HEAT TRANSFER FROM ELECTRICALLY HEATED NICHROME WIRES TO BOILING WATER AT DIFFERENT PRESSURES

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Boiling curves for nucleate and film boiling have been drawn for nichrome wire of three sizes in distilled and degasified water at saturation temperatures under five different sub-atmospheric vapour pressures. It has been observed that (*i*) for the same Q/A (heat transfer), $\Delta\theta$ (excess of wire temperature over saturation point of water) decreases with pressure in both nucleate and film boiling ranges, (*ii*) Both Q/A max. and $\Delta\theta_c$ show a rapid decrease with pressure but these variations become more gradual at higher pressures, and (*iii*) Q/A max. and $\Delta\theta_c$ increase with wire size at all pressures; increase in $\Delta\theta_c$ however, becomes less conspicuous at higher pressures approaching one atmosphere.

The phenomenon of boiling is as ancient as Man's discovery and use of fire. It is indeed surprising that upto this day many features of this common phenomenon are obscure and, therefore, deserve close and critical investigation. Boiling appears to be a far more complex phenomenon than is usually imagined. The subject has aroused special interest after the advent of nuclear reactor rocket engine, cyclotron target, space flight etc., where very large quantities of heat are required to be transferred quickly from small areas. Latest researches have revealed that there is not one but three different types of boiling nucleate, transition and film and that the rate of heat transfer is widely different in each of these types of boiling. Boiling is a complicated process because it is controlled by a number of variables such as surface tension, viscosity, latent heat of evaporation, thermal conductivity, density, vapour pressure, fluid motion, and the conditions of the surface supplying heat to and in actual contact with the boiling liquid.

APPARATUS

A represents a double walled cylindrical copper vessel with three glass windows—two facing each other and the third in middle of them (Fig. 1). The inner vessel filled with distilled water upto 2/3rd of its height can be closed by an airtight rubber lid. The outer vessel is filled with water so as to immerse the inner vessel completely. The same temperature of water in both the vessels is obtained by means of electrical heaters *C*, *D* and D_2 connected through variacs so that the heat losses from the vessels are made up by the heat supplied by the heaters. The temperatures are read by thermometers E & *H*. *B* is the nichrome wire placed horizontally in the liquid contained in the inner vessel. It is connected to the external electrical circuit through copper leads with pin-vice arrangements at their bent ends. The phenomena associated with boiling at the nichrome wire *B* may be observed through the glass windows. A cupshaped condenser *F* meant to condense vapours of the liquid into the inner vessel, is connected to a vacuum pump and a mercury manometer which indicates the pressure in the inner vessel.

The current to the wire *B* is fed from a 24-volt d.c. battery *P*. Accurate values of power input to and resistance of the wire *B* can be measured by a potentiometer 0 (accuracy $\pm\cdot01$ mv.).

EXPERIMENTAL PROCEDURE

For studying the influence of the diameter of the heated wire on the boiling phenomenon and heat transfer, experiments were conducted with Nichrome wires of three different diameters—42 SWG (·01016 cm.), 38 SWG (·01524 cm.) and 34 SWG (·02337 cm.). The ends of the heating wire (4 cm. long) are clamped by pin-vices of the copper leads in order to keep the wire stretched horizontally and perpendicular to the line of sight between the two opposite glass windows. The inner vessel is filled with distilled water upto 2/3rd of its height so that the water level is about 3·5″ above the horizontal wire. The leads connecting the wire are taken out through the lid. A mercury thermometer (accuracy $\pm 0\cdot 1°C$), inserted through the middle of the lid, is immersed in water so that its bulb is about 1·5″ above the wire. The lid is screwed airtight on to the flange at the mouth of the vessel. The space between the outer vessel and the inner one is also filled with water. The condenser returns the steam or water vapour to the inner vessel. The electric connections to the heating element are shown in Fig. 1.

The air from the inner vessel can be pumped out with the aid of the vacuum pump. Air absorbed by the distilled water in the inner vessel is thus removed by the vacuum pump running continuously until no bubbles appear. This eliminates the disturbing influence of the dissolved gases and one is able to study the boiling phenomenon involving only the phase change from the liquid to the vapour state.

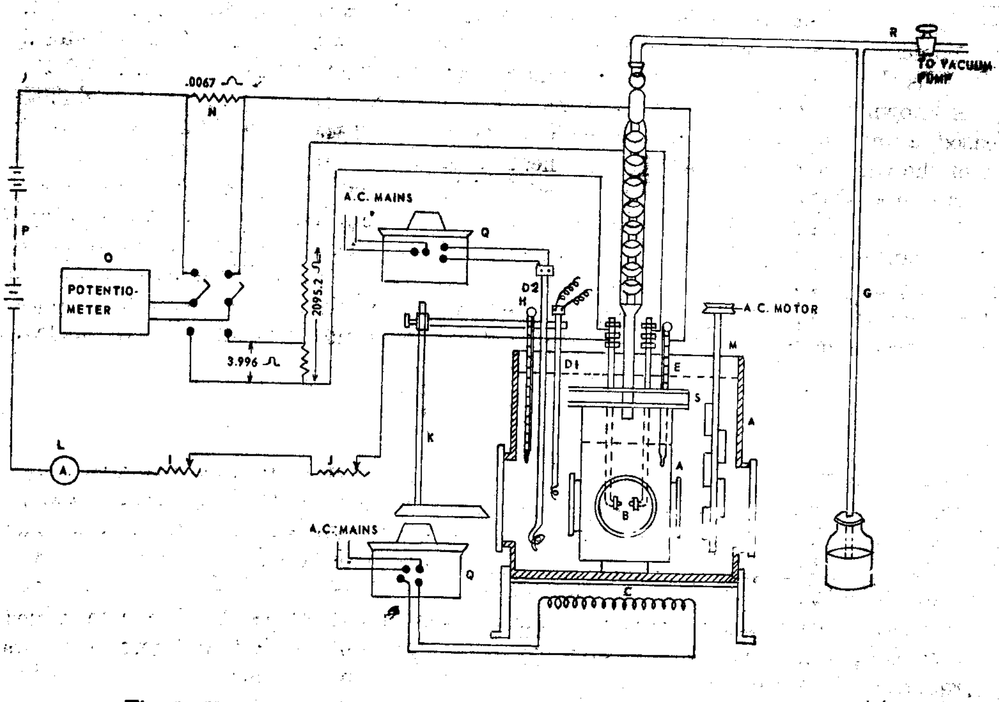

Fig. 1—Experimental set-up for obtaining heat transfer curves.

When the inner vessel containing the experimental liquid is completely evacuated of its air, the pressure acting on the free water surface corresponds[1] to the saturated vapour pressure at the water surface temperature, and one can arrange to induce boiling at any required temperature. A very small electric current is passed through the wire, which does not materially heat the wire. The resistance of the wire is calculated by potential difference across its ends and the current through it by means of potentiometer 0 (Fig. 1). This is its resistance at the water temperature. Now the current is increased to some specified value and the wire gets sensibly heated. Heat is then transferred from the wire to the water in the inner vessel. As soon as a steady state is attained, the heat developed in the wire is used up for transforming the liquid to vapours inside the liquid and at the free surface. Loss by conduction across the boundary of the experimental vessel is practically eliminated by maintaining the temperature of the inner vessel at the boiling point under consideration. The vapours arising from the liquid surface are condensed by the cup-shaped condenser and returned to the inner vessel thus keeping its liquid content constant. Heat transfer is then calculated.

NUCLEATE BOILING AND FILM BOILING

The approach to any particular boiling point is first indicated by the appearance of steam bubbles beginning to form directly on the heated wire. This is the point where the heat transfer passes from that characteristic of simple convective transfer to that of nucleate boiling transfer. The heat diffusion is increased on account of the increased mixing caused by the movement of bubbles originating from the wire and rising towards the free surface. As the current is further increased a stage comes when bubble formation at the wire becomes maximum and the wire is wholly covered by bubbles. The heat transfer at this stage is the maximum in nucleate boiling, and the temperature of the wire at this point is known as the critical temperature. If at this stage the current is even slightly increased, a uniform vapour film is formed at the wire and the current falls as the resistance of the wire increases on account of heat accumulation in it. The wire becomes red hot—its temperature goes up to a high value of 800 to 1000°C and one observes what is known as film boiling. The vapour film on the wire having a much lower thermal conductivity causes a decreased rate of heat transfer. At this stage, current on the wire may be gradually decreased to take several observations at film boiling. Ultimately a point is reached when the vapour film breaks up and nucleate boiling is restored; a further decrease of current results in lowering the temperature of wire below that corresponding to nucleate boiling.

The water in the outer vessel is heated by means of the heaters to a desired temperature, say, 50°C, and when this temperature is attained, the voltage fed to the heaters is lowered by means of the variacs, only to make up heat losses from the apparatus to the surroundings so that the mean temperature of the vessel at 50°C is maintained. A stirrer run by a motor helps to obtain a uniform water temperature in the outer vessel and hence the mean vapour pressure during the experiment. Thus the temperature of water in the inner vessel is also at 50°C, and its saturated vapour pressure (9·23 cm. of *Hg*.) corresponds to this temperature. The whole experiment can now be performed considering that 50°C is the boiling point of water in the inner vessel at a vapour pressure of 9·23 cm. of *Hg*.

BOILING CURVES

The boiling curves showing relationship between (*i*) the excess of wire temperature over the boiling point corresponding to a particular vapour pressure and (*ii*) the rate of heat transfer under each set of steady conditions (as indicated by the corresponding heating amount), have been drawn at various vapour pressures (5·5, 9·2, 15·0, 23·4 and 37·2 cms. of *Hg*.) for three wire diameters (42, 38 and 34 SWG) in the case of distilled and degasified water in nucleate as well as film boiling ranges.

Fig. 2 gives one set of such "boiling curves" showing energy transfer Q/A (K Cals/sq./cm./hr.) against the excess of wire temperature over the boiling point $\triangle\theta$ (in °C) for the different vapour pressures of (5·5, 9·2, 15·0, 23·4 and 37·2 cms. of *Hg*.) in the case of 42 SWG heatings wire. Similar curves are obtained for 38 SWG and 34 SWG. A close study of these curves reveals that (*i*) the boiling curves in these diagrams shift to the left as pressure rises, (*ii*) if we consider a particular value of the heat transfer Q/A, the temperature difference $\triangle\theta$ between the heated wire and the surrounding water, decreases with pressure, and (*iii*) for the same value of $\triangle\theta$, the heat transfer Q/A increases with pressure in the nucleate boiling range.

The maximum values of Q/A (Q/A max.) and the corresponding values of $\triangle\theta$ ($\triangle\theta_c$) have been plotted against vapour pressure in Fig. 3 for the 3 wire sizes. It is observed that initially both Q/A max. and $\triangle\theta_c$ decrease rapidly with vapour pressure. These variations become more gradual at higher pressures.

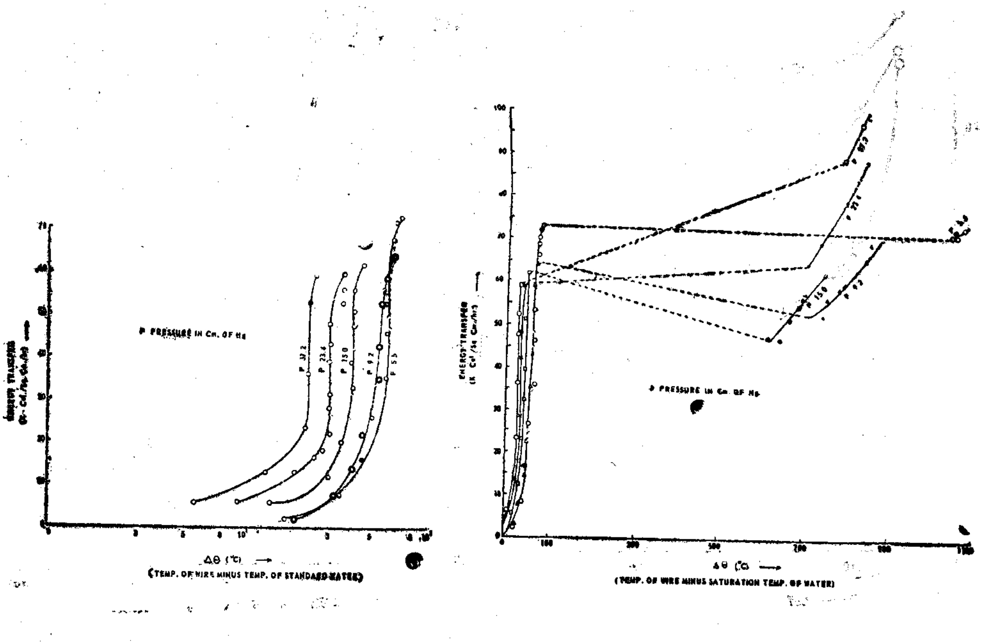

Fig. 2—Heat transfer curves in the case of distilled water for nucleate boiling range on 42 SWG (·01016 cm. dia.) nichrome wire at different vapour pressures (in cm. of Hg).

The values of Q/A (max.) and $\triangle \theta_c$ at different vapour pressures have been replotted against wire-sizes as in Fig. 4. The curves clearly show how at all vapour pressure (*i*) the energy input per unit area of the wire [Q/A (max.)] and (*ii*) $\triangle \theta_c$ increases with wire size.

Q/A (MAX.) IN RELATION TO THE DIAMETER OF HEATING WIRE

The maximum or peak heat transfer for nucleate boiling as well as $\triangle \theta_c$ are greater on a thicker wire than on a thinner one (see Fig. 4). At higher pressure approaching one atmosphere, the increase in $\triangle \theta_c$ with wire size becomes less conspicous. Increase in Q/A (max.) at atmospheric pressure has also been noted by Adams *et al.*[1] in the case of platinum wire of different diameters. Castles[2] observes that there exists a stronger adhesion between solid and liquid in the case of a thicker wire so that bubbles forming on the wire have to overcome this greater adhesive force on a thicker wire. For this purpose these bubbles of a larger size have to develop sufficient buoyancy to overcome the force of adhesion. To enable them to gather more energy, a greater temperature difference $\triangle \theta$ between the wire and the liquid is needed.

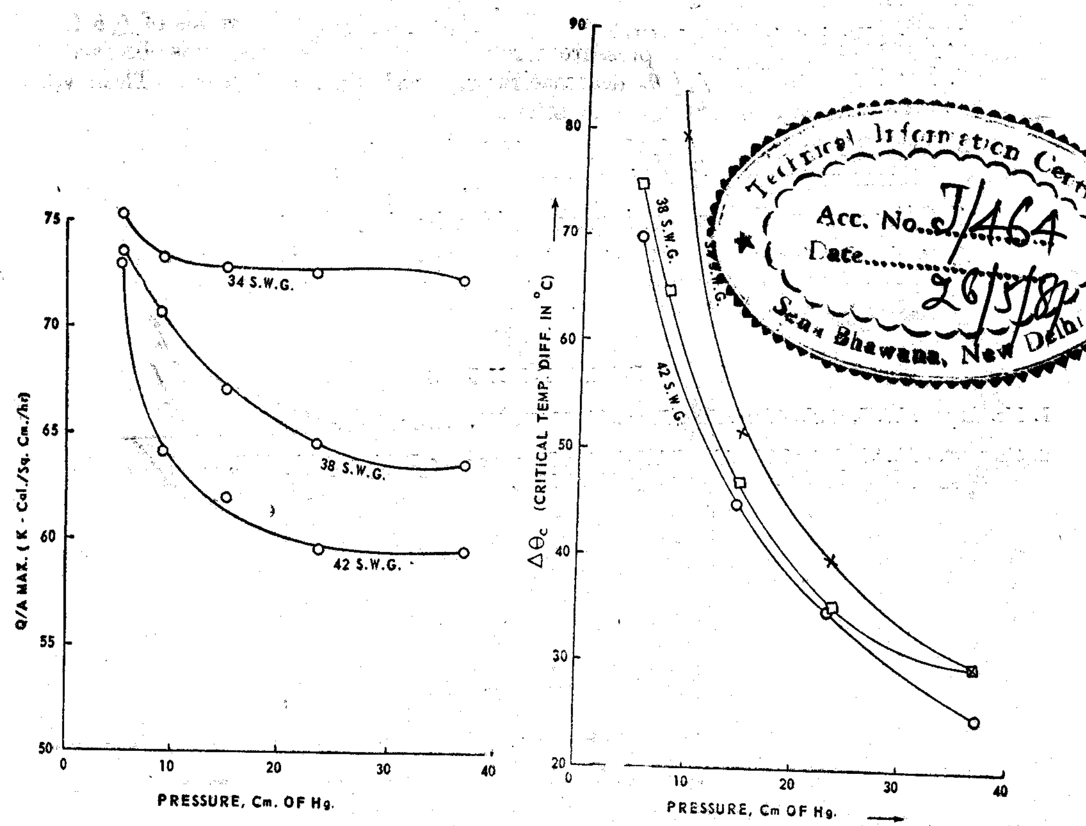

Fig. 3—Variance of the maximum value of Q/A (i.e. Q/A max.) and the corresponding value of $\triangle \theta$ (i.e. $\triangle \theta_c$) with vapour pressure for the three sizes of nichrome wires.

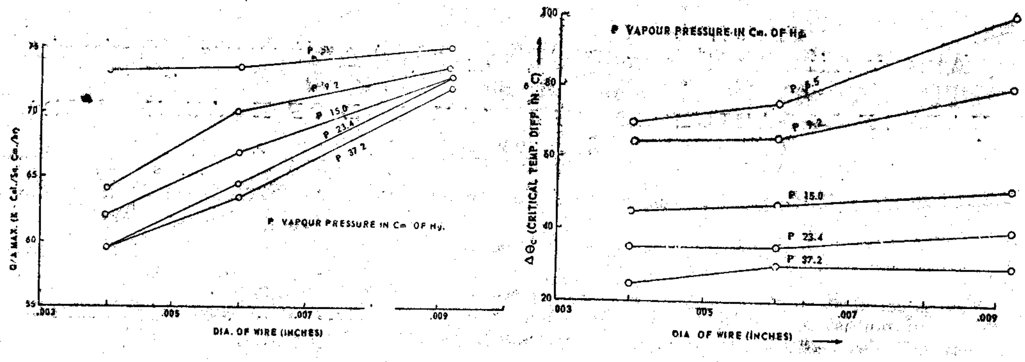

Fig. 4—Plot of the values of Q/A max. and $\Delta\theta_c$ at various vapour pressures against different wire sizes.

RESULTS

The results can be summarized as follows :

1. For all wire sizes the boiling curves shift to the left as the pressure rises.
2. For the same Q/A, $\Delta\theta$ decreases with pressure both in nucleate and film boiling ranges.
3. Both Q/A max. and $\Delta\theta_c$ show a rapid decrease with pressure but these variations become more gradual at higher pressures.
4. Q/A max. at all pressures increases with wire size.
5. $\Delta\theta_c$ also increases with wire size at all pressures, but at higher pressures approaching one atmosphere the increase in $\Delta\theta_c$ with wire size becomes less conspicuous.

REFERENCES

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2. CASTLES, J.T., "Effect of Liquid Solid Adhesion Forces on the Boiling of Liquids", Thesis in Chem. Engg., (Masch Institute of Technology, USA) 1947.