Studies of Boiling Heat Transfer with Electrical Fields: Part I. Effect of Applied A.C. Voltage on Boiling Heat Transfer to Water in Forced Circulation

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Alternating current voltage (60 cycles/sec.) was found to increase boiling heat transfer rates and prevent film boiling for deionized water under forced convection at essentially ambient pressure. Steam was used to supply heat to the interior wall of a 0.292-in. thick annulus, and voltages up to 5,000 v. were impressed across the region of vapor formation. The highest heat transfer rates reached were approximately twice the normal nucleate boiling peak. The application of voltage increased the boiling heat transfer over the entire range tested—mass flow rates up to 5.2 $\times$ 10^5 lb./hr.-sq.ft. and exit qualities up to 4% by weight vapor. Data obtained from tests in which the external wall of the flow annulus was heated indicated an increase in heat flux up to 2,000 v., followed by a decrease in heat flux at voltages above 2,000 v.

In previous work with pool boiling isopropyl alcohol and water, Markels and Durfee (5) showed that heat fluxes on steam-heated tubes could be greatly increased and film boiling prevented by the application of voltage across the region of vapor formation. Similar results on electrically heated wires for several dielectric liquids have been reported by various authors (*1, 2, 7*). The purpose of the present work on voltage effects in a flow system was to determine possible effects of flow rate and exit quality on the applied voltage process of increasing boiling heat transfer coefficients at atmospheric pressure. Other parameters studied with the flow system include water resistivity and test section geometry. All of the data presented in this paper are tabulated in reference 3.

APPARATUS

System Parameters

The flow system was designed to move up to 5 gal./min. of distilled water at its boiling point through a steam heated test section at mass flow rates of 100,000 to 500,000 lb./hr.-sq. ft. The water flowed through an annulus between a ⅜ in. O.D. chrome plated copper tube and the wall of an aluminum cylinder of 0.96 in. I.D., either of which could be heated independently. The effective length of the test section heater was 3 in. for the inside tube and 2.5 in. for the exterior wall. The impressed voltage was 60-cycle a.c. from a 750-v.-amp. transformer capable of 10,000-v. output.

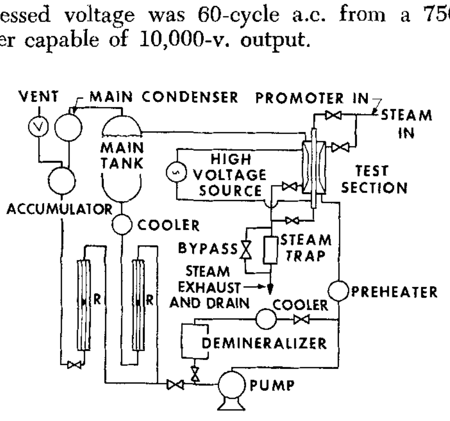

Fig. 1. Simplified flow diagram of the apparatus, showing rotameters (*R*) used for flow measurement.

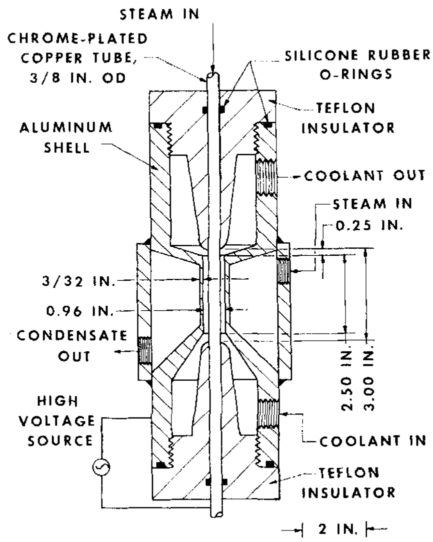

Fig. 2. Interior of test section for heat transfer *flow loop.*

Distilled water in the system was deionized by two mixed bed ion exchangers in series, which were capable of maintaining the resistivity of the water at 10 $\times$ 10^6 ohm-cm. at 20°C. and 8 $\times$ 10^5 ohm-cm. at the atmospheric boiling point. Flow through the deionizers ranged up to 0.15 gal./min. Steam pressures up to 550 lb./sq. in. gauge were available from an electrically powered generator, and the measured steam quality was above 98%.

Steam Operation

The flow system is shown diagrammatically in Figure 1. Distilled water from the main tank was centrifugally pumped through the preheater and then through the test section. Vapor formed in the test section was separated in the main tank, condensed in the condenser, and fed back into the mainstream through a rotameter. The flow rate of condensate through the rotameter served as a measurement of the heat transfer rates. A part of the outlet flow from the pump was diverted through a cooling section and to the demineralizers. The deionized water stream was then fed through a rotameter back into the pump inlet stream.

The steam supply from the generator was used for both the test section and the preheater. Oleic acid promoter was in-

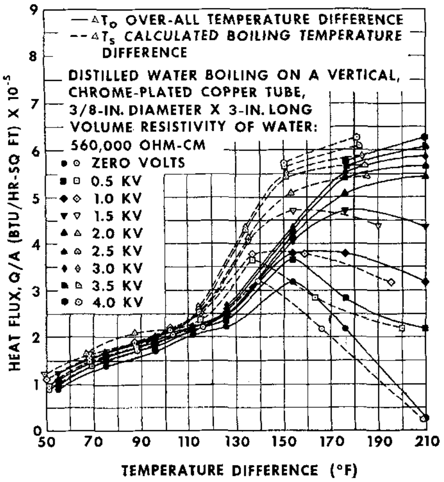

Fig. 3. Effect of 60-cycle a.c. voltage on boiling heat transfer to flowing distilled water at one atmosphere (mass flow rate 3.1 $\times$ 10^5 lb./hr.-sq.ft., internally heated annulus).

troduced into the steam line through a high-pressure lubricator pump at a rate of 3 or 4 ml./hr. The oleic acid promotion, plus a bleed or bypass around the steam trap, insured high steam side heat transfer coefficients.

The test section (Figure 2) was designed so that the flowing water could be heated from the outside wall of the annulus and/or from the copper tube inside. This permitted the determination of the effects of reversing the direction of the gradient of the electrical field on the boiling process. That is, with the inner wall heated, the current lines converge on the heated surface while with the outer wall heated the current lines diverge to the heated surface. In the operation of the flow system with both sides of the test section heated, the copper tube was insulated from ground by means of asbestos and Teflon gaskets incorporated into flanged connections. Electrical resistance attained was about 40,000 ohms during the doubly heated test. When only the outside surface was heated, the copper tube was disconnected from the steam supply line, but acted as the high voltage electrode. With only inside heating the copper tube was grounded and the aluminum shell disconnected from the steam lines served as the high-voltage electrode.

TEST RESULTS WITH CENTRAL TUBE HEATED

The use of steam heating made it possible to control the temperature of the heater wall essentially independent of the heat flux which was the dependent variable. This is in marked contrast to electrical or nuclear heating where the heat flux is the independent variable. Steam heating permits stable operating at any point on the heat transfer curve, limited only by the temperature difference driving force controlled by the steam condensation pressure. Since point heat flux measurements are not available, point condition correlation based on heat flux cannot be made. However, the average heat flux for the test section as a whole was measured accurately and was the fundamental dependent variable of the experiment.

The temperature of the boiling water was the atmospheric boiling point, since the pressure drop from the test section outlet to the atmospheric vent was small. This was confirmed by temperature measurement at the test section outlet. The difference between the boiling point of water at the two pressures then gives the overall temperature difference (ΔT_o). This is the fundamental thermal driving force that is used in the presentation of the data.

In order to derive the thermal driving force for the boiling process, account must be taken of the temperature drops that occurred in the heated wall and in the condensing steam. The precise amount of these two temperature drops depends on the local heat flux, which is not known. However, an estimate of the average test section drops can be made based on the average test section heat flux and the calculated resistances of the wall and condensing steam. For this purpose an average condensing coefficient of 40,000 B.t.u./hr. sq.ft. °F. was estimated based on the steam velocity (about 10 to 20 ft./sec.), oleic acid promotion, and short condensing length (*4*). Subtracting these two temperature drops from the overall temperature difference gives an estimate of the average boiling temperature difference for the test section. These calculated results are also shown in the data presentation for comparison. For the internally heated annulus the major temperature correction arose from the condensing coefficient of the steam. The derived corrections appear reasonable in the light of the experimental result that a change in the steam side velocity did not materially affect the measured heat transfer rate.

Results of tests at three flow rates are presented in Figures 3, 4, and 5. The shapes of the curves are very similar to those from previous work with alcohol (*3, 5*). Film boiling was effectively prevented, in the range of ΔT_o covered, by the application of about 1,000 v. or more. As the flow rate was increased, the only noticeable change in shape of the Q/A vs. ΔT_o plots was slightly steeper slopes, which resulted in lower voltages corresponding to monotonically increasing plots up to and beyond the normal nucleate peak. The displacement of the normal nucleate peak (maximum) to higher fluxes and temperature differences at higher flow rates was consistent with alcohol flow results reported elsewhere (*3*)

The heat fluxes indicated in Figures 3, 4, and 5 were calculated by subtracting the maximum possible ohmic heating (V $\times$ I) of the coolant from the total heat release rate as measured by the loop condensate rate. Other possible corrections included those arising from the pressure drop in the test section, which would tend to increase the measured (Q/A), and subcooling of the stream entering the test section, which would tend to decrease the measured (Q/A). However, since these corrections tended to cancel each other, the heat transfer rates were corrected only for the ohmic heating. For the data in Figures 3, 4, and 5, the ohmic heating corrections varied (with ΔT_o and voltage) from 0.1 to about 10%.

The curves with the thermal driving force corrected to give the calculated boiling temperature difference (ΔT_s)

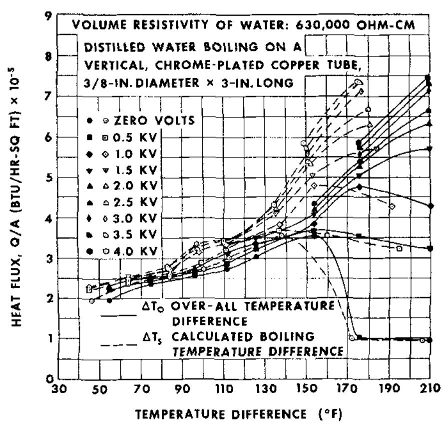

Fig. 4. Effect of 60-cycle a.c. voltage on boiling heat transfer to flowing distilled water at one atmosphere (mass flow rate 4.0 $\times$ 10^5 lb./hr.-sq.ft., internally heated annulus).

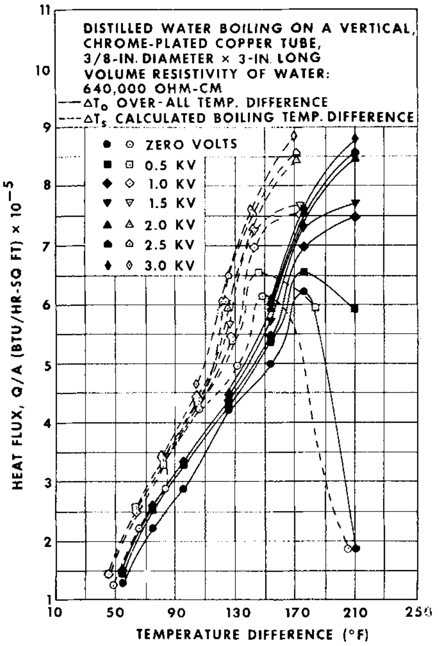

Fig. 5. Effect of 60-cycle a.c. voltage on boiling heat transfer to flowing distilled water at one atmosphere (mass flow rate 5.2 $\times$ 10^5 lb./hr.-sq.ft., internally heated annulus).

are shown by dashed lines in Figures 3, 4, and 5. The corrections are largest at the highest heat fluxes. On this basis the temperature difference at the peak test section heat flux is essentially independent of mass flow rate and the relative effect of the applied voltage is magnified.

It was believed that a measure of the relative effectiveness of the voltage in increasing heat transfer would be useful. This purpose is served by the *amplification factor,* which is defined as the ratio of the increase in heat power output due to voltage (expressed as the heat transfer increase plus ohmic heating due to the applied voltage) to the electrical power input expressed as V $\times$ I at constant overall temperature difference. Since the power factor for alternating current was neglected (measurements in previous pool boiling work indicated a power factor of approximately 0.95), the electrical power input used in the calculation of amplification factors was the maximum. An amplification factor of unity means that the increase in heat power output over the zero voltage case was equal to the ohmic heating, whereas an amplification factor of 10 would indicate that the increase in heat power output realized was ten times the ohmic heating value.

Calculated values of the amplification factor for water flowing at 4.0 $\times$ 10^5 lb./hr. sq. ft. are plotted as a function of voltage (for constant overall temperature differences) in Figure 6. This plot is typical of amplification factor data at the other flow rates tested, and shows that the relative effectiveness of the voltage decreased as the voltage increased. Figure 6 also shows that the amplification factor increased as temperature difference increased. This is believed due to the increased electrical resistance resulting from the presence of more vapor near the heated surface. The increase in vapor in this instance would be a result of the higher heat transfer rate.

A series of tests was performed with water of varying resistivity in order to determine the effect of resistivity on the amplification factor. According to previous work in which alcohol was made conductive with ammonium perchlorate (5), the heat flux would be expected to decrease with increasing volume resistivity of the fluid. At a constant applied voltage, however, the current, and thus the power consumption, would decrease as resistivity increased. The combination of these two effects would result in the measured effect on the amplification factor.

While the variation of heat flux with water resistivity at a constant overall temperature difference showed no strong trend, the amplification factor, plotted vs. resistivity in Figure 7, shows a definite increase with increased water resistivity above about 4 $\times$ 10^5 ohm-cm. The reduction of current by increased resistivity, therefore, had a greater effect on the value of the amplification factor than did the corresponding reduction in heat transfer rate, except at the lowest values of resistivity used.

Tests with External Annulus Wall Heated

A series of tests was made with distilled water in which the liquid was steam heated from the external wall of the flow annulus only. The results of these tests are presented in Figure 8. The calculated boiling temperature difference (T_s) is shown for comparison. In this geometry

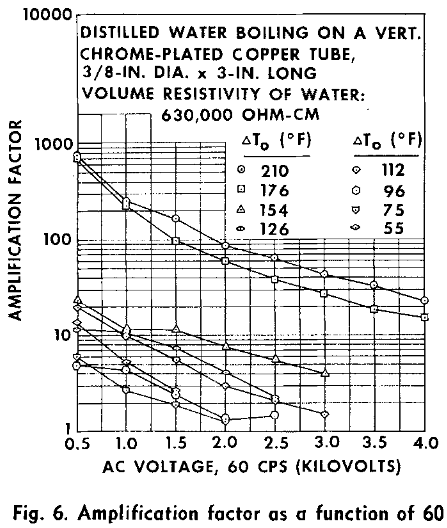

Fig. 6. Amplification factor as a function of 60 cycles/sec. a.c. voltage at various overall temperature differences for distilled water flowing at 4.0 $\times$ 10^5 lb./hr.-sq.ft. (internally heated annulus).

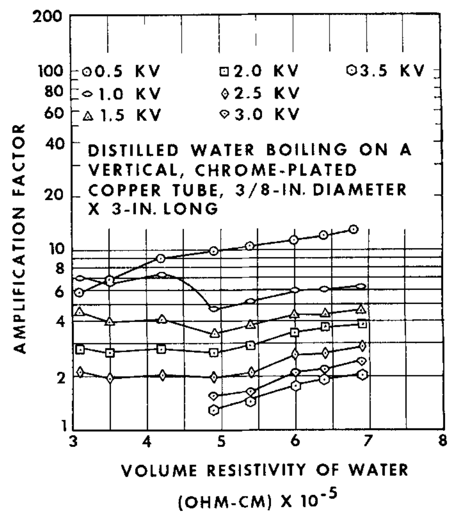

Fig. 7. Power amplification factor as a function of water resistivity for a ΔT_0 of 126°F. (mass flow rate 4.0 $\times$ 10^5 lb./hr.-sq.ft., internally heated annulus).

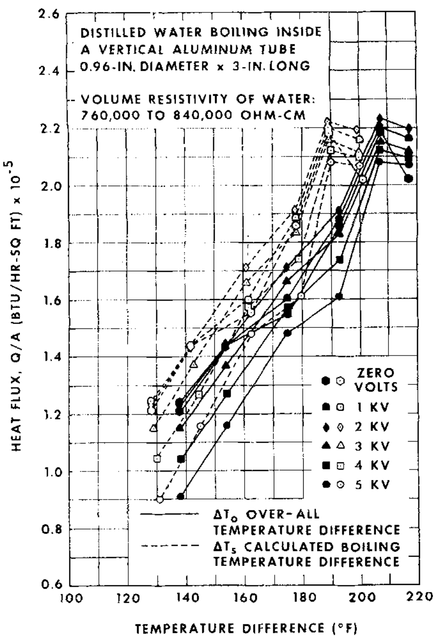

Fig. 8. Effect of 60-cycle a.c. voltage on boiling heat transfer to distilled water flowing through an annulus at 3.4 × 10^5 lb./hr.-sq.ft., and heated on the outside wall only.

the major temperature correction comes from the drop in the aluminum wall.

The effect of voltage on the externally heated annulus was to first increase and then decrease the heat flux. In this case, the effect of dielectrophoresis (*6*) (force on bubbles arising from dipole moments induced by nonuniform field) would be to decrease the heat flux, whereas the condenser force (*3*, *5*) (force on bubbles arising from coulomb attraction of liquid to the wall) would tend to increase heat transfer in all geometries. It therefore appears, based on Figure 8, that the condenser force predominated at the lower voltages and dielectrophoresis was the controlling force at voltages above about 2,000 v. A discussion and a mechanistic interpretation of the forces present and their effects are presented in Part II of this paper.

Differences in system operation, including higher exit qualities and lower heat transfer rates with the externally heated tests as compared with the internally heated tests, may have contributed somewhat to the decrease in heat flux with increasing voltage indicated in Figure 8. In addition, the power factor, cosine θ, which is assumed to be unity, may have decreased due to the presence of more vapor, but not to the extent necessary to suppress the observed effect.

Effect of Heating Both Sides

It was shown in Figure 7 that the amplification factors for distilled water could be increased by increased water resistivity due to a reduction in current. If this were applied to a situation in which both electrodes were heated and were surrounded by a resistive region of vapor formation, then it would appear that the amplification factor should be increased not only by the reduction of current, but also by the fact that two boiling surfaces are affected by the voltage instead of only one. To accomplish this, the test section was heated by steam both through the outer jacket and through the interior tube.

Heat transfer rates and electrical currents were measured at constant voltage (500 v.), overall temperature difference of 154°F., and flow of 3.4 × 10^5 lb./hr. sq. ft. for: (1) heating from the interior tube only; (2) heating from the outer wall only; and (3) heating from both sides simultaneously. The results indicated amplification factors of 9.5, 4.1, and 15.4, respectively, for these three conditions. These results suggest that the applied voltage process was made more efficient by using as electrodes two heated surfaces instead of only one.

DISCUSSION OF FLOW SYSTEM RESULTS

Several significant conclusions could be made based on the low quality boiling regime flow studies.

(1) The heat transfer rate to flowing water can be increased by a.c. voltage applied across the region of vapor formation at any practical mass flow rate.

(2) Based on the increase of heat flux with voltage in the externally heated case at 1,000 and 2,000 v., the condenser effect does influence the heat transfer, and, under some conditions, to a greater extent than dielectrophoresis.

(3) The voltage was generally made more effective by increasing the volume resistivity of the water.

The qualities obtained were in the 0 to 4% range, which is lower than the desirable operating range for nuclear reactors now under development. In this lower range, there was no apparent effect of quality on the voltage process. Similarly, no effects of mass flow rate were observed in the range covered of up to 0.5 × 10^6 lb./hr.-sq. ft., which may be a factor of 3 or 4 lower than mass velocities planned for future reactor applications.

The data presented herein apply only to the specific conditions and geometry used in these tests. Extrapolation of the results to other conditions, especially those under which different flow regimes may be present, must be carried out with caution.

ACKNOWLEDGMENT

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NOTATION

- A = portion of heat transfer area wetted by the coolant during boiling, sq. ft.
- A_w = current from impressed voltage, amp.
- I = heat transfer area, sq. ft.
- Q = average heat transfer rate from surface, B.t.u./hr.
- ΔT_o = overall temperature difference (steam temperature-water boiling point), °F.
- ΔT_s = calculated boiling temperature difference (wall temperature-water boiling point), °F.
- V = voltage impressed on boiling liquid, v.

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