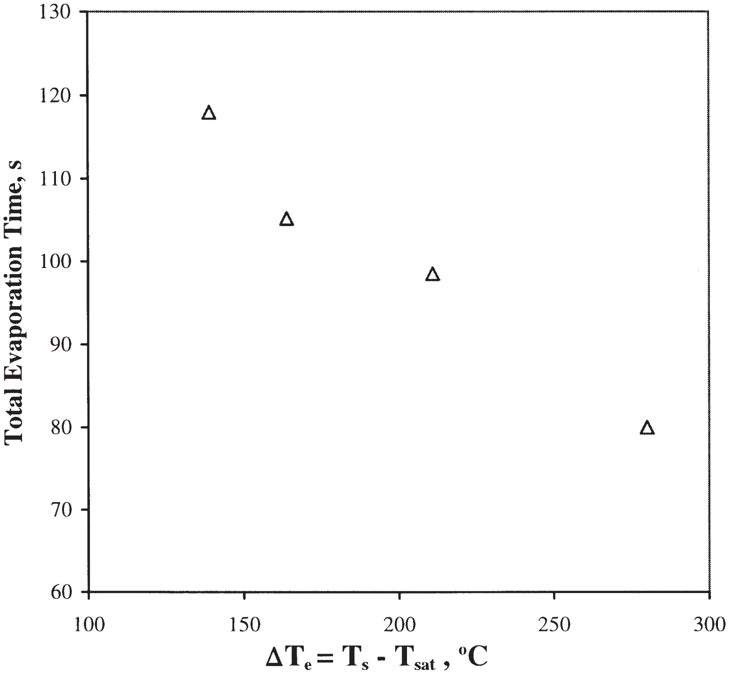

Fig. 8 *Effect of excess temperature on the total evaporation time in the film boiling regime.*

Conclusion

Two boiling experiments were designed to be integrated in the undergraduate heat transfer laboratory. The experimental set-up required to carry out these experiments is relatively simple and the equipment is relatively inexpensive and available in almost all undergraduate heat transfer laboratories.

Acknowledgements

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