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CONVECTIVE HEAT TRANSFER IN WEAK ELECTROLYTES UNDER THE ACTION OF ELECTROLYTIC CURRENTS

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Abstract—Electrolytic currents are produced in a weak electrolyte giving rise to the generation of bubbles, the variation in the rate of heat transfer from a heated platinum wire to the surrounding electrolyte under the action of these currents has been studied. The enhancement of heat transfer with increase in the temperature difference ($\Delta\theta$) between the heating surface and the surrounding electrolyte and with increasing bath temperatures has been graphically exhibited. It is found that whereas a single maximum is obtained in the (h/h_0) versus log I graphs for different values of $\Delta\theta$ at lower electrolyte temperatures (h and h_0 are the heat-transfer coefficients in the presence and absence of electrolytic currents respectively and I is the strength of the electrolytic current), there appear two maxima for (h/h_0) when the electrolyte temperature is raised sufficiently above the room temperature (>45°C in the present experiments). An attempt has been made to investigate the nature of these maxima and to offer a suitable explanation for them.

NOMENCLATURE

A,	heat-transfer area [cm^2];
h,	heat-transfer coefficient in the presence of electrolytic currents $= q/A\Delta\theta$ [cal/sec cm^2 degC];
h_0,	heat-transfer coefficient in the absence of electrolytic currents, i.e. value of h when electrolytic current is zero [cal/sec cm^2 degC];
$\Delta\theta$,	excess of temperature of the heated surface above that of the surrounding liquid [degC];
θ_w	initial temperature of the electrolyte (bath) [°C];
I,	electrolytic current [mA];
I_c,	critical or optimum value of electrolytic current corresponding to the maximum $h_{\max}$ [mA];
(i_c/A),	optimum electrolytic current per unit area [A/cm^2];
(q/A),	heat flux [cal/sec cm^2].

INTRODUCTION

THE RÔLE of electrolytic currents in the variation of heat transfer in weak electrolytes has been the subject of intensive study during recent years [1, 2, 3, 4]. Mixon, Chon and Beatty [1] have investigated the influence of electrolytic bubble evolution on heat transfer and have concluded that there is a slight but inconclusive evidence than an increase in the ionic (electrolytic) current lowers the attainable heat flux at constant $\Delta\theta$ in the high ionic current region under surface boiling conditions. Bhand, Gaur and Gogate [2] have studied the effect of electrolytic currents on heat transfer in weak electrolytes and have found that there is an optimum value of I (the strength of the electrolytic current) for which the heat-transfer coefficient h becomes maximum. They have also found that the enhancement of heat transfer becomes greater when the temperature difference $\Delta\theta$ between the heating surface and the surrounding electrolyte is increased.

In a preliminary note Bhand, Patgaonkar and Gogate [3] have reported the appearance of two maxima for the value of the heat-transfer coefficient h when the temperature of the electrolyte exceeds a certain value higher than the room temperature.

We have recently investigated (a) the variation of h over a wide range of the electrolyte

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temperatures viz: from 2°C to about 77°C and (b) the phenomenon of two maxima for h for different values of the temperature difference $\Delta\theta$ between the heating surface and the surrounding liquid. The object of this paper is to give an account of these investigations and of some interesting results obtained therefrom.

EXPERIMENTAL PROCEDURE

The experimental set up was the same as that used by Bhand, Patgaonkar and Gogate [3] with a slight modification. A thin platinum wire about 0·1 mm in diameter and 10 cm long was stretched horizontally along the axis of a hollow metal cylinder open at both ends (dia. 6 cm), the cylinder was slotted along its length so that the bubbles formed at various points on the wire could escape outside and the whole system was kept immersed in a glass vessel containing a weak electrolyte, for example water mixed with a few drops of dilute sulphuric acid or a dilute solution of calcium bicarbonate. A small current of a few milliamperes was passed through the wire so as to produce a temperature difference between it and the surrounding liquid. An accurate measurement of the current flowing through the wire gave the power input while a knowledge of its resistance was used for determining its mean temperature. Under equilibrium conditions the heat input to the wire becomes identical to the heat transfer from the wire to the surrounding liquid.

A potential difference of a few volts is now established between the wire (as anode) and the metal cylinder so that electrolytic currents are generated in the liquid (electrolyte) and bubbles are formed at various points on the wire due to evolution of gas in the process of electrolysis. This causes changes in the attainable heat flux q/A for a given $\Delta\theta$ (q = heat input and A = surface area of the wire) and gives rise to variation in the value of the heat-transfer coefficient h, which is defined as the ratio of the heat flux q/A to the difference of temperature $\Delta\theta$ between the wire and the surrounding liquid. This variation of h has been determined for different values of the electrolytic current I obtained by subjecting the system to different electrical potentials.

In the above experiments the temperature of the liquid (electrolyte) surrounding the wire was kept almost equal to the room temperature. Experiments for studying the variation of h with I for a fixed value of $\Delta\theta$ were then conducted maintaining the electrolyte at various temperatures, lower as well as higher than the room temperature, so as to examine the variation of $h_{\max}$ with the temperature of the liquid bath.

RESULTS

The values of (h/h_0)* (h_0 is the value of the heat-transfer coefficient h in the absence of electrolytic current) for different strengths of the electrolytic current I for a fixed value of $\Delta\theta$ were calculated and it was found that (h/h_0) goes on increasing with I in the low electrolytic current region.

It was also observed that for bath temperatures below about 45°C, the plots of (h/h_0) against log I give a maximum value of (h/h_0) for some critical (optimum) value of the ionic current I_c as can be seen from the graphs in Fig. 1. The curve A in this figure represents the variation of h with ionic current I when the initial temperature of the liquid bath was 2°C and the temperature difference $\Delta\theta$ between the heated wire and the surrounding bath was 6·1°C. The curves B, C, D and E depict the variations of h with I corresponding to the initial† liquid temperatures 15, 24, 32 and 45°C, respectively maintaining the same value of $\Delta\theta$ viz 6·1 degC. Figure 2 gives similar curves showing the variation of h with the ionic current I for the same bath temperatures as in Fig. 1 but with the value of $\Delta\theta = 10{\cdot}5$ degC. All the graphs in Figs. 1 and 2 indicate an increase in the value of $(h/h_0)_{\max}$ with increasing values of the initial bath temperature θ_w. Again the optimum value of the ionic current I_c generally shows a slight increase with

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* It is found more convenient to use the ratio (h/h_0) than h alone, while considering the variation of heat transfer with ionic current because, though the values of h may vary for different sets of observations under different conditions of temperature, pressure, etc., the value of (h/h_0) remains sufficiently consistent and uniform.

† The total variation in the bath temperature throughout a test does not exceed 0·5°C.

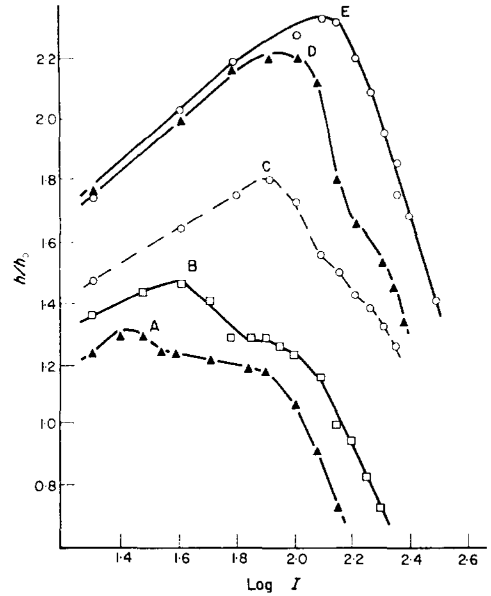

FIG. 1. Plot of (h/h_0) vs. log I showing enhancement of heat transfer with increasing bath temperatures (θ_w below about 45°C) and occurrence of single maximum for (h/h_0), when temperature difference $\Delta\theta = 6{\cdot}1$ degC.

Curve	Initial bath temperature θ_w (°C)	Curve	Initial bath temperature θ_w (°C)
A	2	D	33
B	15	E	45
C	24		

increasing bath temperature. Both these facts are clearly brought out in Table 1.

Figures 3, 4 and 5 demonstrate the general trend of the variation of h with I when the initial temperature of the liquid bath surrounding the wire is above 45°C. The curves in Fig. 3 represent the variation of h with the electrolytic current I, at different temperatures of the liquid bath when $\Delta\theta$ is maintained at a fixed value of 6·1 degC. The graphs in Figs. 4 and 5 depict the variation of h with I for values of $\Delta\theta$ equal to 10·5 and 14·1 degC respectively. A comparison of the graphs in Figs. 3, 4 and 5 with those in Figs. 1 and 2 clearly shows that though the value of (h/h_0) generally goes on increasing with increasing values of electrolytic current I before attaining a maximum and then goes on decreasing in all these graphs, (h/h_0) shows two maxima in Figs. 3, 4 and 5 while it has only one in Figs. 1 and 2. This means that (h/h_0) has only one

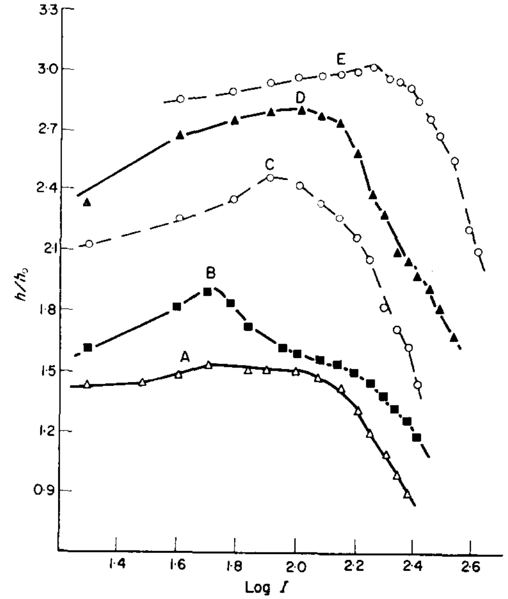

FIG. 2. Single maximum for (h/h_0) with bath temperatures below about 45°C and $\Delta\theta = 10{\cdot}5$ degC.

Curve	Initial bath temperature θ_w (°C)	Curve	Initial bath temperature θ_w (°C)
A	2	D	33
B	15	E	45
C	24		

Table 1. *Values of* $(h/h_0)_{\max}$ *and critical ionic current* I_c *corresponding to the single maximum* (*Figs.* 1 *and* 2) *observed at bath temperatures below* (*about*) 45°C

Platinum wire dia. = 0·01 cm; length = 8·6 cm

Initial bath temperature θ_w	$\log_{10} I_c$	(i_c/A) (A/cm^2)	$(h/h_0)_{\max}$	$h_{\max}$ (cal/sec cm^2 degC)
Temperature difference $\Delta\theta = 6{\cdot}1$ degC				
2	1·43	0·10	1·31	0·167
15	1·60	0·15	1·46	0·224
24	1·88	0·28	1·81	0·288
33	1·94	0·32	2·24	0·375
45	2·20	0·59	2·33	0·446
Temperature difference $\Delta\theta = 10{\cdot}5$ degC				
2	1·70	0·18	1·54	0·206
15	1·73	0·20	1·91	0·243
24	1·92	0·31	2·46	0·352
33	2·00	0·37	2·81	0·463
45	2·25	0·66	3·00	0·561

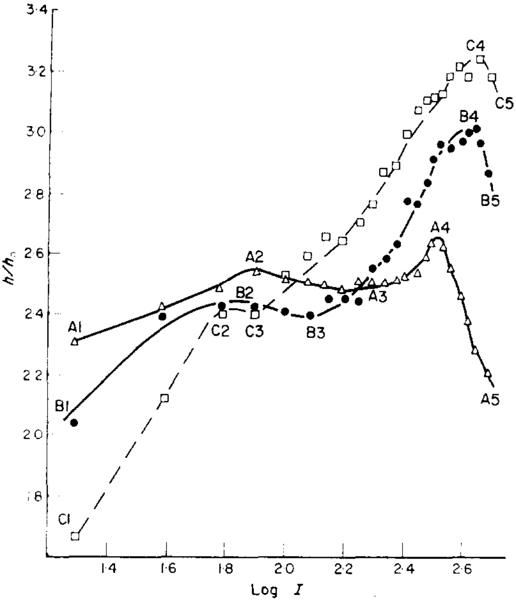

FIG. 3. Plot of (h/h_0) vs. log I showing two maxima for (h/h_0) with bath temperatures above 45°C and $\Delta\theta = 6{\cdot}1$ degC.

Curve	Initial bath temperature θ_w (°C)
A	57
B	66
C	77

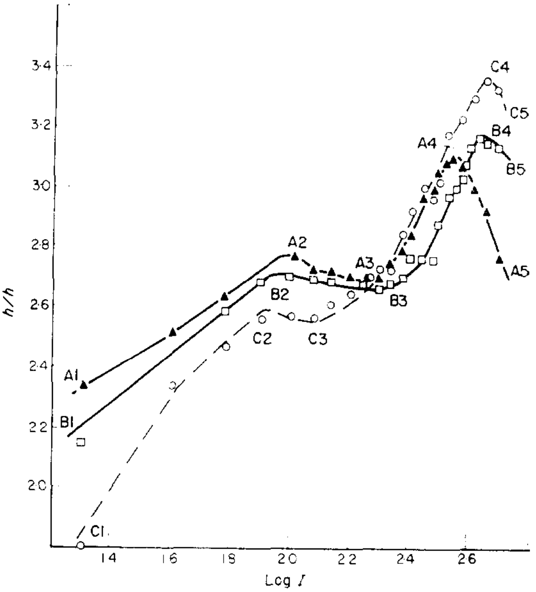

FIG. 4. Two maxima for (h/h_0) with bath temperature above 45°C and $\Delta\theta = 10{\cdot}5$ degC.

Curve	Initial bath temperature θ_w (°C)
A	47
B	57
C	66

maximum when the bath temperature θ_w is below about 45°C and it shows two maxima for values of (h/h_0), above 45°C. In the case of the first maximum for (h/h_0), it is found that the peak value of (h/h_0), i.e. $(h/h_0)_{\max}$ and the optimum value I_c of electrolytic current, for which h/h_0 becomes maximum both these go on decreasing with increasing bath temperature θ_w. On the other hand, in the case of the second maximum for (h/h_0), the peak value of (h/h_0) and the optimum value of I for this peak, both go on increasing with increase in the bath temperature θ_w. These facts can be clearly seen from Tables 2 and 3.

DISCUSSION

That the enchancement of heat transfer produced by the generation of bubbles depends upon the number of active nuclei or the number of bubbles is now an established fact supported by several observations [5, 6]. Accordingly when the electrolytic current is increased for a given value of $\Delta\theta$ there is an increase in the evolution of gas in the form of bubbles which causes the enhancement of heat transfer thus increasing the value of h. This process goes on for some time until the density of bubbles becomes so great that there is a tendency for the formation of a continuous gas film along the length of the heating surface. At this critical value of the electrolytic current, I_c, the value of h becomes a maximum and the process of convection though still going on is accompanied by conduction which possibly takes place over a larger area than convection. The film acts as a barrier in which heat transfer goes on by convection as well as conduction. This gives rise to a lowering of the value of h beyond a certain critical value of I and thus a maximum is obtained for (h/h_0) for this optimum value of I.

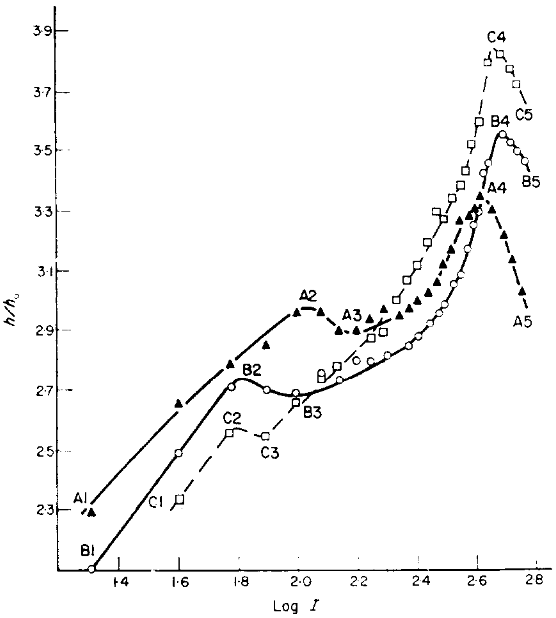

FIG. 5. Two maxima for (h/h_0) with bath temperatures above 45°C and $\Delta\theta = 14{\cdot}1$ degC.

Curve	Initial bath temperature θ_w (°C)
A	47
B	58
C	68

In this way the single maximum for (h/h_0) can be accounted for so long as the temperature of the surrounding liquid (bath temperature) is below about 45°C.

It may be noted here that a somewhat similar maximum for h has been reported by Sims, Aktürk and Evans-Lutterrodt [7] in the case of simulated nucleate pool boiling at saturated temperature by gas injection through a heated porous surface though the value of critical gas injection velocity V'_{cr} used by them was much higher than that of the critical velocity of gas liberated corresponding to the maximum value of the electrolytic current used in our experiments. This maximum for h was found in plots of h versus V' where V' represents superficial gas injection velocity [8].

At higher bath temperatures (<45°C) the surface tension of the liquid would be low and the size of the bubbles becomes smaller. This will

Table 2. *Values of* $(h/h_0)_{max}$ *and critical electrolytic current* I_c *corresponding to the first maximum out of the two maxima observed* (*Figs.* 3, 4 *and* 5) *at bath temperatures above* (*about*) 45°C

Platinum wire dia. = 0·01 cm; length = 8·9 cm

Initial bath temperature θ_w (°C)	$\log_{10} I_c$	(i_c/A) (A/cm²)	$(h/h_0)_{max}$	h_{max} (cal/sec cm² degC)
Temperature difference $\Delta\theta = 6{\cdot}1$ degC				
57	1·90	0·29	2·55	0·791
66	1·85	0·26	2·44	0·807
77	1·80	0·23	2·42	0·831
Temperature difference $\Delta\theta = 10{\cdot}5$ degC				
47	2·00	0·36	2·77	0·799
57	1·96	0·33	2·72	0·855
66	1·91	0·29	2·58	0·899
Temperature difference $\Delta\theta = 41{\cdot}1$ degC				
47	2·03	0·39	2·97	0·831
58	1·82	0·24	2·74	0·874
68	1·79	0·22	2·58	0·905

Table 3. *Values of* $(h/h_0)_{max}$ *and critical electrolytic current* I_c *corresponding to the second maximum out of the two maxima observed* (*Figs.* 3, 4 *and* 5) *at bath temperatures above* (*about*) 45°C

Platinum wire dia. = 0·01 cm; length = 8·9 cm

Initial bath temperature θ_w (°C)	$\log_{10} I_c$	(i_c/A) (A/cm²)	$(h/h_0)_{max}$	h_{max} (cal/sec cm² degC)
Temperature difference $\Delta\theta = 6{\cdot}1$ degC				
57	2·51	1·17	2·64	0·819
66	2·60	1·44	3·02	0·999
77	2·65	1·62	3·24	1·139
Temperature difference $\Delta\theta = 10{\cdot}5$ degC				
47	2·55	1·28	3·09	0·891
57	2·64	1·58	3·16	0·994
66	2·68	1·73	3·36	1·171
Temperature difference $\Delta\theta = 14{\cdot}1$ degC				
47	2·62	1·51	3·34	0·934
58	2·68	1·73	3·54	1·129
68	2·70	1·82	3·83	1·820

give rise to the production of a larger number of bubbles and hence more nucleation sites for a given volume of the gas liberated under the electrolytic action. The higher temperature of the bath also causes a greater evaporation of the liquid into the bubbles. Thus the two effects of higher bath temperatures, namely, the lowering of surface tension and the increased evaporation of the liquid into the bubbles lead to high heat fluxes by augmenting the bubble formation.

When the temperature of the liquid is further increased (>45°C), the evaporation of the surrounding liquid into bubbles becomes predominant and in the low ionic current region when the number of nucleation sites is sufficient, a thin film of vapour begins to form, along the length of the wire. This may result in the lowering of h in the low ionic (electrolytic) current region after the first maximum of (h/h_0) is reached, at the points A_2, B_2 and C_2 in Figs. 3, 4 and 5.

At a still higher bath-temperature, due to increased evaporation, lesser value of the ionic current would suffice to bring about the formation of the thin vapour film and this may account for the decrease in (1) Optimum value of electrolytic current I_c and (2) $(h/h_0)_{\max}$ corresponding to the first peak in Figs. 3, 4 and 5.

An increase in the strength of electrolytic current causes greater agitation of the vapour film which gets more and more rarefied and then disappears. This naturally brings about some enhancement in the heat flux and increases the value of h with increasing I. This process goes on until the great volume of gas liberated causes almost the whole length of the wire to be covered by a gas film which tends to decrease the heat flux and hence the value of h the phenomenon of heat transfer now occurring mostly by conduction through the film, convection becoming almost negligible at this stage. This appears to be the main reason for the appearance of the second maximum of (h/h_0) at the points A_4, B_4 and C_4 in Figs. 3, 4 and 5.

A possible explanation for the maximum might be that the kinetic energy of the evolved gas is so small that it can be neglected leaving only the buoyancy forces to remove the gas from the surface. Thus the size of the bubbles leaving the surface is independent of the rate of gas evolution (it depends upon the buoyant and surface tension forces only) and blanketing occurs when the bubble site density is large enough for neighbouring bubbles to coalesce while still attached to the wire.

It thus appears reasonable to suppose that the first maximum in the (h/h_0) versus log I curve is due mainly to the evaporation of the liquid while the second maximum owes its origin to the great volume of the gas evolved under the action of electrolytic currents.

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Résumé—Des courants d'électrolyse sont produits dans un électrolyte faible en donnant naissance à des bulles, la variation de vitesse de transport de chaleur à partir d'un fil de platine chauffé à l'électrolyte environment sous l'action de ces courants a été étudiée. L'augmentation du transport de chaleur avec celle de la différence de température ($\Delta\theta$) entre la surface chauffante et l'électrolyte environnant et avec l'augmentation des températures du réservoir a été montrée graphiquement. On trouve que tandis qu'on obtient un seul maximum pour la courbe représentant h/h_0 en fonction de log I pour différentes valeurs de $\Delta\theta$ à de faibles températures de l'électrolyte (h et h_0 sont les coefficients de transport de chaleur respectivement en presence te sans les courants d'électrolyse et I est l'intensité du courant d'électrolyse), il apparaît deux maximums pour (h/h_0) lorsque la température de l'électrolyte est augmentée suffisamment au-dessus de la température ambiante (>45°C dans les expériences actuelles). On a essayé de rechercher la nature de ces maximums et d'un offrir une explication convenable.

Zusammenfassung—In einem schwachen Elektrolyten werden elektrolytische Ströme erzeugt, die das Entstehen von Blasen verursachen. Die Änderung des Wärmeüberganges von einem beheizten Platindraht an den umgebenden Elektrolyten, in dem diese Ströme wirken, wurde untersucht. Das Ansteigen des Wärmeüberganges bei wachsender Temperaturdifferenz $\Delta\theta$ zwischen der Heizfläche und dem Elektrolyten und bei ansteigender Badtemperatur wurde graphisch erfasst. Es zeigte sich, dass man für verschiedene Werte von $\Delta\theta$ bei niedriger Elektrolytentemperatur ein einziges Maximum im (h/h_0)—I Diagramm erhält, (h und h_0 sind die Wärmeübergangszahlen bei fliessendem bzw. nicht fliessendem Strom im Elektrolyten und I ist die Stärke dieses Stromes), wohingegen bei gegenüber der Raumtemperatur genügend hoher Temperatur des Elektrolyten (bei diesen Versuchen >45°C) zwei Maxima für (h/h_0) auftreten. Es wurde versucht, die Natur dieser Maxima zu untersuchen und eine zutreffende Erklärung dafür vorzubringen.

Аннотация—Токи, создаваемые в слабом электролите, вызывают образование пузырьков. Изучалось изменение скорости переноса тепла от нагретой платиновой проволоки к окружающему электролиту под действием этих токов. Графически представлено усиление теплопереноса с ростом разности температур ($\Delta\theta$) между поверхностью нагрева и окружающим электролитом, а также с ростом температуры ванны. Установлено, что при низких температурах электролита имеется единственный максимум на графике зависимости (h/h_0) от log I для различных значений $\Delta\theta$ (h и h_0-коэффициенты теплопереноса при наличии и отсутствии электролитических токов соответственно, а I-сила электролитического тока), а когда температура электролита значительно превышает комнатную (в данном эксперименте >45°C) для значений (h/h_0), появляется два максимума. Сделана попытка изучить природу этих максимумов и дать соответствующее объяснение.