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Mechanism of condensation heat transfer enhancement in an electric field and the role of capillary processes

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Abstract—The paper presents experimental results on condensation heat transfer enhancement in the presence of an electric field and a study of the state of equilibrium of a two-phase system with various shapes of interface. It has been shown experimentally that enhancement of the condensation process in an electric field is caused by interface deformation and by the associated effect of phase equilibrium displacement, which in the case of interface deformation is the driving force of capillary processes; the considered cooling effect has been used as an example.

1. INTRODUCTION

The effect of electric fields on the intensity of heat and mass transfer processes in phase conversions has been the object of growing attention of research and practical workers owing to its high efficiency, rapid response and ease of control. Apparently, Velkoff and Miller [1] were among the first to show experimentally the possibility of a 5–7-fold increase in the condensation heat transfer enhancement with extremely small power expenditures and, based on the analysis of the material obtained, to point out the possible causes of the mechanism behind the field effects. By this time, a comparatively large volume of experimental evidence has been accumulated on the effect of electric fields on the processes in phase conversions which allows the present method of intensification to be considered as being the most efficient.

Thus, the investigations reported in ref. [2] have demonstrated the possibility of attaining a 10–20-fold increase in the condensation rate of Freon-113, *n*-hexane and diethyl ether. If it is remembered that the use of an electric field allows for a simple control of the process, the technical value of the method is indisputable.

Even so, investigations and practical applications in the field are as yet far from being completed, bearing in mind that the existing generalizations are of an exploratory nature and the familiar simulations are not devoid of substantial conventions.

Beginning with the work of Choi [3], model concepts rested upon the classical Nusselt-model modification with attempts to coordinate the observed enhancement with the electrostatic disturbance of the film surface. At the same time the film disturbance was considered only in relation to the stability problem for the surface exposed to the destabilizing effect of the field, and the stabilizing effect of the surface tension in conjunction with other forces. Reference [4] illustrates this approach in the most complete form.

In addition to the problem of electrostatic stability of the film, mention should be made of another aspect associated with the modification of the hydrodynamic part of the Nusselt model. Neglecting the effect of surface tension, Joos and Shaddon [5] introduced into the model an additional velocity vector caused by the jump in the external electric-field strength near the film surface. It is exactly this fact that, in their opinion, can make an important contribution to the effect of enhancement.

All the same, the satisfactory agreement achieved between each model and experiment cannot be thought of as favourable, since no asymptotic correspondence has been attained as yet between separate approaches, indicating in turn the incompleteness of our knowledge about the physical aspects of the phenomenon.

It is worth noting here one of the latest works of Cooper and Allen [6], in which the authors turned their attention again to the problem of the effect exerted by electric fields on the process of condensation.

Comparison of several heat transfer enhancement techniques was made, including those with electric fields, in regard to heat pipes and their effect on the film surface.

The efforts to obtain some complete physical idea about the mechanisms involved in the intensification of the processes under the effect of an electric field culminated at the beginning of the 1980s in the opening up of a new approach which, in contrast to the existing models, is based on the thermodynamic analysis of the effect.

The fact that the film surface or the interface possess some energy and thereby can affect the state of the

NOMENCLATURE

E	field strength [kV cm^{-1}]
p	pressure [Pa]
q	heat flux density [W m^{-2}]
r	heat of phase transition [J kg^{-1}]
R	individual gas constant [J kg^{-1} $^{\circ}\text{C}^{-1}$]
t, Δt	temperature on empirical scale and temperature difference, respectively [°C]
T	absolute temperature.

Greek symbols

α	heat transfer coefficient [W m^{-2} $^{\circ}\text{C}^{-1}$]
γ	surface change [C m^{-2}]
$\rho = l/V$	density [kg m^{-3}]
σ	surface tension [J m^{-2}]
τ	radius of surface curvature
φ	electric potential [V].

Subscripts

c	capillary
E	in the field
l	according to Labuntsov
L	liquid
Nu	according to Nusselt
o	initial
v	vapour
w	wall.

vapour and condensed phases is known from the analysis of the Laplace and Thomson equations. However, so far preliminary estimates on the basis of these equations have not offered encouragement for the hope of revealing any noticeable contribution of the surface to the state of the two-phase system.

Another reason which prevents the thermodynamic analysis of surface phenomena resides in the fact that, for the time being, no relationship has been established between the interface characteristics and the properties of the vapour and condensed phases, thereby making it difficult to apply the classical thermodynamic models to the analysis of surface phenomena. An attempt at analyzing the possible effect of phase-equilibrium displacement neglecting the role of surface effects, made in ref. [7], results in the conclusion about the influence of the external electric field on the intermolecular interaction, which contradicts the inferences of the molecular-kinetic theory.

A direct consequence of the Thomson equation

$$\Delta T = \frac{2\sigma T}{\rho_{\mathrm{L}} r \tau} \quad P = \text{constant} \tag{1}$$

is the fact that deformation of the interface from the flat shape (at $\tau = \infty$) to any finite curvature leads to a change in temperature. It is precisely this fact which was investigated in the experiments in ref. [8] as a result of which, using the infrared imaging thermography, the appearance of non-isothermicity was discovered along the interface deformed by electric field. The detected temperature difference turned out to be of the order of degrees and greatly exceeded the predictions of equation (1). In calculations, no provision was made for the fact that the surface tension σ in the electric field decreases according to the Laplace–Gibbs law

$$\left[\frac{\partial \sigma}{\partial \varphi}\right]_{P,T} = -\gamma. \tag{2}$$

The experiments also allowed a conclusion that the temperature gradient originating along the deformed interface generates an additional heat flux also directed along the interface, but in the opposite direction.

The point of view set forth provides good reasons to consider the effect of heat transfer enhancement in phase conversions as a consequence of the interface deformation, generating the origination of an additional heat flux of a capillary nature.

2. EXPERIMENTAL FACILITY

The experiments performed had a twofold purpose. First, it was intended to demonstrate experimentally that the phenomenon of intensification could be observed every time the interface shape varied. In other words, the interpretation of the enhancement effect from the viewpoint of capillary nature affords the possibility to consider any intensification proceeding from more general positions. Second, it was intended to show that basic to the capillary analogy of the enhancement effects is the phenomenon of the change in the conditions of the two-phase system equilibrium caused by the change in the interface shape. The formulated problems specified the choice of experimental facilities.

The experiments were carried out using a set-up the schematic diagram of which is shown in Fig. 1. The working liquid was heated to boiling in an evaporator (1) and placed in a water bath (2) with electric heaters (3). Through a vapour pipeline (4) the vapour was introduced into a condenser (5) where it condensed on a heat transfer surface (6) made from a copper plate of dimensions 120 mm × 220 mm cooled by water from the thermostat recirculation loop (7). The use of a thermostat makes it possible to provide a constant flow rate, thereby decreasing the pulsations of the heat flux and wall temperature and minimizing the error of measurements.

The condensate then returned to the evaporator (1)

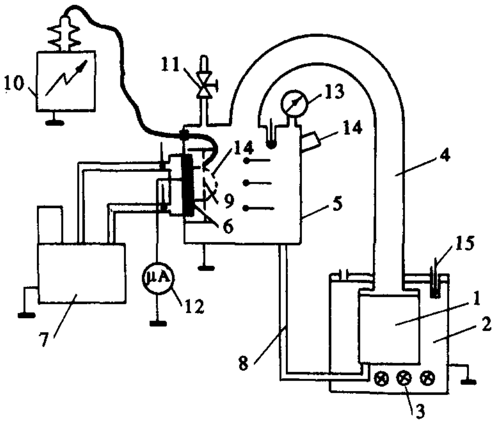
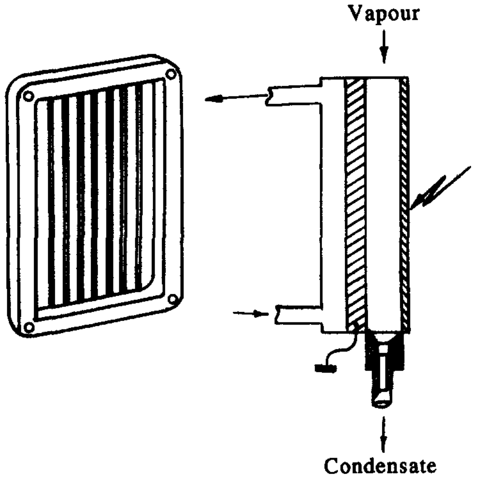


Fig. 1. Schematic diagram of the experimental set-up.



(a) (b)

Fig. 2. Layout of nozzles on the condensation surface: (a) with capillary deformers; (b) calorimeter.

through the main (8), thereby ensuring continuous operation of the set-up. An electric field was applied in the gap between the grounded condensation surface (6) and a high-voltage electrode (9) connected to a controllable high-voltage source (10). The condenser design provides for the possible replacement of electrodes, variation of the interelectrode gap, and also installation on the condensation surface of extra units such as a condensate tank and a nozzle with capillary deformers. Air was removed through a valve (11), and the current in the circuit of the grounded condensation surface was controlled by a microammeter (12). The vapour pressure in the condenser was indicated by a standard manometer (13). To observe the process visually, the condenser was fitted with viewing windows (14).

In the process of the experiments, the condensation surface temperature was measured by a resistance thermometer, the vapour temperature by copper–constantan thermocouples (15), the temperature difference between the cooling water at the inlet and exit of the condensation surface by a differential thermocouple, and the voltage at the high-voltage electrode by the leakage current.

Figure 2 presents two extra units mounted on the condensation surface (6). The unit shown in Fig. 2(a) is a nozzle with capillary deformers; it includes a frame securing a set of wires 0.1 mm in diameter made from copper or lavsan. The choice of the material for the deformers was dictated by the necessity to analyse the role of the intrinsic thermal conductivity of the deformer material. The step between separate wires was selected so as to ensure the similarity between the deformed interfaces obtained in the present case and at field strengths of 50–60 kV cm^{-1}. In Fig. 2(b) a calorimeter nozzle is depicted involving a condensate tank that ensures the set-up operation in the continuous-flow calorimeter regime. The nozzle consists of a Π-like frame made from Teflon pressed against the condensate surface along the contour with the aid of the solid high-voltage electrode. At the lower part of the frame the condensate tank is located which collects condensate for measuring the flow rate.

Unfortunately, the second part of the task posed in the work could not be attained using the set-up described above, since in the real condensation process the effect of the capillary displacement of equilibrium manifests itself indirectly whereas the attainment of the equilibrium *per se* is rather problematic. For this reason an additional cell was used the diagram of which is presented in Fig. 3. The cell is made from rigid-vinyl plastic in the form of a cylinder (4). The cylinder houses a high-voltage (1) and a grounded (2) plate. The grounded copper plate was inserted into the container wall and one of the layers of the differential thermocouple (3) was fixed to its outer side.

An identical copper plate was also mounted at the other part of the container and also served to fix a thermocouple. The inner space of the container was filled with 50–70 ml of Freon-113, and, after air evacuation, it was hermetically sealed.

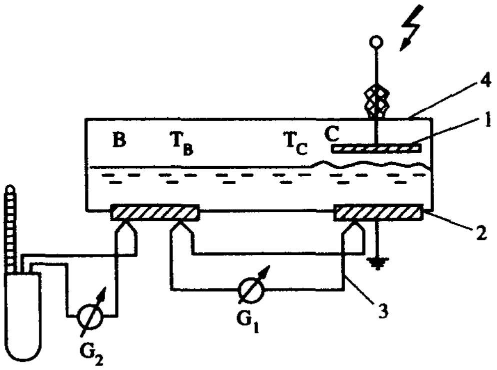


Fig. 3. Diagram of a capillary cell for studying the effect of phase equilibrium displacement.

The temperature measurement system is constructed on the basis of differential thermocouple sensitive elements (data units) and consists of two circuits: a circuit for determining the temperature difference between the B and C cell-ends registered by the device C, and a circuit for determining the temperature of the cell-end B by means of the device C; in the experiments self-balancing recording potentiometers were applied.

Calibration of the thermocouples and gauging of the measuring system guarantee temperature measurements in the range from 20 to 10°C within ±0.05°C, which is prerequisite for the experiments described.

3. EXPERIMENTAL RESULTS

In order to determine more accurately the overall error of the experimental data and thereby to determine the reliability of the procedure adopted, a series of control experiments was carried out. Particular attention was given to the elucidation of the degree of the complementary error introduced by special nozzles mounted on the condensation surface. The control results obtained were compared with the data determined from both the Nusselt equation and Labuntsov correlation, i.e. taking account of the corrections for the change in the thermophysical properties over the film profile and also for the wave formation on its surface. The results of this series of experiments are presented in Fig. 4. Note that with the use of the calorimeter nozzle [Fig. 2(b)], the heat flux was determined in two ways: from the amount of heat removed by the cooling water through the condensation surface (6) (Fig. 1) and from the amount of condensate collected. The results of these measurements are shown in Fig. 5 taken together and separately for the Nusselt and Labuntsov correlations; the experimental error did not exceed 20%. The error of the calorimetric technique of determining the phase transition heat of the given material in comparison with its tabulated value amounted to ±3%. The experiments were carried out in succession in such a manner that the condensate film surface was first disturbed by the electric field, and then by the nozzle with capillary deformers. The configuration of the capillary deformers was selected so that the geometries of the film surface disturbed by the field and by the deformers would be similar. The results of this series of experiments are presented in Fig. 5. Line 1 represents the enhancement degree at the field strength of 50 kV cm^{-1}. The other two lines reflect the effect produced by the capillary deformers made from copper (2) and lavsan (3). The basic idea underlying the condensation heat transfer enhancement effect is the change in the geometry (deformation) of the film surface, with the magnitude of the effect being determined by the shape of the film surface obtained.

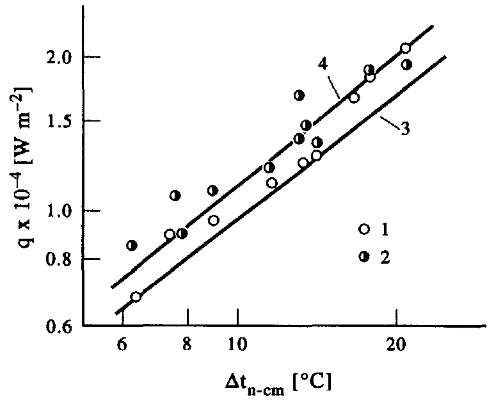


Fig. 4. Results of calibration experiments on determining the heat flux: (1) removed through the surface of condensation; (2) from the amount of the condensate formed; (3) from the Nusselt equation; (4) according to Labuntsov.

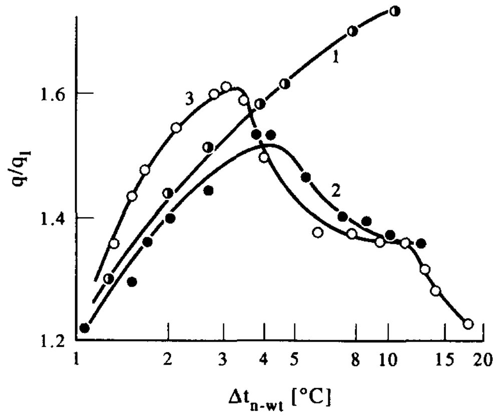


Fig. 5. Dependence of the enhancement degree on the vapour–wall temperature difference in the case of: (1) electric field of the strength of 50–60 kV cm^{-1} and employment of capillary deformers made from copper wire (2) and lavsan (3).

Thus, on exposure of the condensate film to an electric field, the origination of a regular wave structure at the interface was observed to be similar to that described in ref. [2]. The form of the wave structure practically persisted during variation in the mean thickness of the film achieved by changes in the 'vapour–wall' temperature difference.

An exception was the lower side of the condensate film, the thickness of which exceeded the mean value and which was drawn away onto the high-voltage electrode as the vapour–wall temperature difference increased. When capillary deformers were used at small vapour–wall temperature differences, condensation started directly along each of the deformers. As the temperature difference increased, the growth was observed in the regions of liquid near the separate deformers which subsequently merged into a continuous film between two adjacent deformers.

The attainment of this regime corresponds to the highest heat flux density for a given vapour–wall temperature difference (curves 2 and 3 in Fig. 5). In this regime, in spite of the existence of a continuous film,

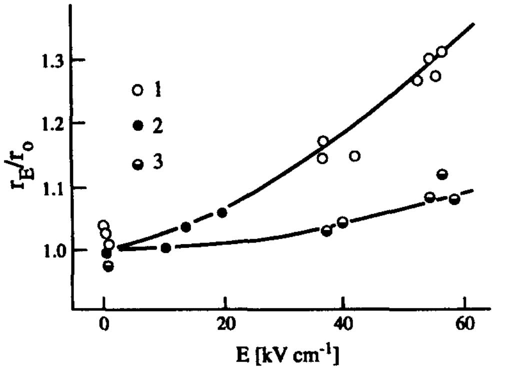


Fig. 6. Dependence of phase transition heat on the field strength determined: (1) calorimetrically in the process of condensation; (2) by the effect of phase equilibrium displacement to the cells of Fig. 3; (3) predicted by equation (3).

the deformers project above the interface, thereby creating a wavy form like the one produced by an electric field. A further increase in the temperature difference results in a gradual flooding of the deformers which begins in the lower part of the condensation surface and then spreads upwards. This process leads to a decrease in the heat flux density as the temperature difference increases, and is attributed to the gradual disappearance of the wave structure.

As the experiment demonstrates, the degree of enhancement attained with the use of capillary deformers has the extreme point when $\Delta t \sim 3$–5°C, after which the effect decreases.

The vapour–wall temperature difference at which the heat flux density attains a maximum value depends on the single deformer diameter. By increasing the latter within the film thickness limits, it is possible to shift the maximum to the region of larger temperature differences.

The experiments performed make it possible to easily show that the enhancement effect observed is associated exactly with the formation of a regular wave structure and exists as long as this structure is maintained. This property of the enhancement effect is called the capillary analogy.

In order to show subsequently that the basis behind the capillary analogy is the change in the two-phase system equilibrium conditions with variation in the system capillary characteristics and thus to achieve the second objective of the present investigation, control over the pressure and phase-transition heat was accomplished in the process of the experiments described above.

The supplementary nozzle on the condensation surface [Fig. 2(b)] made it possible to measure the amount of condensate formed in the condensation process under the effect of an electric field. The data obtained allowed the determination of a certain effective calorimetric heat of phase transition, depending on the applied external field strength (Fig. 6, curve 1). Simultaneously, the effective heat of phase transition was also measured by the change in the vapour pressure using the integral form of the Classius–Clapeyron equation

$$r_E/r_o = 1 + RT_s \ln P_s/P_e \qquad (3)$$

where r_e and r_o are the values of the phase-transition heat with and without the field, and P_s and P_E are the saturated vapour pressures at the temperature T_s in the absence of the field and the vapour pressure in the field of strength E, respectively.

The results of these measurements are presented in Fig. 6 (curve 3). They demonstrate that despite the increase in the heat flux density due to the interface shape modification, this process is not accompanied by an adequate increase in the amount of the condensate. Relation 1 (Fig. 6) shows that with an increase in the field strength the calorimetric heat of phase transition grows and, consequently, when the same amount of condensate forms in the field and in its absence, a larger amount of heat should be removed in the first case.

Another important result of the experiments is that the quantities of the phase transition heat, determined calorimetrically and with the aid of equation (3) from the vapour-pressure data are different, with the former being larger.

Note that the calorimetric phase transition heat is a single characteristic which takes into account not only the change in the state of liquid and vapour in the process of condensation, but also the change in the state of the interface [9]. At the same time, the value of the phase-transition heat determined from equation (3), like the Nusselt model of condensation, neglects capillary effects, reflecting only the thermal effect associated with the transition from the vapour to the liquid state. Therefore, the difference between the calorimetric phase-transition heat and the heat determined from equation (3) gives the value of adsorption heat, i.e. the amount of heat released or absorbed by a two-phase system in the process of transition of one of the phases to the surface layer. The absorption heat is a strictly capillary characteristic of the process, since it is associated with the change in the interface shape. Therefore, in what follows use is made of the term 'Nusselt heat flux' to characterize the heat flux representing only the phase-transition heat, determined in this case with the aid of equation (3), and not accounting for the heat associated with capillary effects. Another definition of heat flux, named henceforth as overall heat flux, is associated with the calorimetric heat of phase transition and is an additive characteristic of the condensation process, representing the sum of the Nusselt flux and of the capillary heat flux, attributable to the heat of adsorption.

Thus, the results of calorimetric measurements presented in Fig. 6 show that the enhancement phenomenon observed in the presence of an electric field is associated with the increase in the capillary heat flux due to a significant increase in the interface area. It is

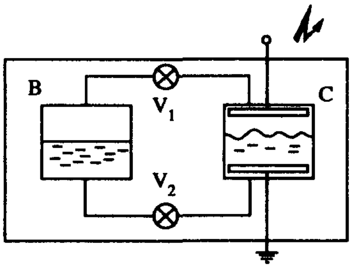


Fig. 7. Diagram on the study of the phase-equilibrium capillary.

obvious that this mechanism is also responsible for the intensification observed with the use of capillary deformers. However, in the electric field the increase in the interface area turns out to be much larger than in the case of employing capillary deformers due to the formation of drops in the interelectrode gap and transfer of a condensate portion to the high-voltage electrode. Therefore, the capillary heat flux turns out to be more noticeable and attains 20–30% as compared to the Nusselt heat flux.

The point of view presented above reflects a new approach to the description of the enhancement effect induced by the interface deformation. Obviously, for this trend to be developed successfully, it is necessary to acquire a better understanding of the physical mechanisms involved in the formation of capillary heat flux. Theoretical and experimental investigations bearing upon this subject are presented in ref. [10]. The studies covered are very extensive and cannot be considered within the scope of the present paper. Therefore, only one of the numerous experiments described in ref. [10] will be resorted to for illustrating the capillary heat flux driving forces. It was carried out with the aid of a cell depicted in Fig. 3. The use of a supplementary cell for detecting a capillary heat flux is quite apparent, since it is very difficult, as shown above, to separate the capillary heat flux from the phase transition-induced heat flux. This fact also specifies the experimental conditions. The diagram presented in Fig. 7 illustrates the idea of the experiment. Enclosed in a quasi-adiabatic thermostat are two cells, B and C, containing liquid and vapour in a state of thermodynamic equilibrium. The difference between these cells is that cell C comprises a system of electrodes, one of which is located in the vapour and the other is immersed in the liquid. The vapour and liquid regions of the cells are connected through valves V_1 and V_2 which are initially closed.

At the start of the experiment there is thermodynamic equilibrium between cells B and C inside the thermostat. After the application of the potential to the electrodes in cell C and origination of wave instability, one should expect a change in the state of the two-phase system. However, the state inside the thermostat remains invariable, since valves V_1 and V_2 are closed.

Suppose the interface deformation in cell C resulted in pressure decrease. Then, after the opening of valve V_1, the same pressure is to be set in cell B. The process of pressure decrease in cell B seems to be possible only due to the evaporation of a portion of the liquid and a decrease in its temperature T_E with respect to the thermostat temperature T_o. Since the opening of valve V_1 will lead to the appearance of a temperature difference between cells B and C, this will give rise to a continuous heat removal from cell C, where the vapour evacuated from cell B will condense.

The process described must continue until all the liquid from cell B is transferred over to cell C, or the electrodes in cell C are flooded. Thus, the system will attain a new state of equilibrium. In order to return the system again to the initial state, it is necessary to open valve V_2. As soon as the liquid is redistributed between cells C and B, the cycle will be repeated.

In contrast to the scheme considered above, the experimental cell depicted in Fig. 3 had no valves V_1 and V_2. This made it possible to observe the cycle continuously as long as there was electric field. On the application of a potential of 6–10 kV to the electrodes, instability of the interface starts, with the current passing through the cell amounting to about 0.5 μA. The origination of the wave instability and the associated effect of the phase-equilibrium capillary displacement resulted in the appearance of a temperature difference between ends E and C of the experimental cell. The temperature-difference behavior is illustrated in Fig. 8. After the switching-on of the field, the temperature of end C of the experimental cell grows fairly quickly and attains a value 0.5°C higher than the ambient temperature. At the same time, the temperature of end E of the cell becomes 0.5°C lower than the ambient temperature. This state of the cell is maintained as long as the field is present. The system rapidly regains equilibrium on the switching-off of the field. Notwithstanding the applied field, the temperature difference disappears in those cases when, as a result of the rotation, both electrodes occur only in the vapour or only in the liquid phase, and the interface is not located in the interelectrode space.

In the process of the experiment, control was made

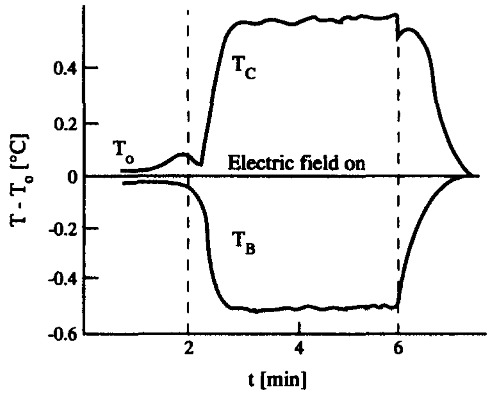


Fig. 8. Dynamics of temperature difference origination in the cell of Fig. 3 at t_o = 20°C.

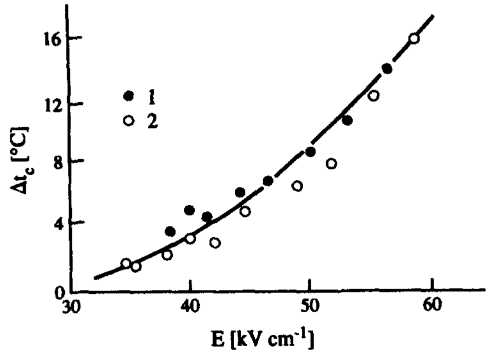


Fig. 9. Dependence of the temperature difference of the phase equilibrium capillary displacement on the field strength at $t_o = 55$°C: (1) experimental observations; (2) according to the data of ref. [2].

over the absolute temperature in the evaporation region of the cell, using which the corresponding value of the phase-transition heat at a given field strength was found with the aid of the tabular interpolation. These results are also presented in Fig. 6 (curve 2) for comparison.

The experiment described allows us to conclude that the driving force of capillary heat flux is the temperature difference between the interface region exposed to deformation and its non-deformed portion. The origination of this temperature difference is caused, in turn, by the change in conditions of phase equilibrium with varying shape of the interface, i.e. by the effect of the phase-equilibrium capillary displacement.

In the process of the experiment, a number of isolating fluids was approbated (*n*-hexane, kerosene, etc.), but the greatest equilibrium displacement was observed for Freon-113, since this fluid has the lowest (among those considered) saturation temperature at atmospheric pressure. The established temperature difference of about 1°C at room temperature turns out to be at least an order of magnitude higher than that predicted by the Thomson formula (1), but appears to be too small to be accounted for in practical computations. Nevertheless, the temperature difference caused by the effect of the phase-equilibrium capillary displacement grows appreciably with the thermostat temperature T_o. The dependence of this temperature difference on the field strength at the temperature $T_o = 323$ K (which corresponds to the saturation temperature at the atmospheric pressure) is presented in Fig. 9. A similar relation can be found directly from the condensation experiments on the set-up depicted in Fig. 1.

Now suppose that in a certain steady-state regime there occurs the process of condensation, and a heat flux of density a is transferred. The application of an electric field will lead to a change in the concentration regime and to an increase in the overall heat flux due to the additional capillary flux.

Hereafter, if in the presence of electric field the heat flux density in the process of condensation is diminished to the value observed in the absence of electric field, then the vapour–wall temperature difference must decrease by a value equal to the temperature difference of the effect of the phase-equilibrium capillary displacement. Using the experimental data of ref. [2] and the method suggested, results were obtained as presented in Fig. 9, which are in satisfactory agreement with the data obtained in our experiments.

Thus, to determine the degree of the condensation process enhancement in the electric field, provided the heat flux density is constant, one can write down:

$$\alpha_E \, \Delta t_E = \alpha_o \, \Delta t_o. \tag{4}$$

In this case, the temperature difference in the field Δt_E will be always smaller than that in the absence of a field Δt_o by a value determined by the effect of the phase equilibrium capillary displacement Δt_c the relation for which is presented in Fig. 9.

$$\Delta t_o = \Delta t_E + \Delta t_c(\mathrm{E}) \quad q = \text{constant}. \tag{5}$$

Then the enhancement degree k from equation (4), with equation (5) taken into account, can be presented in the form:

$$k = \frac{\alpha_E}{\alpha_o} = \frac{1}{1 - \Delta t_c(E)/\Delta t_o}. \tag{6}$$

Henceforth, using the relation for the temperature difference Δt_c, it is possible to find from Fig. 9 the dependence of the enhancement degree on the field strength, which is presented in Fig. 10.

For comparison, this figure also contains a similar relation to that obtained experimentally in ref. [2]. Consequently, these relations are in satisfactory qualitative and quantitative agreement.

In summary, it can be concluded that the enhancement phenomenon observed on exposure to electric field is attributed to the interface deformation. The enhancement can be observed with any deformation of the interface and in this sense this phenomenon possesses an analogy. An increase in the overall heat-flux density is of capillary nature and is attributed to the origination of an additional capillary heat flux

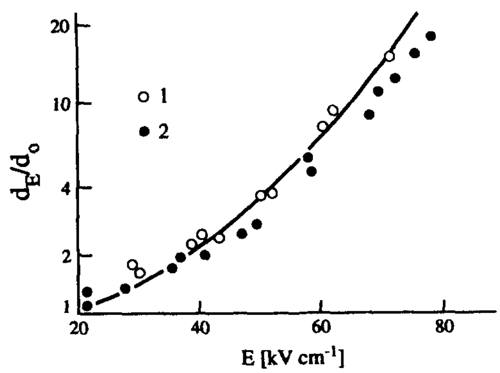


Fig. 10. Dependence of the enhancement degree on the field strength: (1) according to equation (6); (2) according to the data of ref. [2].

simultaneously with the heat flux due to phase transition. If the latter fact is directly associated with the transition of the phase from the rarefied (vapour) to the condensed state, then the heat-flux capillary component is conditioned by phase transition from the rarefied phase to the surface layer and is intended for maintaining the prescribed shape of the interface. Therefore, the phenomenon of enhancement in the case of interface deformation can be considered from the point of view of practical application more as a method for heat transfer at small temperature differences (or, in prospect, as the means for generating refrigerating effect), than as a method for increasing the amount of condensed phase.

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