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Experiments on Time Dependent Film Boiling on a Sphere

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Abstract

A number of the experiments on the phenomenon in which the thermal energy was transferred from a hot sphere to the surrounding water through the film boiling process had been conducted. As the sphere only carried the thermal energy associated with its initially high temperature but did not contain any other thermal source, the film boiling was only driven by the decreasing temperature of the sphere and, thus, was time dependent. The results from the experiments showed that the temperature of the sphere was slowly decreased in the beginning. This corresponded to the period in which the sphere was penetrating the water surface. Later, when the sphere was fully submerged and the transition film boiling was observed over the whole surface, the temperature of the sphere was decreased relatively much faster. In the last stage, the temperature of the sphere was again slowly decreased. This was considered caused by the relatively low temperature of the sphere, which reduced and later ceased the film boiling process. In addition, the estimation of the departure rate of the steam bubbles from the film layer was also correlated for the experiments.

1. Introduction

At the Department of Nuclear Technology, Faculty of Engineering, Chulalongkorn University, a small facility was set up to conduct the experiment on the time dependent behavior of the film boiling process when the hot object was dropped into a pool of still water. A number of experiments had been conducted in order to study the process in which the molten fuel was quenched. By observing how the temperature of the hot object changed over time, it was expected that a pattern that described the process could be obtained and analysed. Later, with the addition of the more elaborate instruments such as the high speed camera, the information regarding the formation over time of the vapor film on the surface of the object could be obtained and analysed.

2. Setup for the Experiments

As a simplification, a sphere was used to simulate a lump of the molten fuel. For the experiments, the sphere was a stainless steel bearing ball with the diameter of 5.0 cm. A 0.5 cm. diameter hole was drilled on its side to the center along its radial direction in order to accommodate the thermocouple and the metal pulling cable, both were put together in the long insulating tube. In order to ensure that the thermocouple had full contact with the body of the sphere, the thermocouple was inserted into the hole before it was filled with the molten lead. After that, the cable was then put into the hole. Finally, the hole was tightly closed with an aluminum tube plug. This arrangement was as shown in figure 1.

For the heating furnace, the sphere releasing system and the data acquisitor, they were arranged as shown in figure 2 and 3.

The experiments had been conducted with the temperature of the sphere in the range of 125 C to 520 C and with the water level in the water tank of 100 cm. The distance between the suspended sphere and the water surface was also 100 cm. The temperature of the water was at the room temperature (25 C). While this was not controlled and could be varied by several Celsius, the variation of this temperature as compared with the temperature of the sphere should not significantly affect the obtained results.

3. Experimental Results

A number of experiments had been conducted for the initial temperatures of 125 C, 157 C, 179 C, 306 C, 310 C and 520 C. Many of these experiments were conducted mainly to calibrate the instruments, especially the thermocouple and the data acquisitor, while some were also conducted to confirm the ability to repeat the experiments. Consequentially, they did not provide enough information to be analysed. Only the cases with the initial temperature of the sphere of 306 C and 520 C were conducted specifically to obtain the data for the analysis. The variations of the temperature of the sphere over time obtained from these two cases were as shown in figure 4. In both cases, the time at which the sphere made contact with the water surface was set as time zero.

It was observed from figure 4, for the case with the initial temperature of 520 C, that the variation of the temperature of the sphere over time could be divided into

3 stages. The first stage (**I**) was begun when the sphere started penetrating the water surface. At this period, the temperature of the sphere was still very high that the film boiling over the surface of the sphere was rather stable. Due to its low conductivity and low thermal capacity, the presence of the film somewhat impeded the heat transfer process. The result was that while the temperature of the sphere was decreased with time, it was at the relatively low rate. The second stage (**II**) of the sphere's temperature variation was when the sphere fully submerged into the water. At this point, the film boiling had become unstable and was mainly in the transition period. The collapsing of the film and the departure of the steam bubbles that occurred at this stage contributed to accelerate the heat transfer process. Consequentially, the temperature of the sphere was observed to decrease at the higher rate. The temperature of the sphere soon dropped to the point that the boiling had become local, i.e. subcooled nucleate boiling. This entered the last stage (**III**) of the variation of the temperature of the sphere. The heat transfer at this stage was relatively low and the temperature drop at the lower rate. Later, the temperature would decrease to the point that the boiling would cease and only the convection by the liquid water would contribute to the heat transfer process.

It should be noted that the result obtained from the experiment with the intial temperature of the sphere of 306 C, while it had a similar profile, did not clearly show the transition between stages as in the case with the initial temperature of 520 C. The reason for this lack of transition as observed might be due to the fact that the initial temperature of 306 C was relatively low. Therefore, it took longer to finish the first stage and with the lower heat transfer rate. Its relatively low temperature also resulted in a very brief period of the second stage. Consequentially, it was the third stage that had been mostly observed.

4. Estimation of Film Separation Rate

It was postulated that the heat given up by the sphere was primarily taken away by the generated steam that very soon departed from the surface of the sphere as the bubbles. Since they could later be collapsed and deposited their heat contents in the liquid water far away from the sphere, the separation of these bubbles was considered one of the effective methods for heating the bulk liquid. The analysis of the results obtained from the above two experiments were performed to estimate the rate at which the bubbles departed, i.e., the film separation rate.

The film separation rate F was calculated as

$$F = \frac{\rho c V}{h_{fg'}\Delta T}\frac{dT}{dt}.$$

For the above equation, $h^*_{fg}\Delta T$ was the amount of heat per unit mass that was carried away by the steam and was defined as

$$h_{fg'}\Delta T = h_{fg} + c_p(T_{\text{sat}} - T_0).$$

The definition of each constant were as in the following list:

ρ	density of the sphere,
h_{fg}	latent heat of the water at room pressure,
c	heat capacity of the sphere,
c_p	water heat capacity at constant pressure,
V	total volume of the sphere,
T_{sat}	saturating temperature at room pressure,
T_0	stratified temperature of the water.

The result from the analysis were as shown in figure 5. This results were in agreement with the explanation for dividing the process into three stage. For the case of the initial temperature of 520 C, the transition from the first stage to the second stage was at around 2 second while the transition between the second and the third stage was at around 6 second. For the case of 306 C, there were around 3 and 5 second.

5. Conclusion

The experiments showed that for the quenching process a hot spherical object by the liquid water, the process can be divided roughly into three stages. The first stage began from the time at which the sphere made contact with the water surface and passed into the second stage when the temperature started decreasing rapidly, at which point the sphere had already fully submerged. The film boiling in this stage was likely to be stable for the sphere with the very high initial temperature. The film boiling in the second stage was less stable, which allowed the liquid water to have direct contact with the hot surface. The result was the much higher decreasing rate of the temperature. The third stage was at about the end of film boiling. The temperature decreasing rate was again lower. Very soon the boiling would stop and only the convection by the liquid water would be responsible for the heat transfer process.

The analysis of the film separation rate showed that the film separation rate was low in the first and the third stage while it was much higher in the second. This confirmed the above assessment.

The initial temperature was likely to affect the length of the fisrt and the second stage and the maximum heat transfer rate, which in trun affected the temperature decreasing rate. The lower temperature resulted in the lower maximum heat transfer rate but with the extension in duration of the first stage. The second stage was, however, shorten such that the transiton could be difficult to be observed.

6. Acknowledgement

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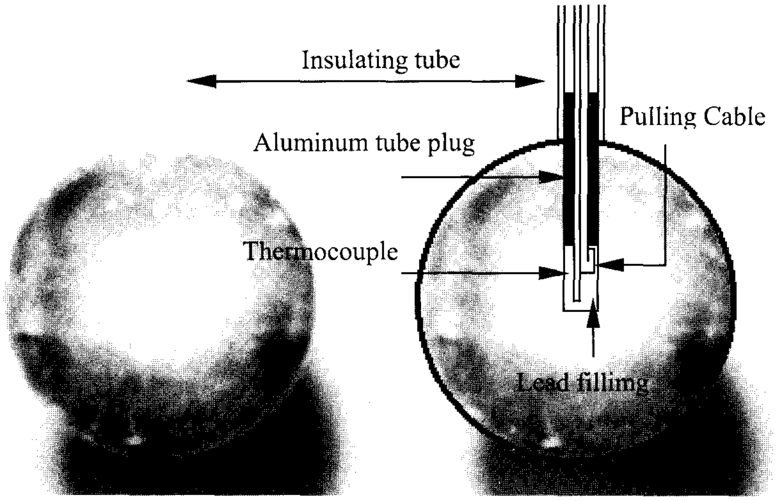

Figure 1. Arrangement of the sphere

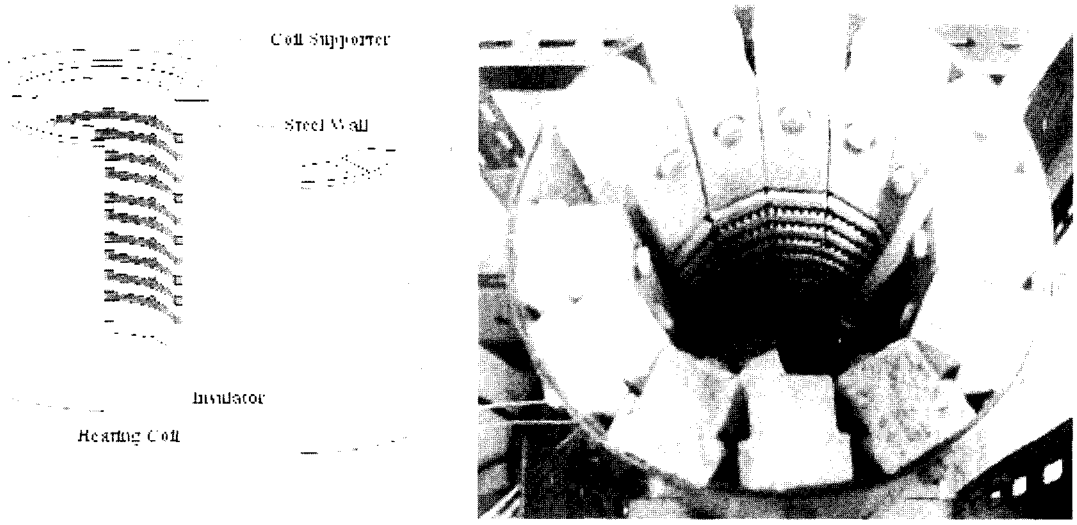

Figure 2. Heating furnace

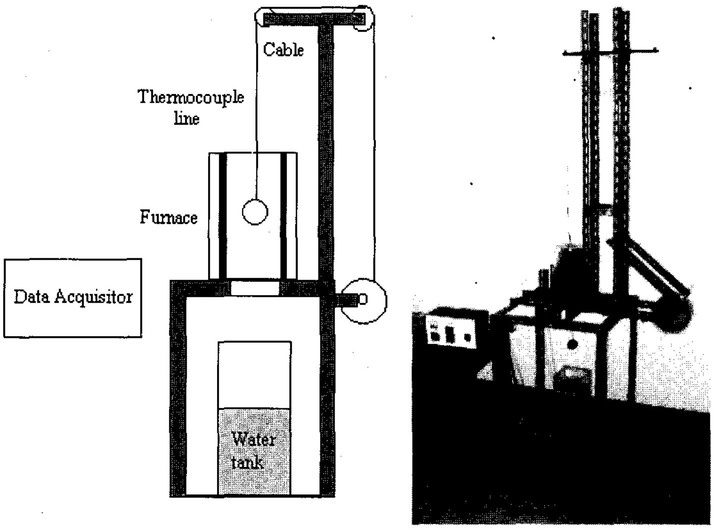

Figure 3. Complete installation

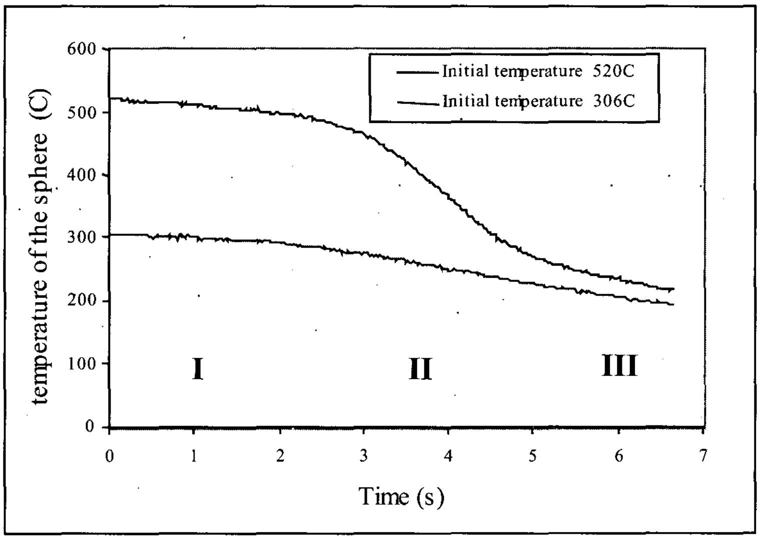

Figure 4. Temperature variations over time from the experiments

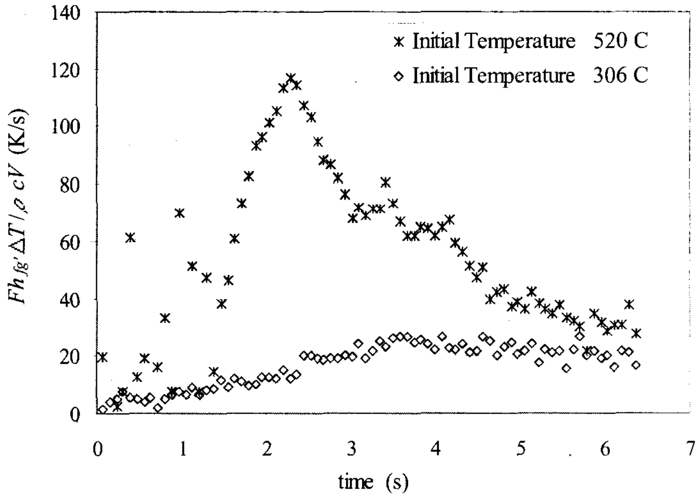

Figure 5. Film seperation rate