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ENHANCEMENT OF FLOW BOILING HEAT TRANSFER WITH POLYMER ADDITIVES

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NOMENCLATURE

C,	concentration of polymer in the aqueous solution [p.p.m.];
D_o,	outside diameter of the heating element;
L,	length of the heating element [cm];
q,	heat flux at the surface of the heating element [W/cm^2];
R,	particle size of the polishing powder [grit];
Ω,	resistance of the electric heating element [Ohm];
r_o,	outer radius of the heating element [cm];
T_b,	boiling point of the test fluid [deg];
T_w,	temperature of the heating surface [deg];
T_1,	inlet temperature of the boiling chamber [deg];
T_2,	outlet temperature of the boiling chamber [deg];
ΔT_s,	$T_w - T_b$;
ΔT_{sub},	$T_b - (T_1 + T_2)/2$;
V,	voltage across the heating element [V];
v,	velocity of the boiling liquid [cm/s];
W,	power of the heating element [W].

INTRODUCTION

IT WAS found by Kotchaphakdee and Williams [1] that the pool boiling heat transfer rate of water increased significantly when it was dosed with small amounts of soluble polymers. The polymers that they have studied are: hydroxyethyl cellulose of molecular weight about 7×10^4 and two kinds of polyacrylamides of molecular weights about 10^6 and 2×10^6. The polymer concentration that they used was no more than 500 p.p.m. This is an important discovery because if proven to be applicable under industrial flow boiling conditions it will lead to a considerable increase in the power level of all boilers and boiling water nuclear power reactors without any increase in size or operating temperature. Hence, it is important to confirm the effect of these polymer additives under flow boiling conditions. In this work, a boiling loop is constructed for this purpose.

THE APPARATUS

Figure 1 shows the detail of the boiling chamber. The heating element H is housed in a glass tube B. This glass tube is connected to and lined up with the stainless steel tubes at both ends by a set of mechanical supporting and sealing devices as shown in the figure. The system fluid flows upward through the annular space between H and B. The boiling substances on the surface of the heating element H can be illuminated, observed and photographed conveniently from outside.

Two kinds of tubular heating elements are used in this work: electric and steam. The electric heating elements are made of thin wall stainless steel tubing of 1/16″, 1/8″ and 3/16″ o.d. and various lengths. They are soldered at both ends to 1/4″ o.d. heavy wall copper tubes as shown in Fig. 1. These copper tubes serve as leads for the electric current passing through the heating element. They are insulated from the other parts of the apparatus by Teflon tape and connected to an adjustable d.c. power supply of 200 A and 30 V capacity. A calibrated Teflon coated 0.009″ dia. Cole Parmer T type thermocouple is inserted to the inside of the tubular heating element through one of the copper tubes. It is tightened by tying to it a thin thread and pulling through the other copper tube at the opposite side of the heating element. The joint of the thermocouple can therefore be adjusted exactly to any desired position in the heating element. The temperature of the outer surface can be calculated from the power generation per unit volume of the electric heating element [2]. The

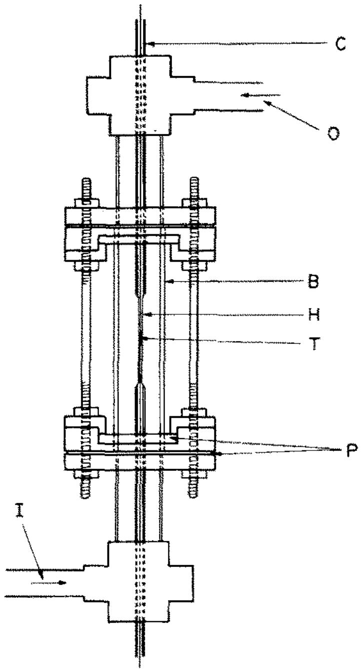

FIG. 1. The boiling chamber. I: water inlet; O: water and vapour outlet; C: 1/4″ copper tube; B: glass tube; H: stainless steel tubular heating element; T: thermocouple joint; P: packing material.

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voltage across the heating element, V, is recorded constantly. The total power generation, $W = V^2/R$, and the heat flux at the surface of the heating element, $q = W/(2\pi r_0 L)$, can therefore be computed.

The 1/2" o.d. tubular heating elements are made of stainless steel or copper tubes and the heat is supplied by steam of 0–100 psig from a generator of 6 kW capacity. Steam enters the top end of this heating element and the condensate is constantly blown out along with some uncondensed steam through a partially open valve at its lower end. In order to avoid unnecessary condensation, the inner wall surface of the tubular heating element is lined with 1 mm of Teflon except for the test section where boiling on the outer surface is desired. The length of the test section is 5 cm. The temperatures of the outer and inner surfaces of the test section are measured by the "plated thermocouple" [3].

RESULTS AND DISCUSSION

The water soluble polymers used in this work were polyox, supplied by the Union Carbide Corp., and Natrosol 250 HR and 250 GR supplied by the Hercules Powder Co. Polyox is a polyethylene oxide of molecular weight 2–4 × 10^6. Natrosol 250 HR and 250 GR are hydroxyethyl cellulose of molecular weight 2 × 10^5 and 7 × 10^4, respectively. The system fluid was allowed to boil for at least 2 hours to age the heating surface before any experimental data were recorded. The experimental results are summarized as follows:

1. *The increase of boiling heat transfer coefficient*

The addition of small amounts of soluble polymers makes the heat flux significantly higher for the same superheat at the heating surface, ΔT_s. For the same boiling heat flux, the necessary ΔT_s becomes lower. This favourable effect, shown in Figs. 2 and 3, is more pronounced when the polymer concentration is higher and when the molecular weight of the same type of polymer is higher.

2. *The difference in boiling behaviour*

The addition of a small amount of soluble polymer makes the boiling behaviour quite different from that of pure water. This is shown in the photographs of Fig. 4. The necessary incipient boiling superheat becomes smaller and the vapour bubbles are formed more easily. In comparison with that of pure water, the vapour bubbles are smaller in size but larger in number and tend to stay on the heating surface in a relatively orderly manner without coalescence.

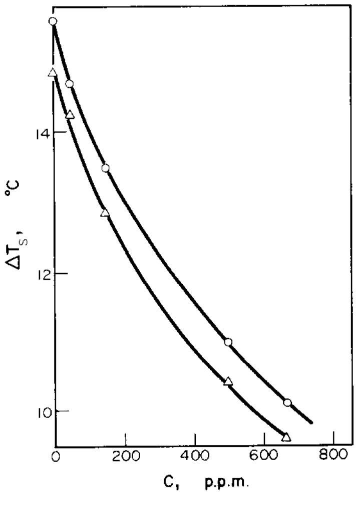

FIG. 2. Effect of the concentration of the Natrosol 250 HR aqueous solution on the boiling superheat ○: q = 100 W/cm²; Δ: q = 140 W/cm².

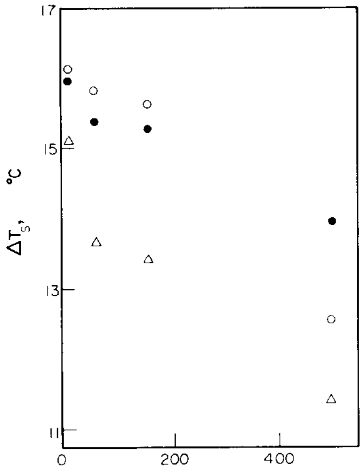

FIG. 3. The boiling superheat of the aqueous solutions of various polymers. (q = 22 W/cm², v = 31.8 cm/s. Δ: polyox; ○: Natrosol 250 HR; ●: Natrosol 250 BR.

At high subcoolong and high liquid velocity, the detachment of the vapour bubbles from the heating surface becomes difficult. This is probably because that heat is removed from the top of the vapour bubbles promptly by forced convection and further growth and detachment of the bubbles are therefore prevented. The shaded areas in Fig. 5 are the regions where the entire heating surface are covered by vapour bubbles. This phenomenon causes the boiling heat transfer rate of the dilute polymer solution to become even lower than that of pure water when the heat flux is low and the liquid flow rate is high as shown in Fig. 6. This undesirable effect is not observed when the liquid flow rate is made slower as shown in Fig. 7.

3. *The effect on the critical heat flux*

It is observed that the boiling curves of the dilute Natrosol 250 HR solutions have broad peaks over a relatively large range of ΔT_s values. This is quite different from the boiling curve of pure water. A similar phenomenon was also observed for the case of pool boiling of a dilute solution of polymers in cyclohexane [4].

4. *The effect of liquid velocity*

It is shown in Fig. 8 that there always exists an optimum liquid velocity at which the necessary superheat at the heating surface is the lowest for the same boiling heat flux. This phenomenon, observed in all experiments of this work, is probably because that higher liquid velocity has both the favorable effect of increasing the convective heat transfer rate and the negative effect of preventing the detachment of the vapour bubbles from the heating surface.

5. *The heating surface*

Figure 9 shows the well known fact that the increase of roughness of the heating surface causes the necessary superheat, ΔT_s, for the same boiling heat flux, to decrease. This figure also shows the favorable effect of the addition of soluble polymer and the phenomenon that the ΔT_s–liquid velocity relationship always has a minimum. Figure 8 shows that the effect of a soluble polymer is more pronounced on the nickel plated heating surface than on the stainless steel heating surface. The nickel plated heating surface has to be aged enough to make the experimental data reproducible. At

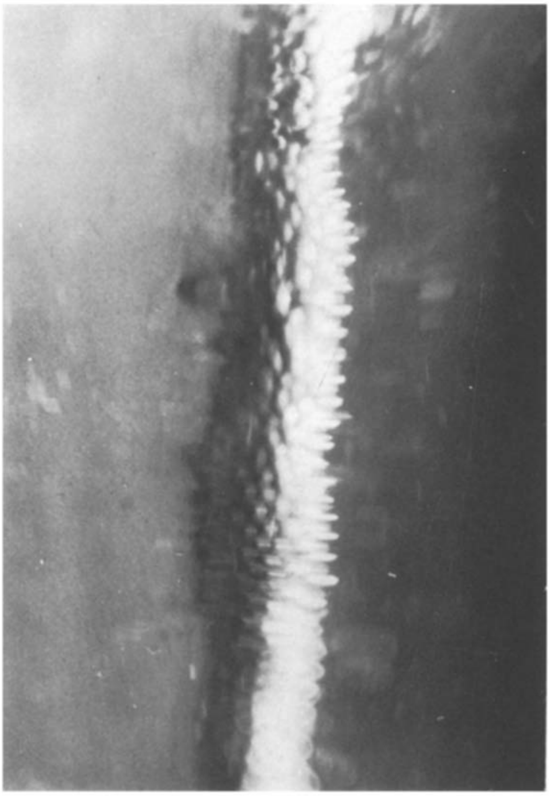

FIG. 4. Boiling of 500 p.p.m. Natrosol 250 aqueous solution on the nickel plated 1/16" o.d. electric heating element ($v = 25.8$ cm/s, $q = 63.1$–66.1 W/cm^2, supercooling: 15°C).

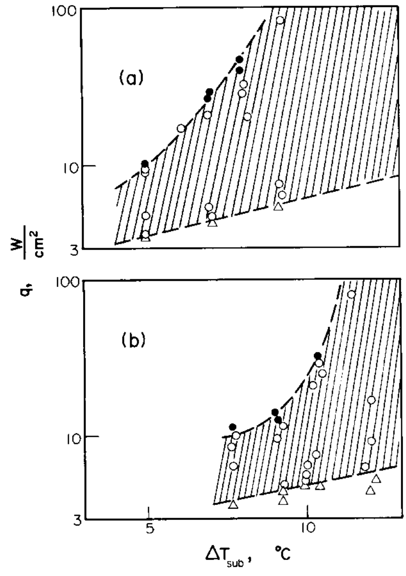

FIG. 5. The detachment of vapour bubbles from heating surface in the boiling of the 500 p.p.m. Natrosol 250 aqueous solution. (a) $v = 25.8$ cm/s; (b) $v = 19.4$ cm/s: Δ: no vapour bubbles are generated; ○: the entire heating surface is covered by the vapour bubbles; ●: vapour bubbles appear only at the active sites on the heating surface.

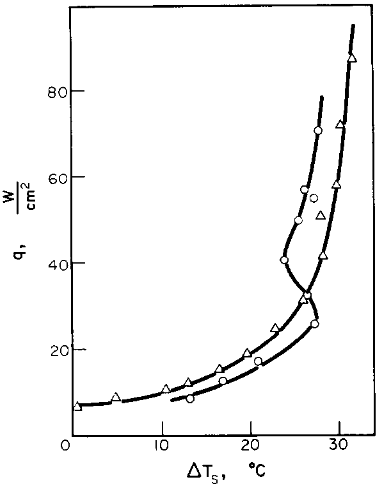

FIG. 6. Boiling on the nickel plated 1/8" o.d. electric heating element. $v = 25.8$ cm/s; Δ: distilled water; ○: 500 p.p.m. Natrosol HR aqueous solution.

the beginning of each experimental day, we let the boiling go on for at least 2 hours before readings were made. Only data of the same day were compared with each other to avoid misleading conclusions. Such precaution is unnecessary when stainless steel or chrome [1] heating surfaces are used. It was also observed that the larger the diameter of the heating element the smaller the necessary ΔT_s for the same boiling heat flux. This phenomenon was also observed previously [5].

CONCLUSIONS

The enhancement of boiling heat transfer of water by small amounts of polymer additives, discovered previously for the case of pool boiling [1], is confirmed in this work for flow boiling, which is more widely used in industrial heat transfer processes. A few hundred p.p.m. of these additives causes the boiling heat transfer rate of water to increase considerably. The peak of the boiling curve also becomes much broader.

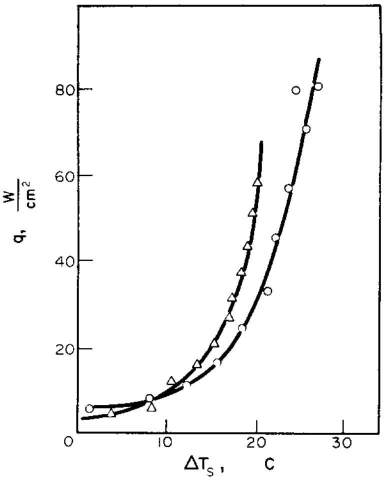

FIG. 7. Boiling on the nickel plated 1/8" o.d. electric heating element. $v = 10.7$ cm/s; ○: distilled water; Δ: 500 p.p.m. Natrosol 250HR aqueous solution.

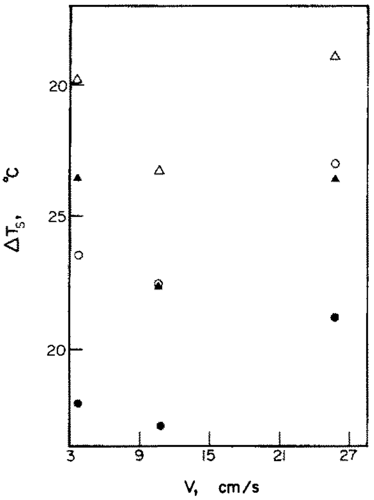

FIG. 8. The effect of liquid velocity (q = 72 W/cm^2). Δ: boiling of distilled water on stainless steel surface; ○: boiling of 500 p.p.m. Natrosol 250 HR aqueous solution on stainless steel surface; ▲: boiling of distilled water on nickel plated surface; ●: boiling of 500 p.p.m. Natrosol 250 HR aqueous solution on nickel plated surface.

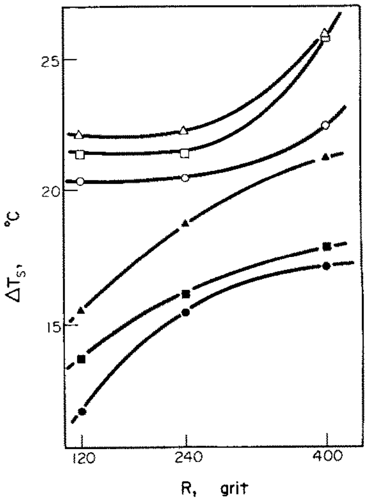

FIG. 9. The effect of surface roughness on the boiling of Natrosol aqueous solution on nickel plated surface (q = 66 W/cm^2). Δ: C = ○ p.p.m., v = 25.8 cm/s; ▲: C = 500 p.p.m., V = 25.8 cm/s; □: C = 0 p.p.m., v = 3.7 cm/s; ■: C = 500 p.p.m., v = 3.7 cm/s; ○: C = 0 p.p.m., v = 10.8 cm/s; ●: C = 500 p.p.m., v = 10.8 cm/s.

The added soluble polymers have the effect of preventing the vapour bubbles on the heating surface from coalescing and from being detached. The boiling behaviour is quite different from that of pure water, and there is always an optimum liquid velocity at which the necessary superheat at the heating surface is lowest for the same boiling heat flux. Further studies of the vapor–liquid–solid interfacial properties are perhaps necessary for a true understanding of the above phenomena.

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