Int. J. Heat Mass Transfer. Vol. 27, No. 7, pp. 959 970, 1984
Printed in Great Britain

0017-9310/84 $3.00 + 0.00
Pergamon Press Ltd.

THE MAXIMUM AND MINIMUM VALUES OF THE HEAT Q TRANSMITTED FROM METAL TO BOILING WATER UNDER ATMOSPHERIC PRESSURE*

SHIRO NUKIYAMA†

J. Japan Soc. Mech. Engrs **37**, 367–374 (1934)

Abstract—The quantity of heat transmitted from a metal surface to boiling water increases as the temperature difference ΔT is increased, but after the ΔT has reached a certain limit, quantity Q decreases with further increase in ΔT. This turning point is the maximum value of heat transmitted. The existence of this point was actually observed in the experiment. Under atmospheric pressure, ΔT corresponding to the maximum value of heat transfer for water at 100°C falls between 20–40°C, and Q is between 1 080 000 and 1 800 000 kcal/m^2 h (i.e. between 2000 and 3000 kg/m^2 h, if expressed in constant evaporation rate at 100°C); this figure is larger than the maximum value of heat transfer as was previously considered. Also, the minimum value of heat transfer was obtained, and in the Q–ΔT curve for the high temperature region, the burn-out effect is discussed.

INTRODUCTION

THE IMPROVING of evaporation rate (i.e. the quantity evaporated per unit time per unit area) for an evaporator is important, because it reduces the size of the evaporator of a fixed capacity as well as shortens the time required for the generation of steam. If the evaporation rate, hence the heat-transfer quantity Q, has a maximum value, the determination of this value is certainly necessary if one is to control the evaporation rate at all. This article is mainly a report of the experimental determination of the maximum value of heat transfer, although the related minimum value of heat transfer was also obtained experimentally.

As the boiling phenomenon is so involved and complicated, the analysis for boiling heat transfer is an almost impossible problem. Even with the powerful dimensional analysis, the research to date was not very satisfactory; besides, the reported work available in the literature was all experimental.

Now

$$Q = \alpha(\Delta T), \tag{1}$$

where Q is the heat transmitted from the metal surface per unit area per unit time to the water; α is the heat-transfer coefficient, and ΔT is the temperature difference between the surface and the water. Equation (1) has been used for obtaining the relationship between ΔT, α and Q. Among the researchers on boiling heat transfer are Austin [1], and Jakob and Linke [2].

For the purpose of comparison, the work of previous workers is indicated by a, b, c, in Fig. 1. Austin [1] proposed that α asymptotically approaches 7000 kcal/m^2 h °C (0.194 cal/cm^2 s °C), and the quantity Q increases with ΔT without limit.

In the process of boiling, the water is fully agitated by the generated steam bubbles, and the degree of agitation first increases with increase in ΔT, but because of the lower heat-transfer rate of steam ($\frac{1}{20}$ of the heat-transfer rate of water), α is not a monotonically increasing function of ΔT. When the boiling is mild, the agitation by the steam bubbling has more effect on the heat transfer, so α and Q both increase as the ΔT is increased. Whereas, if the generation of steam becomes too fast, most of the metal surface is covered by the steam bubbles. As a result, there is no more water which is in direct contact with the metal surface to be agitated. Therefore, the negative effect (lowering of α) takes place and it becomes a matter of heat transfer between metal surface and steam. Thus, contrary to the conclusion of the previous workers, the value of α at 100 or 200°C ΔT is conceivably limited (in the order of 1 kcal/m^2 h °C). Therefore, in the ΔT–α curve, the ordinate first increases with increase in ΔT (Fig. 2) to a critical point, then it must decrease for further increase in ΔT. Since Q is the product of α and ΔT, it should not decrease when α first starts to decrease. Differentiating equation (1) and letting $\mathrm{d}Q = 0$, one gets $\alpha/\Delta T = -\mathrm{d}\alpha/\mathrm{d}(\Delta T)$; thus at the point b, Q also starts to decrease (Fig. 2), and that is the maximum value of heat transfer, $Q_{\max}$. If ΔT continues to increase, the radiation from the metal surface becomes pronounced and the values of α and Q can go very high, so that the α- and Q-curve should be concave upward again. The relational function of α or Q on ΔT is as presented in Fig. 2, where c is the point for the minimum value of Q. Nevertheless, the bc part of the curve (as will be discussed later) is so unstable that it is hard to obtain in practice.

FURTHER DISCUSSION ON THE $Q-\Delta T$ AND $\alpha-\Delta T$ CURVES (FIG. 2)

Some special equipment might be used to maintain the metal surface at a constant temperature although, in general, equilibrium temperature is attained when the heat transmitted to the water is equal to the heat supplied by the heat source. Let Q be the heat supplied

---

* Translated from the Japanese by Dr C. J. Lee, while he was a graduate student in the School of Chemical Engineering, Oklahoma State University, Stillwater, Oklahoma. Dr Lee's present address is Heat Transfer and Process Equipment Research Section, Phillips Research Center, Phillips Petroleum Company, Bartlesville, Oklahoma, U.S.A.

† Professor, Tohoku-Imperial University, Japan.

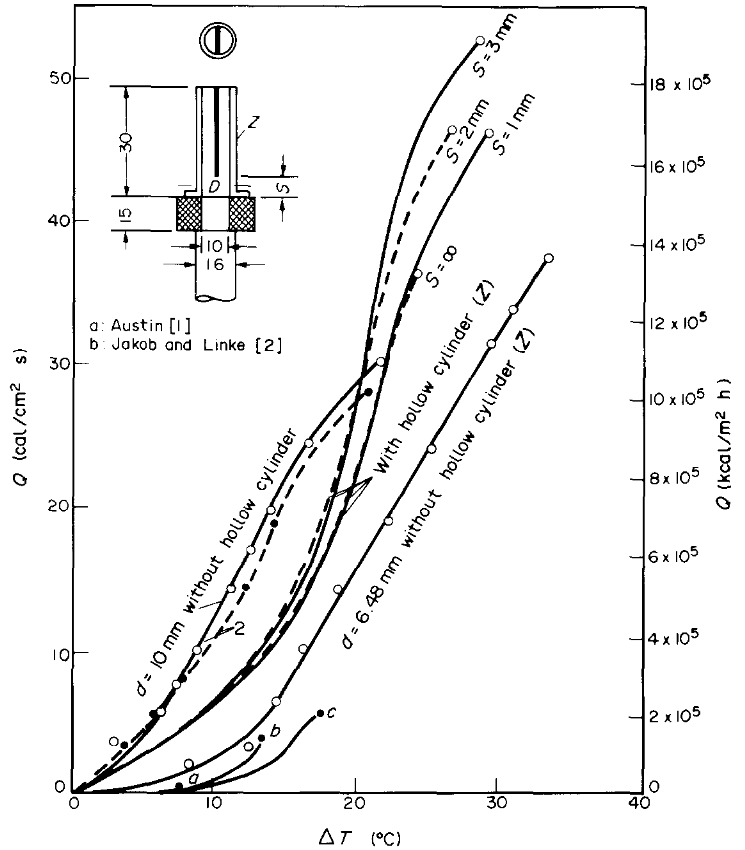

FIG. 1. ΔT vs Q curve; water temperature = 100°C.

and the heat transmitted to water at equilibrium state; the temperature of the metal surface at this value of Q (point P in Fig. 2) is then the sum of the corresponding ΔT and the temperature of water. At this point, if the supplied heat is increased by a small amount, P is moved closer to b and attains another equilibrium state. Suppose, P reaches b now, and if we supply a little bit more heat to increase ΔT, then P goes beyond b and Q starts decreasing. Therefore, the excess heat (the difference between supplied heat and the Q from Fig. 2) accumulates in the metal material so ΔT is further increased. From there, Q is becoming less and less as ΔT continuously increases, P then moves rapidly following the *bcd* curve, and finally reaches the equilibrium state at d, where it has the same value of Q as at point b (Fig. 2). In the experiment, one supplies the heat to the heat-transfer area, gradually increasing from zero, and records the surface temperature; at point b, the surface temperature will suddenly change; from this, one notices that the maximum point has been reached. As will be discussed, the value of $Q_{\max}$ at point b varies with different curvature of heat-transfer surfaces, but in general, it is over 30 cal/cm^2 s. If we assume that $Q_{\max} = 30$ cal/cm^2 s and calculate α for the heat transfer between the metal surface and the generated steam, we find that the temperature at point d is in the order of magnitude of the melting point of platinum. As a consequence, for most metals, when they go beyond b, they follow the curve *bcd* rapidly and melt before they reach d. The ΔT corresponding to b for water is below 40°C; accordingly the temperature of the metal surface at point b is lower than 140°C. Ordinary metals are solid at this temperature. As will be discussed later, the experiments were run with metal wires of iron, nickel, nichrome and platinum. These wires actually melt at point b just like the fuse of low melting point (170°C) does. Only when using an extremely thin platinum wire for the heat-transfer surface would the point d really exist, because the wire has a small diameter, hence a

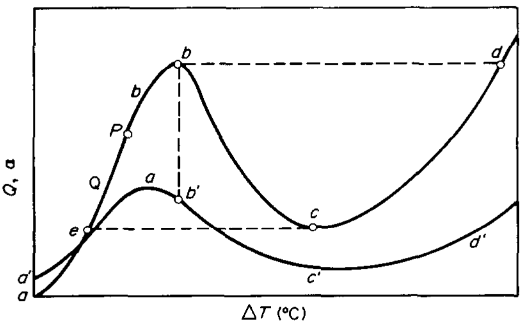

FIG. 2.

small value of $Q_{\max}$. Now, if we reduce the value of Q little by little, the curve would not reverse from d to b but it goes along dc (as a result of decreasing ΔT), and suddenly jumps to point e from point c, for the same reason as for the jump from b to d. We call the region from d to c the spheroidal state.

The purpose of this investigation is to study experimentally the above-mentioned phenomenon. But, owing to the large value of $Q_{\max}$, we have to select a suitable type of heat-transfer surface. We were not able to supply necessary heat for a flat surface which was used by Austin [1] and by Jakob and Linke [2]. When we used a thin metal plate as the transfer surface, contacting water on one side of the plate and heating directly with a Bunsen lamp from the other side in order to supply the heat, we could supply only a few per cent of the $Q_{\max}$. For various reasons, we have used the following two methods: (a) A thin metal wire for the heating element as well as the heat-transfer surface; the wire is set in the water and supplied with the necessary heat by running electric current through the wire. The experiments were run with different metals of various diameters. Subcooled water was also used in obtaining b. The minimum value of heat transfer was obtained with a thin platinum wire. (b) With a special equipment set-up, the same experiments were repeated on two circular flat plates of 10 and 6.48 mm diameters.

EXPERIMENT I—THE Q, α AND ΔT RELATIONS FOR THE SURFACE OF METAL WIRES

In Fig. 3(a), D is the Pyrex glass vessel of 15 × 15 × 24 cm for distilled water. D was set up in a sand bath and was heated with gas or with insulated electric resistance wires in the sand to keep the water at boiling temperature under atmospheric pressure. ab is a metal test wire of 20 cm length; its ends are welded to aA and bB, respectively. These silver or nickel plated copper wires are 3 mm in diameter. A, B are connected to copper wires of larger diameter which carry the electric current to supply the necessary heat to ab. The current going through the wires is about 10 A D.C.; so if aA and bB were bare, or if a metal vessel was used for D, the purity of water inside the vessel might have been affected because of the electrolysis. In order to prevent it, aA and bB are cased by glass coating. Alternating current had been tried with the consideration that it might eliminate the electrolysis, but it was not suitable due to the difficulties encountered in the measurement of temperatures, current, voltage, etc.

The electric flow scheme is shown in Fig. 3(b). $CDEF$ forms the Wheatstone bridge, and the test wire ab is fixed in between CD. The wires other than for ab are rather large in diameter so that only a few ohms from the resistance in ab were counted for the resistance between section CD. R_1, R_2, R_3, are manganin wires. The resistance of R_2 and R_3 is many hundred ohms, so that most of the current from the source goes to CDE, and less than 1% of the total will go through R_2 and R_3.

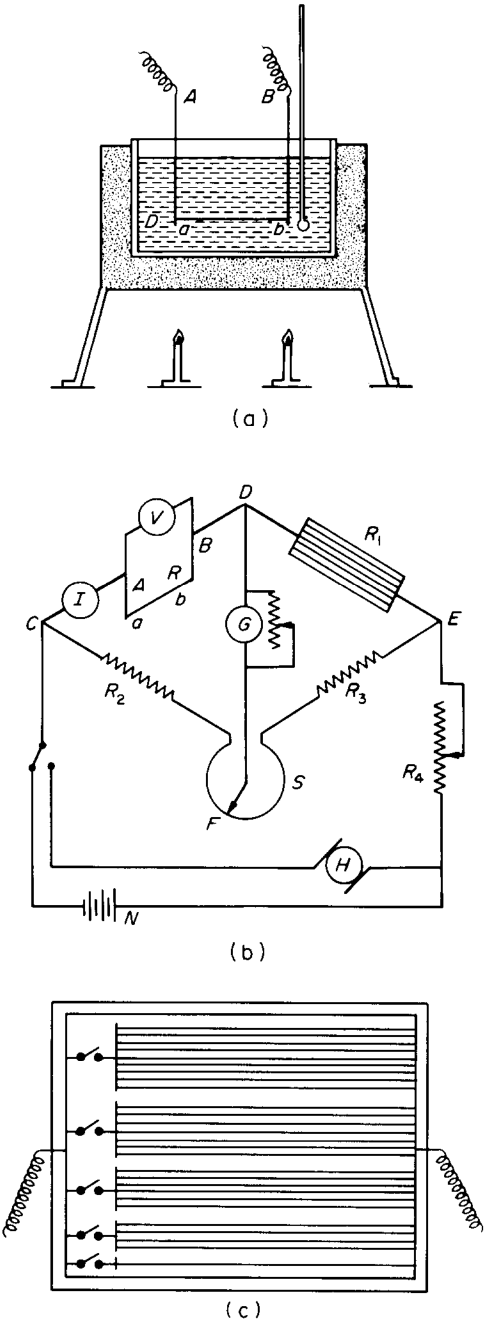

Fig. 3. Equipment for metal wire experiments.

R_2 and R_3 are put in an oil bath to avoid the temperature variation due to the heat generation from the resistors. R_1 carries the same amount of current which flows through ab. In Fig. 3(c), we have shown that R_1 is a rheostat which was constructed with some 40 thin manganin wires stretched between a copper frame and immersed in an oil bath. The resistance is adjusted to the same magnitude as the resistance of the test wire ab during the experiment. Because of the strong current which is flowing, the temperature of oil during an experiment may rise more than 20°C, but since the manganin wires were used, the variation in R_1 can be assumed negligible in this experiment. S is a 30Ω variac; G is a galvanometer; N is a set of battery cells; H is a D.C. generator; V is a voltmeter; and I is an ammeter.

THE EXPERIMENTS AND THE RESULTS OF THE DETERMINATION OF THE MAXIMUM VALUE OF Q

Some calibration should be provided before the temperature of *ab* can be read from the Wheatstone bridge during the experiment: immerse *ab* in the oil bath, and vary the oil temperature between 50 and 150°C (this temperature was measured by mercury thermometer to $\frac{1}{10}$°C precision), take the reading of variac S and plot it against oil temperature when the weak current supplied by N is at equilibrium with the reading in G. Since the current used in this calibration is so weak that the temperature of the wire can be taken as the temperature of the oil bath, the calibration curve can be approximated as the reading of S vs the temperature of the wire. When performing the experiment, the temperature of the test wire *ab* is therefore obtained from the reading together with the calibration curve.

The calibration with oil may destroy the surface of the metal wires, thus introducing a bad effect in the main experiment. To avoid this, we have run only one point each for a certain kind of metal wire for such calibration with oil, then checked the same calibration with water instead at the temperature from 50 to 100°C; for temperatures above 100°C, we can extrapolate the result of the calibration.

ab is fixed in the container D [Fig. 3(a)], and after the water in D is heated by Bunsen flame to the required temperature (100°C), a current is supplied by H [Fig. 3(b)] and by adjusting R_4. Beginning with 1 A, the current is gradually increased by 0.5–1 A, and the corresponding I, V, S, readings are recorded. When Q is close to the maximum value, the variac S is used in addition to R_4 [Fig. 3(b)] to keep G at an equilibrium position. When $Q_{\max}$ is reached, part of the wire *ab* melts out and G will sense a violent shock. At this moment, the readings of I, V, S, are carefully taken, and from this, ΔT corresponding to the $Q_{\max}$ is obtained. But, to prevent the burn-out of the metal wire, an automatic shut-off device has been applied. During experiments, the electrolysis occasionally introduced some error in the temperature readings. Therefore, in order to shorten the period of one run, the readings in the lower current region were roughly taken. Let d be the diameter of the metal wire in cm, L be the length in cm, the reading of the ammeter and the voltmeter be I and V, respectively, the value of Q is then calculated by the following equation:

$$Q = \frac{1}{\pi\,\mathrm{d}L}\cdot\frac{IV}{4.184}\quad \mathrm{cal/cm^2\,s.} \tag{2}$$

The temperature difference between water and the surface of the metal wire ΔT was obtained from the reading of S and the mercury thermometer; however, there are two points which must not be overlooked:

(1) If there were any difference between the temperature of the surface of wire T_r and that of the center of the metal wire T_0, it would introduce an error in the value of ΔT. To correct it, we assume that the heat generation from the metal wire due to the current is uniform throughout the wire, and $(T_0 - T_r)$ can be calculated by the following equation (as given in any general heat-transfer book [3]):

$$T_0 - T_r = Wr^2/4\lambda, \tag{3}$$

where W is the quantity of heat generated by the metal wire per unit time per unit volume of the wire, r is the radius and λ is the thermal conductivity of this metal wire. Since the heat transmitted from the surface of a unit length of wire to the water is $2\pi rQ$, which must be equal to the heat generated from the corresponding surface, $\pi r^2 W$, then, from equation (3):

$$T_0 - T_r = Qr/2\lambda. \tag{4}$$

This $(T_0 - T_r)$ is within 1°C for platinum and nickel wire, and is less than 2–3°C for nichrome wire. If we would make more precise correction, we should also consider the variation of the electric resistance due to the temperature difference of the surface and the interior of the metal wire; i.e. the surface of the wire may carry more current because of its lower temperature and its lower resistance. With this consideration, $(T_0 - T_r)$ could be obtained by solving a simply formulated Bessel function. When it is done, the value of $(T_0 - T_r)$ is actually less than the one obtained from equation (4), and is within $\frac{1}{2}$°C. In the present experiments, we can never neglect the correction made with equation (4), because of the imperfect reproducibility of the experimental results and of item (2) to be discussed. Although the correction can be easily done, it may not positively assure the improvement of the final result. This will be better explained in item (2).

(2) The surface temperature of the metal wire is by no means uniform. This is due to the non-uniform, local generation of steam from the surface. When the vaporization is mild, the bubbles are seen first from the surface where there are scratches or impurities on the surface, then gradually the same bubbling is observed from other locations of the surface after a few seconds. Once the vaporization gets vigorous, most of the surface is covered with steam bubbles, but still there is some part of the surface which is in direct contact with water instead of with steam bubbles. Therefore, the surface temperature will never be everywhere the same, and the surface temperature we recorded during the experiment is therefore only an average value. The degree of non-uniformity of this surface temperature is not yet certain; however, it may be in the order of magnitude of ΔT, if we consider the temperature for the surface where it is in direct contact with the water to be 100°C. But, actually the temperature of this part of surface is higher than the boiling point of the

surrounding water, and therefore the degree of temperature non-uniformity of the metal surface is less than ΔT [4]. In view of all these considerations, the few degree centigrade non-uniformity in temperature is not very surprising. Inaccurate measurements may also introduce this amount of error.

The experiments were run with platinum, nickel, nichrome, iron and fuse wires. The results with iron and fuse wire were similar to those with others, except that their surfaces were more seriously affected by electrolysis. Thus, we have omitted the data for iron and fuse. The experimental results were not quite reproducible, therefore, the average value from several runs of the same size and same kind of metal has been taken. The dimension of metals and the number of runs is summarized in Table 1.

Table 1

Metal	d Diameter (mm)	L Length (mm)	No. of runs
Platinum wire	0.14	200	8
Nickel wire	0.14	200	10
Nickel wire	0.40	200	20
Nichrome wire	0.535	200	7
Nichrome wire	0.575	200	9

Tables 2 and 3 are lists of some data for illustration. Table 2 is for Run No. 6 with nickel wire of $d = 0.14$ mm and Table 3 is for Run No. 3 with nichrome wire of $d = 0.575$ mm. The experimental data and the calculated Q and α are listed in these tables. The numbers in the last lines of Tables 2 and 3 are the values for the moment when the metal wires burned out, but in the columns for α, the maximum values appear in bold type before the last line in Tables 2 and 3. Figures 4–9 are the plots of Q vs T (the temperature of the metal wires) from the experimental data for various metal wires. The curves have been drawn in such a way that a straight line is connected between every two adjacent experimental points. The temperature for water has been assumed at 100°C for all cases, and the last point in every graph represents the point when the metal wire burned out. The results as shown are rather scattered among each individual set of data; however, a representative curve is drawn in Fig. 10 for each metal wire. Figure 11 is the α vs T curve, where α is calculated from experimental data. The α-curves for metal wire of $d = 0.14$ mm were omitted, because of inconsistent results.

INTERPRETATION OF RESULTS

As has been previously mentioned, different positions on the surface of a metal wire may have

Table 2. Experimental results for Run No. 6, nickel wire of $d = 0.14$ mm

A	V	W	cal	Q (cal/cm^2 s)	ΔT	a (cal/cm^2 s °C)	a (kcal/m^2 h °C)
1.2	0.25	0.3	0.0715	0.0284	0.8	0.0355	1277
4	0.8	3.2	0.763	0.303	4.7	0.0645	2320
8	1.6	12.8	3.05	1.214	9.3	0.130	4680
10	2.0	20	4.76	1.896	10.5	0.181	6500
15	3.1	46.5	11.07	4.41	12.5	0.353	12 700
20	4.1	82.0	19.52	7.775	14.3	0.544	19 560
25	5.2	130	30.96	12.33	17.0	0.726	26 100
30	6.1	183	43.57	17.35	19.3	0.913	32 900
34	7.0	238	56.68	22.57	23.5	**0.965**	**34 600**
35	7.3	255.5	60.85	24.23	26.5	0.915	32 900
38	7.9	300	71.5	28.46	30.0	0.949	34 200
39.4	8.2	323	76.9	30.6	32.5	0.942	33 900

Table 3. Experimental results for Run No. 3, nichrome wire of $d = 0.557$ mm

A	V	W	cal	Q (cal/cm^2 s)	ΔT	a (cal/cm^2 s °C)	a (kcal/m^2 h °C)
1	0.8	0.8	0.191	0.0527	3	0.0176	634
5	4.2	21.0	5.0	1.385	8	0.173	6230
10	8.25	82.5	19.6	5.44	13.5	0.403	15 500
15	12.8	192	45.7	12.66	18.8	0.674	24 300
20	17.0	340	81.0	22.42	25.7	0.873	31 400
22	18.7	411.4	98	27.15	31.0	0.876	31 600
24	20.5	492	117	32.43	35.5	0.914	32 900
25	21.4	535	127.4	35.29	38.0	**0.928**	**33 400**
26	22.3	580	138	38.22	44.0	0.869	31 300
26.7	23.0	614	146	40.48	46.5	0.860	31 000

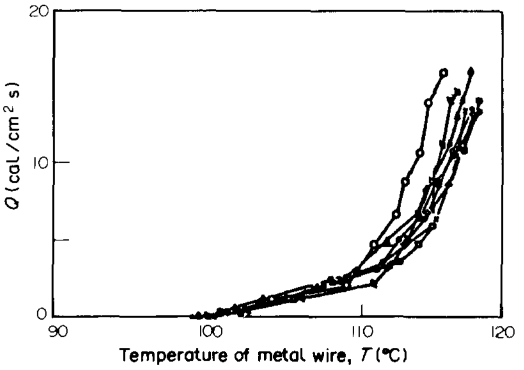

FIG. 4. Platinum wire, $d = 0.14$ mm; water temperature = 100°C

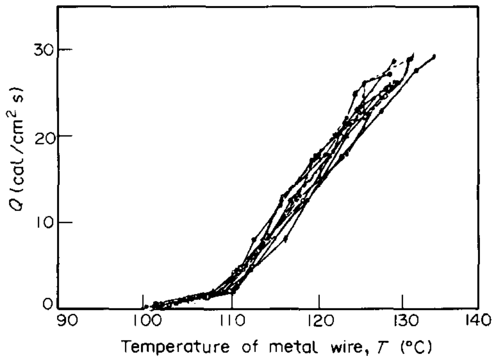

FIG. 7. Nickel wire, $d = 0.40$ mm (Nos. 11–20); water temperature = 100°C.

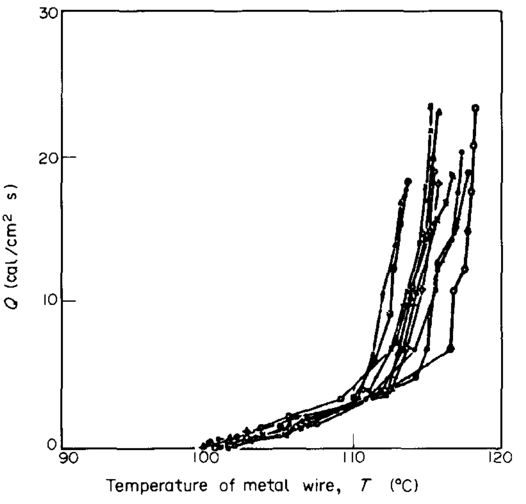

FIG. 5. Nickel wire, $d = 0.14$ mm; water temperature = 100°C.

different *ab* curves (Fig. 2), because the temperature varies from position to position on the surface; however, when any of these points reaches *b*, the wire burns out. Experimentally, sometimes the wire burned out before it reached point *b*. Suppose on the average, the wire will burn out at b_1; then the differences between *b* and b_1 will depend on the diameter of the wire—the smaller the diameter of the wire the smaller will be the difference, so the value $Q_{\max}$ and the corresponding ΔT are smaller for wire of smaller diameter. In Fig. 10 the burn-out point observed for $d = 0.14$ mm is at the point where the Q-curve begins to show a change of slope, though the burn-out points as experimentally detected lie below the $Q_{\max}$ the α calculated in most cases is beyond the maximum point in the curves (Fig. 11). The result varies somewhat with the material used. However, if we take into account the possible experimental error involved, we conclude that the result may be independent of the material used.

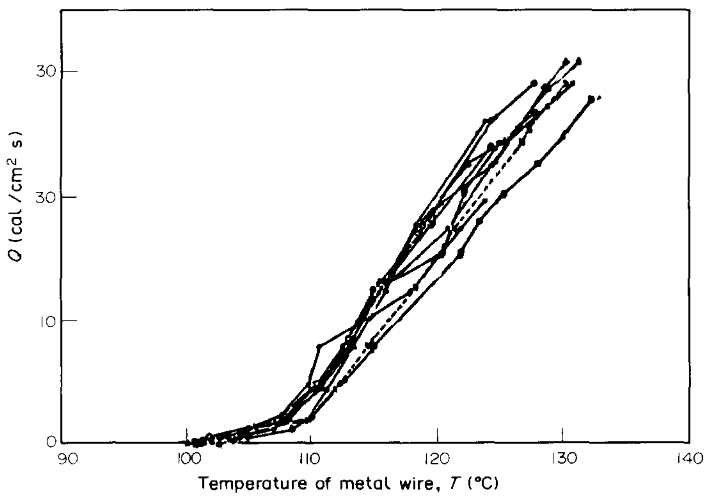

FIG. 6. Nickel wire, $d = 0.40$ mm (Nos. 1–10); water temperature = 100°C.

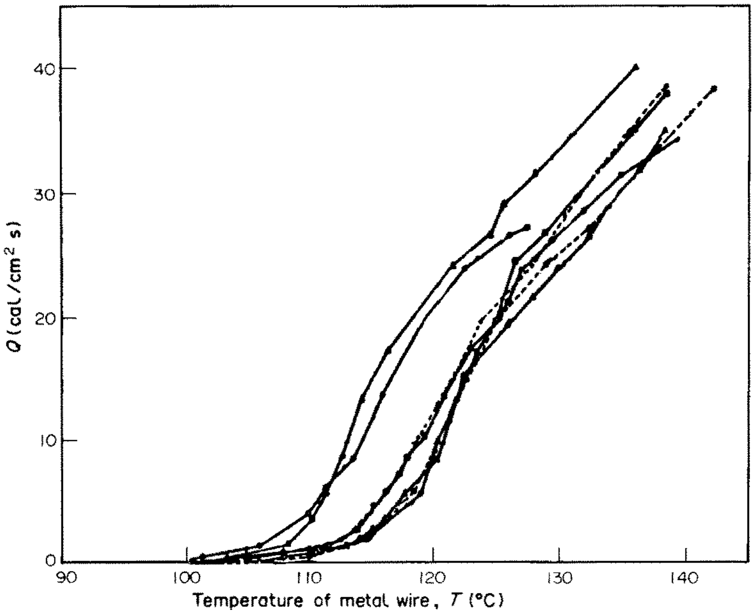

FIG. 8. Nichrome wire, $d = 0.535$ mm; water temperature = 100°C.

Figure 12 is the result of the experiments with nickel wire of $d = 0.19$ mm and with water temperature at 70, 80, and 90°C, respectively. Q_{max} is rather great when the temperature of water is low. The experiments with water at these temperatures were more difficult to control, and there might have been introduced an error of about 10°C in the value of ΔT. Figure 13 presents the values for α as obtained from Fig. 12.

THE EXPERIMENTS AND THE RESULTS OF THE DETERMINATION OF THE MINIMUM VALUE OF Q

The equipment is the same as the previous one; however, in order to lower the temperature at d (Fig. 2), the platinum wire of 0.14 mm diameter was used because it has a smaller value of Q_{max} and is more durable at higher temperature. When the state moves from b to d in Fig. 2, the electric resistance of the platinum wire R increases rapidly due to the rise of the temperature. When the resistance R_4 in the circuit $CDER_4H$ (Fig. 3) is greater than R, the current I is not lowered much by the increase of R; hence, the quantity of heat I^2R is very much increased. In this case, point d of Fig. 2 is at a position higher than point b and at a temperature so high that even the platinum wire is melted. However, if we reduce the value of R_4, the difference between the Q at d and the Q at b is lessened. For this reason, we have used a smaller value of R_4 in order to prevent the burn-out of the platinum wire. (Recall that we have used large values of R_4 in the determination of Q_{max}. The change to smaller R_4 is to obtain a more adjustable range of the current.) Even so, the point tends to jump from lower position to a higher position as shown by the arrow in Fig. 14. Experimentally, the minimum value of Q was determined by reducing the current from the high temperature regime beyond the point b. In the vicinity of the minimum value of Q, the platinum wire turns from shining color to red or dark-red spot, and when it passes the point Q_{min}, the temperature rapidly decreases and the galvanometer fluctuates, the brightness of the wire disappears completely and the wire returns to the initial state. Experiments were run with 12 platinum wires and the results are shown in Fig. 14. The resistance vs temperature curves for platinum wire at higher temperature were extrapolated from the data obtained for the calibration with oil at temperatures below 200°C. The resistance vs temperature curve for a platinum wire changes every time after the wire is used once. The reason for this may be due to the annealing

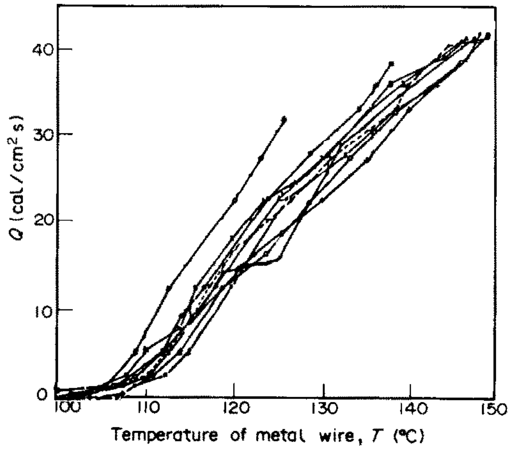

FIG. 9. Nichrome wire, $d = 0.575$ mm; water temperature = 100°C.

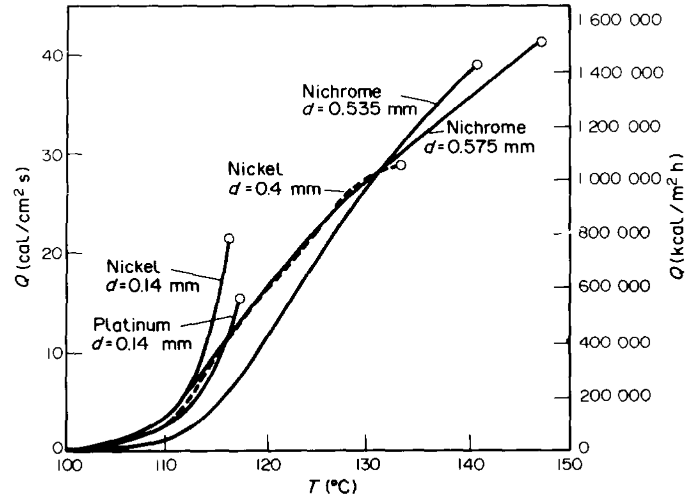

FIG. 10. Average value of Q for various metal wires; water temperature = 100°C.

effect or the expansion of the platinum wire under tension during the strongly heating process, or may be due to the effect of electrolysis. It is not yet completely explored. We presume that all these have caused some 10°C.of error in ΔT, especially at higher temperatures.

During the tempering process, the metal is changed from high temperature along the Q vs ΔT curve. When it reaches Q_{min}, it instantaneously passes Q_{max}, and liberates a large amount of steam. The wire finally becomes black. The Q vs ΔT curves can be used to determine the temperature change of the material. Therefore, if we study the case of water in motion or use other liquids instead of water to obtain the similar Q vs ΔT curves for each case so as to investigate the mechanism of tempering of metals, we may be able to get some very interesting results.

EXPERIMENT WITH A FLAT PLATE AS HEATING ELEMENT

A horizontal flat plate with the water boiling on the top surface was used. The Q vs ΔT curve must vary with the size of the flat surface used. Facing the difficulties of being not able to supply sufficient heat to the large flat surface, we had to limit ourselves to two circular surfaces of small diameter, 10 and 6.58 mm, in order to obtain the Q_{max} for the flat plate. Figure 15 is the apparatus set-up: A is a copper solid cylinder with a smaller neck in B, where ab is the heat-transfer surface. C is a cap made of ebonite or of porcelain in the inside and carbonized corks in the outside parts. They were used as the heat insulators. But, if one uses the porcelain and carbonized corks, care must be taken to avoid

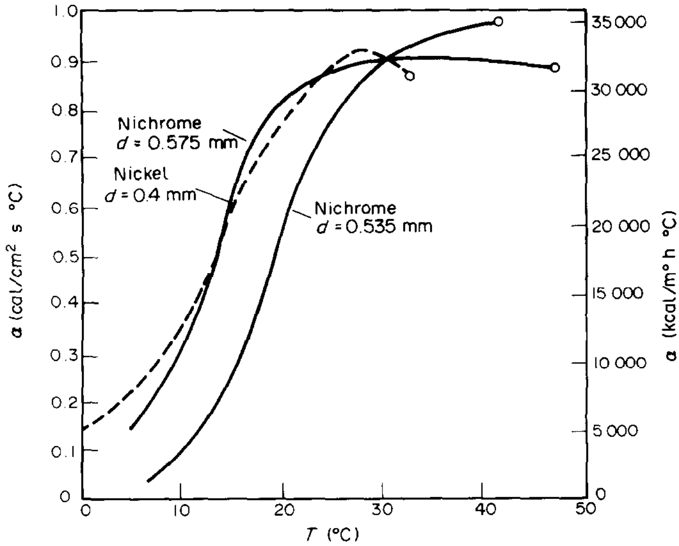

FIG. 11. Average value of α for various metal wires; water temperature = 100°C.

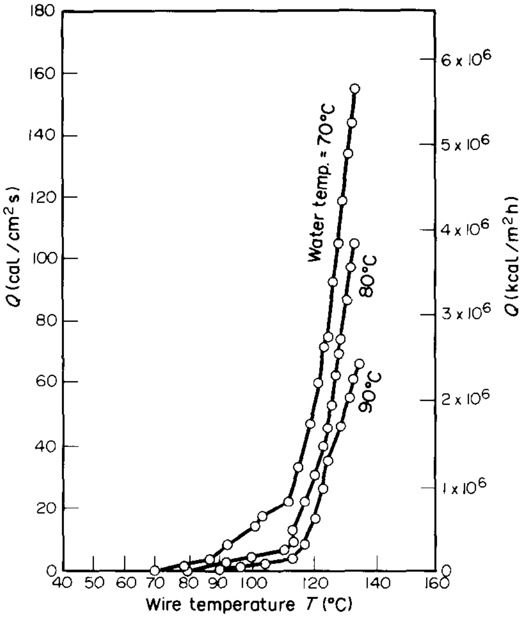

FIG. 12. Q curve for water temperature below 100°C.

absorbing water. The resistance wire D was wound on the electrically insulated surface of A and the whole system was insulated with asbestos. The heat generated in D is transmitted to the good conductor A and then to the surface ab by means of B. In this way, we have been able to supply the necessary heat to the surface ab. There might be some heat loss through C, but it is very small compared to the magnitude of the heat transmitted to the water through ab, because the conductivity of C is only $\frac{1}{1000}$ of the conductivity of B. This fact was experimentally tested by attaching thermocouples (copper–constantan) to two positions of B, and to a point in the water close to the surface ab. The axial temperature distribution as shown in Fig. 16 is a straight line. Thus, the radial heat loss from ab to the water was calculated from T_1 and T_2 (Figs. 15 and 16) and the thermal conductivity of copper. The thermal conductivity of copper was taken as 320 kcal/m h °C = 0.89 cal/cm s °C.

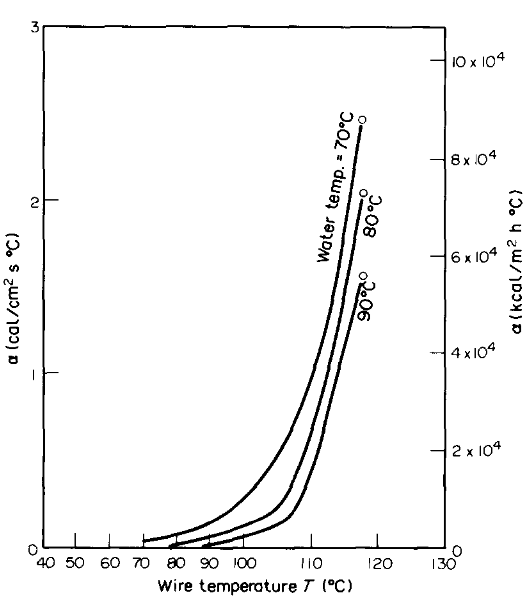

FIG. 13. α curve for water temperature below 100°C; platinum wire, d = 0.19 mm.

The copper element AB can hold 10 cal of heat, so that we have to reduce the frequency of the current variation. But, it was found that the frequency of current variation did not affect the experimental results very much. The temperature of ab was found by extrapolating the line between x_1 and x_2 (see Fig. 16).

The heating current, I, was recorded in addition to T_1 and T_2. When Q reaches the maximum value, T_1 and T_2 change very rapidly, and with our measuring devices, we could only record T_1 and I. T_2 is then obtained from T_1, I and Fig. 16. With the T_1 and T_2 we can calculate the value of $Q_{\max}$ and the corresponding ΔT. The results are shown in Fig. 1, where for a smaller heating surface, we have a larger value of Q at a certain ΔT reading, such that $Q_{\max}$ is also greater for smaller heating surface. To go a step further, we have designed a device to study the effect of the flow pattern on the $Q_{\max}$. The 10 mm circular surface, with a hollow, ebonite cylinder of the same diameter as the copper surface (top of Fig. 1) was used to control the flow of water adjacent to the copper surface. Notice that there is an adjustable thin plate which divides the ebonite cylinder into two parts. The experiments were repeated with various S, which is the distance between the dividing plate N and the surface ab. When inserting the dividing plate N, the steam bubbles arise along the sides of N and the circulation of water is laminar even with vigorous boiling. Experiment for each value of S was repeated 4–5 times and the average results are presented in Fig. 1. Lifting the distance S 1 mm each time speeds up the flow of water, so that Q has a greater value at a certain ΔT, and so $Q_{\max}$ is also greater. But, when S becomes infinity, i.e. without the dividing plate N, the flow becomes very turbulent and the $Q_{\max}$ becomes small again. Figure 17 is the α-curve as calculated from the above results, which is similar to Fig. 11 for the case of metal wires.

CONCLUSIONS AND SOME AUXILIARY OBSERVATIONS IN THE EXPERIMENTS

There exists a maximum value of Q for the Q vs ΔT curve, which is independent on the material of the metal heating surface. The values of $Q_{\max}$ are rather great compared to the value of ΔT, which are about 20–40°C as has been determined experimentally. The $Q_{\max}$ is about 30–50 cal/cm^2 s for all dimensions of different heating surfaces, except for the tiny metal wire, provided there is no disturbance to the natural convection of the water. This value for $Q_{\max}$ is far greater than the value which was conventionally accepted. In ordinary evaporators, the value for Q is less

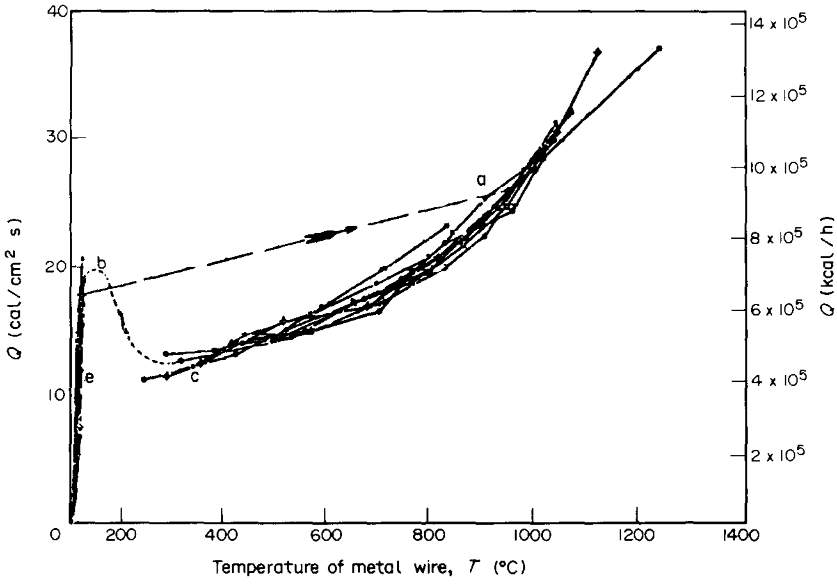

FIG. 14. The determination of $Q_{\min}$ for the platinum wire of $d = 0.14$ mm.

than 3 cal/cm^2 s even at the position where it is closest to the furnace. Therefore, under normal conditions, the heating surface will never reach the spheroidal state, except possibly when there is scaling on the surface of the evaporator. The problem of scale and the cases for local pressure difference will be treated in the later study.

In the experiments with metal wires some sparks along the surface of the wire were observed. As has been mentioned previously, when Q is small, the bubbling is mild [1], but when ΔT is about 12°C, no matter if the temperature of water is 100°C or lower, the generation of steam bubbles becomes suddenly violent, so that all the heating surfaces are covered, and Q abruptly increases at this temperature in the Q vs ΔT curve.

What is the temperature of water in contact with the surface, when ΔT is 20 or 30°C? Granting that there should not be a sudden change on the interface of solid and liquid, we conclude that the water is being superheated. Partridge and White [5] has experimentally studied the mechanism of steam generation from the dry spot, mn on a surface (Fig. 18). The temperature

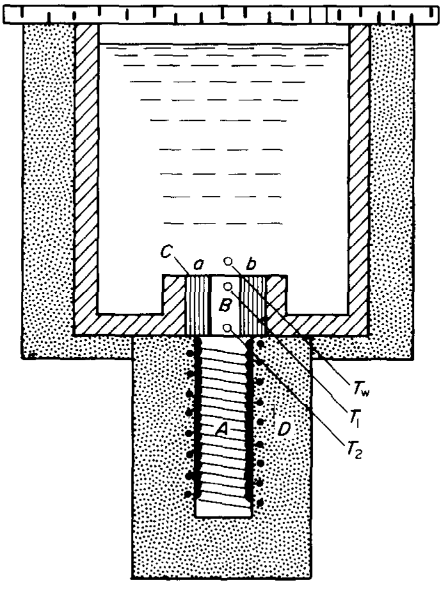

FIG. 15. Apparatus for the flat plate experiment.

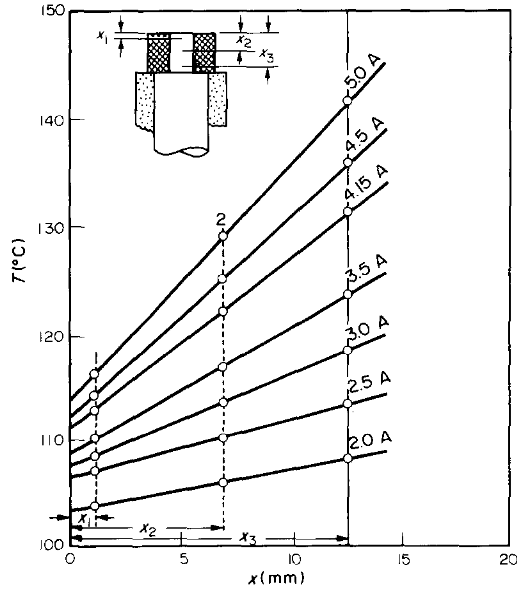

FIG. 16. Axial temperature distribution for the flat plate experiment.

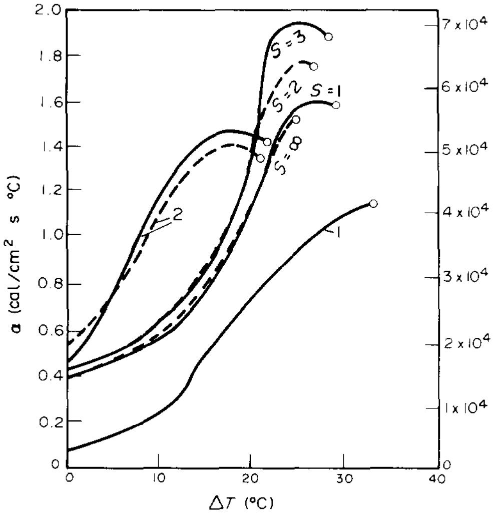

FIG. 17. ΔT vs α curve; water temperature = 100°C.

at this spot on the metal surface is much higher than that of water; therefore, we should say that the ΔT is actually the average of the temperature of a few higher temperature spots and most of the 100°C parts.

Of course, superheating is required before the pressure can overcome the surface tension of water to generate steam bubbles in the water. The present author has been attempting for years to measure the degree of superheating, but has unfortunately failed. In 1932, Jakob and Fritz [4] first succeeded in the measurement and they confirmed that it is superheated somewhere near the heating surface. But, this measurement was at the position about 1 mm from the surface, and only 1°C superheating was reported. It remains as an area for someone to measure the degree of superheating at a location closer to the surface.

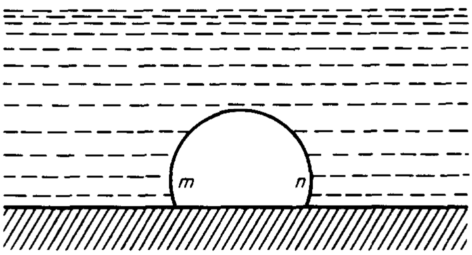

FIG. 18.

In the present experiments, the temperature of water should be able to keep at 100°C with heating on the outside of the water container and with the inside heating element. But, as Q becomes large, the water temperature sometimes dropped 0.2–0.5°C; and the experiment was forced to pause (to find the possible cause of discrepancy). The author thinks that it might be due to the steam bubbles which encourage the vaporization and subcooling of the adjacent water and there is a heat flow from the bulk water to the water adjacent to the steam bubbles; therefore, the temperature of the bulk water dropped.

REFERENCES

1. L. Austin, *Z. Ver. Dt. Ing.* **46**(2), 1890 (1902).
2. M. Jakob and W. Linke, *Fors.* **3**, 75–80 (1933). (Also refer to abstract No. 82, *J. Mech. Soc.* (1933).)
3. K. Oga, *Introduction to Heat Transfer and its Application*, p. 139.
4. M. Jakob and W. Fritz, *Fors.* 441 (1931).
5. E. P. Partridge and A. H. White, *Ind. Engng Chem.* **21**, 834 (1929).

LES VALEURS MAXIMALE ET MINIMALE DE FLUX THERMIQUE Q TRANSMIS DU METAL A L'EAU BOUILLANTE SOUS PRESSION ATMOSPHERIQUE

Résumé—Le flux de chaleur transmis d'une surface métallique à l'eau bouillante croît quand la différence de température ΔT croît, mais après que ΔT ait atteint une certaine limite, le flux Q diminue si ΔT continue d'augmenter. Ce point de changement est la valeur maximale du flux transmis. L'existence de ce point a été observée dans les expériences. Sous la pression atmosphérique, le ΔT correspondant à la valeur maximale de transfert pour l'eau à 100°C est à 20–40°C, et Q est entre 2000 et 3000 kg/m^2 h. Ce résultat est supérieur à la valeur maximale antérieurement considérée. Aussi la valeur minimale du transfert thermique a été obtenue et sur la courbe Q–ΔT pour la région des fortes températures, on discute l'effet de brûlage.

MAXIMALE UND MINIMALE VON METALL AN SIEDENDES WASSER ÜBERTRAGENE WÄRME BEI ATMOSPHÄRENDRUCK

Zusammenfassung—Die von einer Metalloberfläche an siedendes Wasser übertragene Wärme nimmt mit steigender Temperaturdifferenz zu. Nachdem jedoch ΔT eine bestimmte Grenze erreicht hat, fällt der Wärmestrom mit weiterhin zunehmendem ΔT ab. Dieser Wendepunkt gibt die maximal übertragene Wärme an. Es wurde im Experiment beobachtet, daß dieser Punkt tatsächlich existiert. Beim maximalen Wärmestrom für Wasser bei 100°C liegt ΔT zwischen 20 und 40°C, und Q erreicht Werte zwischen 1 080 000 und 1 800 000 kcal/m^{2}h (d. h. 2000 bis 3000 kg/m^{2}h, wenn man es durch eine konstante Verdampfungsgeschwindigkeit bei 100°C ausdrückt). Dieser Wert ist größer als das Maximum der übertragenen Wärme, von dem man früher ausging. Weiter wurde das Minimum der übertragenen Wärme ermittelt, und der Burnout-Effekt anhand der Q–ΔT-Kurve für den Hochtemperaturbereich diskutiert.

МАКСИМАЛЬНЫЕ И МИНИМАЛЬНЫЕ ЗНАЧЕНИЯ КОЛИЧЕСТВА ТЕПЛА Q, ПЕРЕДАВАЕМОГО ОТ МЕТАЛЛА К КИПЯЩЕЙ ВОДЕ ПРИ АТМОСФЕРНОМ ДАВЛЕНИИ

Аннотация—Количество тепла, передаваемого от металлической поверхности к кипящей воде, увеличивается по мере увеличения разности температур ΔT, но после достижения этой разностью некоторого предельного значения количество тепла Q с дальнейшим ростом ΔT уменьшается. В этой точке величина передаваемого теплового потока максимальна. Существование такой точки действительно наблюдалось в эксперименте. При атмосферном давлении величина ΔT, соответствующая максимальному значению передаваемого количества тепла для воды при 100°C, лежит в пределах 20–40°C при Q, равном 1 080 000–1 800 000 ккал/м^{2}час или 2000–3000 кг/м^{2}час, если выразить через постоянную скорость испарения при 100°C. Это значение выше максимального значения теплового потока, полученного ранее. Кроме того, рассчитано и минимальное значение теплового потока. Обсуждается участок кризиса кипения на кривой Q–ΔT в высокотемпературной области.