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BOILING OF SUSPENSION OF SOLID PARTICLES IN WATER

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INTRODUCTION

THE ULTIMATE goal of researchers in the field of heat transmission is to obtain the highest heat flux by applying the smallest temperature difference. In the case of boiling, efficiency of heat transfer can be enhanced by various means including the use of additives to modify the fluid and flow properties [1–5]. The boiling of water containing suspended solid particles was studied experimentally by various authors [6–9], but the solid contents used were usually rather high. The experimental results for the boiling of suspensions of solid contents less than 1% showed that the addition of solid particles caused the heat transfer coefficient to decrease and shifted the nucleate boiling curve to a higher value of ΔT at a given heat flux [9]. The rheological properties of a suspension of solid particles may be quite different from that of the pure host liquid. In a boiling process, the thermal boundary layer is disturbed by the motion of the suspended particles. Hence, some difference in the boiling behavior and an improvement, instead of a decrease, in the heat transfer coefficient caused by the addition of a small amount of solid particles should be expected. In order to clarify this controversy, careful experimental studies of the boiling of dilute suspensions of alumina particles in water were carried out in this work. Al_2O_3 powders of size 0.05, 0.3 and 1.0 μm supplied by Buehler Ltd. were used for the preparation of the suspensions.

THE APPARATUS

Figure 1 shows the pool boiling apparatus used in this work. An electric heating element is made of a 3.2 mm O.D. stainless steel tube packed with silicon carbide powder. The junction of a thermocouple is placed at the central position in the powder. Because the heating element is sufficiently thin and long, heat conduction in the axial direction can be neglected. Since there is no temperature gradient in the radial direction in the silicon carbide powder, the thermocouple actually reads the temperature of the inner tube surface. The heat flux released from the heating element to the surrounding liquid is controlled by the applied voltage and the outer tube surface temperature can be computed from the inner tube surface temperature and the heat flux values. Another heater, 5, is installed for the purposes of bringing up the temperature of the liquid pool at the beginning of the experiment and maintaining it at the boiling point of the test fluid during the period of operation. The pool temperature is indicated by a calibrated thermometer, 7. A reflux condenser, 6, is provided for condensing the water vapor generated in the pool. The sedimentation of the suspended particles is prevented by constant agitation using a magnetic stirrer, 3, and the centrifugal effect caused by the stirring is obstructed by baffles, 2. In order to eliminate the effect of entrained air in particles, after each addition of the Al_2O_3 powder, the test liquid was first heated up to the boiling point and allowed to boil at the maximum possible heat flux until the surface temperature of the heating element became stable.

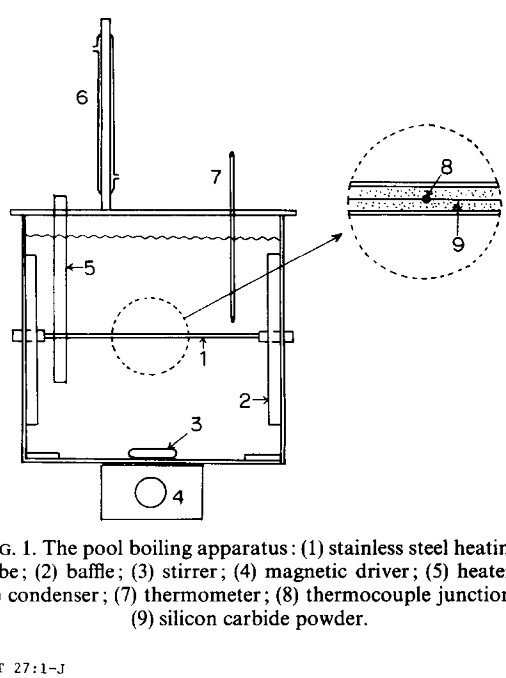

FIG. 1. The pool boiling apparatus: (1) stainless steel heating tube; (2) baffle; (3) stirrer; (4) magnetic driver; (5) heater; (6) condenser; (7) thermometer; (8) thermocouple junction; (9) silicon carbide powder.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Boiling experiments were carried out under identical stirring conditions in the apparatus described above and the results were presented mainly as plots of heat flux, q, vs ΔT, the difference between the temperature of the outer surface of the heating element and the boiling point of water. The reproducibility of the experimental data is assured by repeating the experiment under the same condition after a number of runs under different conditions. Frequently, after several experiments using the dilute suspensions, a run using pure water is made in order to check if there is any deviation in the q–ΔT relationship caused by the changes, if any, of the

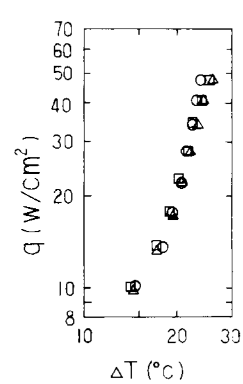

FIG. 2. Date of pure water runs made between series of runs with solid particles.

surface of the heating element. The agreement among data of these pure water runs is good, as shown in Fig. 2, and we can therefore compare the experimental results made at different times with confidence. The experimental data reported in the following are taken from the power descending legs of the boiling curve.

Figure 3 shows that suspended solid particles, within the concentration range used in this work, have no effect on the rate of convective heat transfer between the heating element and the surrounding liquid. The addition of small amounts of solid particles makes the heat flux considerably higher as soon as nucleate boiling begins.

Figure 4 shows that for solid particles of the same size the enhancement of nucleate boiling heat flux is stronger when the solid content in the suspension is higher. Figure 5 shows that for the same solid content (wt %), the smaller the particle size the more effective this enhancement phenomenon. These effects of particle size and solid content are also demonstrated in Fig. 6 as the boiling ΔT of the suspensions divided by that of pure water necessary for transmitting the same heat flux.

It is interesting to note in Fig. 7 the hysteresis of the boiling curve of water containing suspended Al_2O_3 particles. A similar phenomenon was observed previously [9]. This phenomenon happens in all the boiling experiments of this work with various particle sizes and solid content. The q value for the same ΔT is always higher on the descending boiling curves than that on the ascending ones. This phenomenon is not observed in the boiling of pure water.

Because in the early stage of nucleate boiling, the vapor bubbles are relatively far apart from each other, fluctuation of the heating element temperature is caused by the birth, growth and detachment of these bubbles. This fluctuation is stabilized by the addition of suspended solid particles in the boiling water. This phenomenon is observed in most of the experimental runs. The traces of the recorded temperature of the heating element during the boiling processes, as shown in Fig. 8, show that this stabilization effect is more significant in the range of medium heat flux which corresponds to the early stage of nucleate boiling.

CONCLUSIONS

The addition of a small amount of suspended solid particles in water increases the boiling heat flux considerably. This

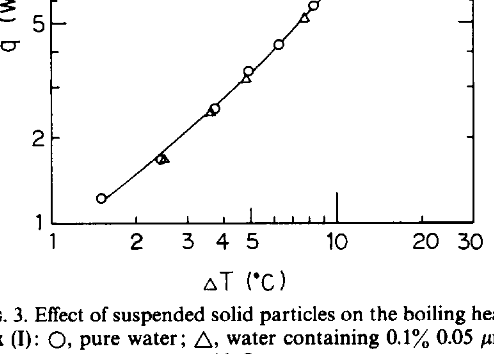

FIG. 3. Effect of suspended solid particles on the boiling heat flux (I): ○, pure water; △, water containing 0.1% 0.05 μm Al_2O_3.

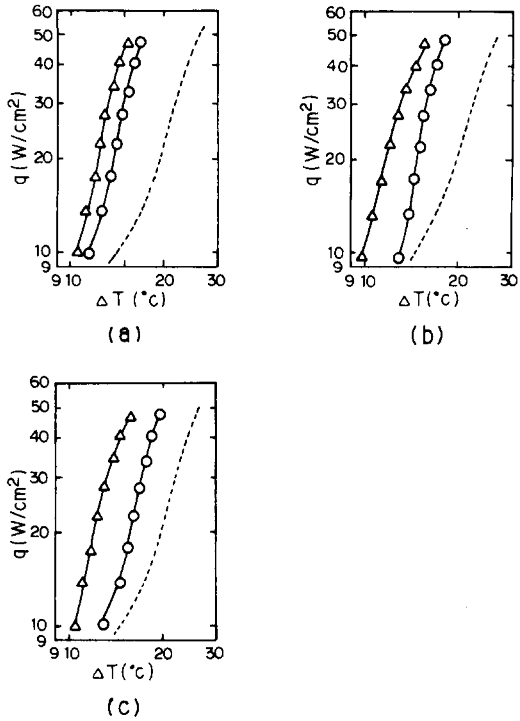

FIG. 4. Effect of suspended solid particles on the boiling heat flux (II). Solid content: ○, 0.1%; △, 0.5%. Particle size: (a) 0.05 μm, (b) 0.3 μm, (c) 1.0 μm. Reference runs with pure water, --------.

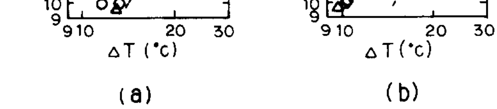

FIG. 5. Effect of suspended solid particles on the boiling heat flux (III). Solid content: (a) 0.1%; (b) 0.5%. Particle size: ○, 0.05 μm; △, 0.3 μm; ⬡, 1 μm. Reference runs with pure water, --------.

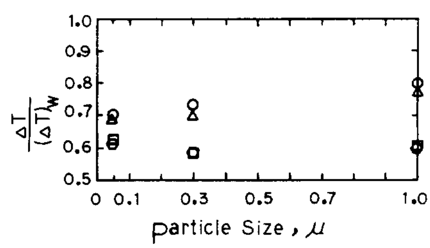

FIG. 6. The reduction of ΔT by the addition of suspended solid particles, solid content (%), heat flux (W cm^{-2}): ○, 0.1%, 20 W cm^{-2}; △, 0.1%, 30 W cm^{-2}; □, 0.5%, 20 W cm^{-2}; ⬡, 0.5%, 30 W cm^{-2}.

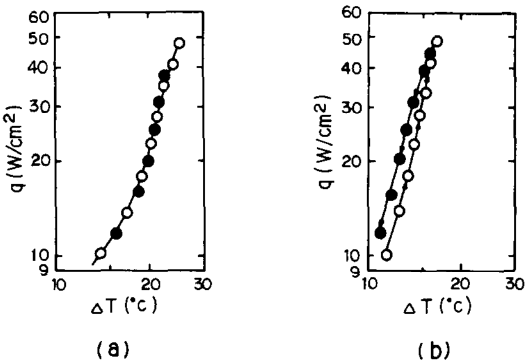

FIG. 7. Hysteresis of the boiling curve: (a) pure water runs; (b) water containing 0.1% of 0.05 μm Al_2O_3. ○, ascending; ●, descending.

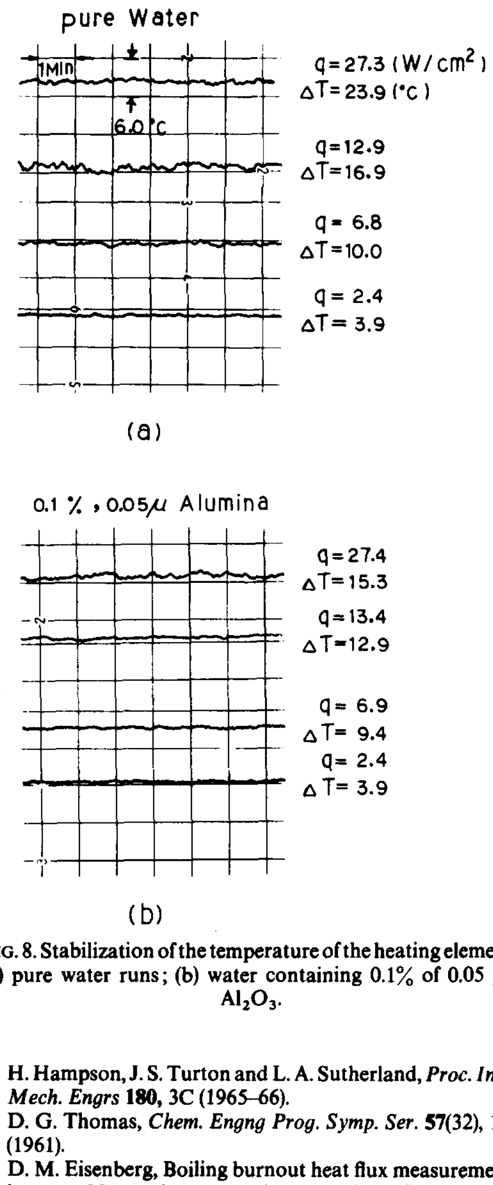

FIG. 8. Stabilization of the temperature of the heating element: (a) pure water runs; (b) water containing 0.1% of 0.05 μm Al_2O_3.

implies higher power density in the boiling water type nuclear reactors and better efficiency in the industrial boilers and steam generators. Aluminum is one of the metals often used in connection with the nuclear reactor because the half-life of its isotope produced by neutron radiation is very short. Have Al_2O_3 particles the same advantage if added to the boiling water? How serious is the erosion effect of the suspended particles? Does it damage the heating surface or merely prevent the scale to form? These experimental problems need to be carried out. In this work, in addition to the increase of boiling heat flux, hysteresis of the boiling curve and stabilization of the heating element temperature caused by the suspended particles were also observed. The theoretical explanation of these phenomena is academically interesting and practically important. Further studies are desirable.

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