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VAPOUR FILM CONDENSATION HEAT TRANSFER AND HYDRODYNAMICS UNDER THE INFLUENCE OF AN ELECTRIC FIELD

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Abstract—The paper presents experimental results on heat transfer and hydrodynamics in film condensation of a stagnant pure vapour on vertical short surfaces in an electric field of different strength, frequency and uniformity. A twenty-fold increase in the heat transfer coefficient with negligible power expenditure on setting up an electrostatic field is attained. Enhancement of heat transfer under the electrohydrodynamic effect is shown to be due to reduction of the film thickness caused by condensate spraying into the vapour phase and formation of transverse waves. It is shown that under the action of a constant electric field the film condensation heat transfer obeys the laws that govern laminar film flow. Correlation of the experimental data for different working fluids in the form of similarity relations has been carried out.

NOMENCLATURE

E,	electric field strength [V m^{-1}, kV cm^{-1}];
U,	voltage drop across the electrodes [V, kV];
σ,	specific electrical conductivity of liquid [Sm m^{-1}];
ε,	dielectric permeability of liquid;
ε_0,	8.85×10^{-12} F m^{-1}, electric constant;
τ,	time of electric charge relaxation in liquid dielectric [s];
S,	coefficient of surface tension at the liquid–vapour interface [N m^{-1}];
ρ,	liquid density [kg m^{-3}];
r,	specific heat of phase change [J kg^{-1}];
λ,	thermal conductivity of liquid [W m^{-1} °C^{-1}];
ν,	kinematic viscosity of liquid [m^2 s^{-1}];
g,	free fall acceleration [m s^{-2}];
q,	heat flux density [W m^{-2}];
t,	temperature [°C];
t_{sat},	saturation temperature [°C];
Δt_{v-w},	'vapour–wall' temperature difference [°C];
α,	vapour condensation heat transfer coefficient [W m^{-2} °C^{-1}];
p,	saturation pressure [Pa];
H,	height of condensation surface [m];
h,	electrode gap [m];
F,	electric force [N m^{-3}];
δ,	liquid film thickness [m];
R_t, R_e,	working tube and electrode radii [m];
λ^*,	wave length [m];
ρ_k,	volumetric density of free charges [C m^{-3}].
E,	in the presence of electric field;
0,	in the absence of electric field;

Subscripts

1,	vapour phase;
N,	by Nusselt equation;
cr,	critical value corresponding to the start of the electric field effect on heat transfer.

Note: physical parameters of the liquid and the electric field strength in the liquid phase are given in the text without subscripts.

Similarity numbers

Re,	$\bar{q}H/r\rho\nu$ or $\bar{\alpha}\cdot\Delta t_{v-w}H/r\rho\nu$;
Z,	$(g/\nu^2)^{0.33}\,\lambda\cdot\Delta t_{v-w}H/r\rho\nu$;
V,	$\varepsilon_0\varepsilon_1E_1^2h/S$;
Π,	$\sigma h^2/\varepsilon_0\varepsilon\nu = h^2/\tau\nu$;

Pr is the Prandtl number. Bar over α and q means averaging over the entire heat transfer surface.

1. INTRODUCTION

THE USE of an electric field to control thermal processes offers great challenges in thermal physics and electrohydrodynamics since it allows one to markedly improve heat transfer processes; to alter their parameters along the specified lines; to use the electric forces not only for mixing, but for transportation of the working medium as well. The topicality and practical importance of the problem of vapour film condensation heat transfer increase were time and again emphasized in literature and are quite obvious. The results obtained in the present work make it possible to recommend the use of the electric field attack on a falling condensate film which offers the main thermal resistance to heat transfer from vapour to the cooling medium. This particular method of increase of heat transfer holds the promise for weakly conducting liquids (organic and organosilicon heat agents), which, as compared with water, have low heat transfer coefficients and high electrical resistivity. The said agents are used in radioelectronics, electrical, refrigerating, chemical, petrochemical, chemico-pharmaceutical and heat-and-power engineering. The power expended to set up a constant electric field constitutes fractions of a per cent of the transmitted heat flux which is attributed to a small current (of the order of several microamperes) passing in a high-voltage circuit.

A number of studies are available [1–5] which show that the electric field of different geometry and frequency may provide an effective means for enhancing the vapour film condensation heat transfer; the conditions and the nature of the interface disturbance in the electric field are determined. The investigations were carried out, however, in a narrow range of the process parameters and electrophysical properties of heat agents and no attempt was undertaken to study the hydrodynamic characteristics of film flow in the fields of different strengths. The emphasis was given to such factors as the action of electric forces in the bulk of the film, the presence of ions in the vapour phase, volumetric vapour condensation on a spray of droplets, turbulization of film flow. The explanation of reasons for heat transfer increase under electrohydrodynamic (EHD) effect is hypothetical and is in need of experimental verification. On account of this, investigations have been undertaken to study the behaviour and the mechanism of the EHD effect on heat transfer and hydrodynamics of pure vapour film condensation.

2. EXPERIMENTAL FACILITY

Investigations were carried out on a set-up which is shown as a schematic diagram in Fig. 1. The working liquid was heated to boiling in the evaporator. The vapour, after having passed through a moisture separator and vapour superheater (a superheat of around 1–2 °C), entered condenser (1). The condensation surface (2) was a vertical copper plate 220 mm high and 120 mm wide with a resistance thermometer imbedded in it. The plate was cooled by running water draining down into a metering vessel.

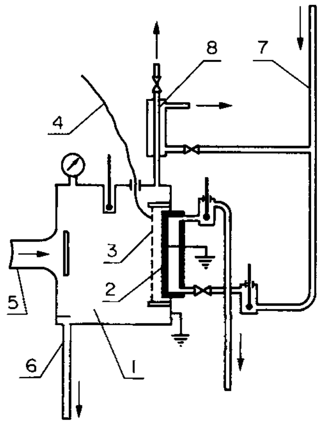

Fig. 1. Schematic diagram of the experimental set-up; 1 condenser; 2 heat transfer surface; 3 high-voltage electrode; 4 cable to the high-voltage source; 5 vapour pipeline from evaporator; 6 condensate pipeline to evaporator; 7 cooling water pipeline; 8 condenser for air blowing.

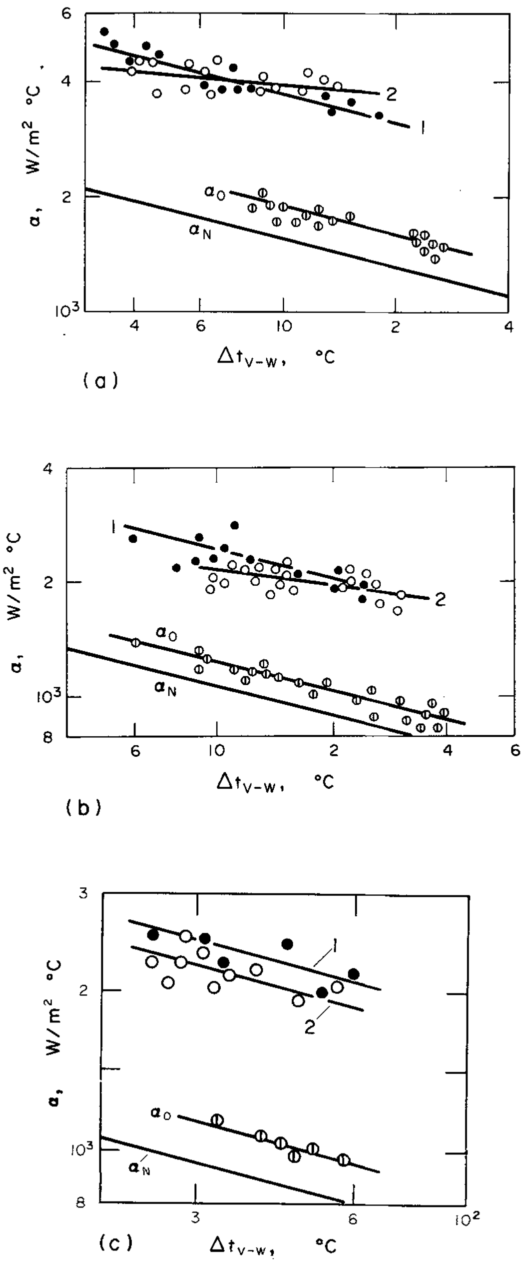

Fig. 2. Dependence of the heat transfer coefficient on the temperature difference and high-voltage applied; horizontally slotted electrode-plate; h = 5 mm: (a) diethyl ether, t_{sat} = 60 °C (p = 233 kPa), voltage 20 kV; (b) Freon-113, t_{sat} = 62 °C (p = 160 kPa), voltage 35 kV; (c) n-hexane, t_{sat} = 110 °C (p = 322 kPa), voltage 35 kV; 1 direct current voltage; 2 alternating current voltage.

The condensate returned to the evaporator thus completing the closed cycle. A transverse electric field was set up in the gap between the grounded condensation surface and a high-voltage electrode (3) connected to a controllable high-voltage source.

The working fluids were non-polar and polar dielectrics which had been selected in order that the EHD effect on condensation could be studied in a wide range of electrophysical properties of heat agents. Thus, the electric conductivity of the working fluids at the temperature of boiling and at atmospheric pressure amounted to 2.2×10^{-13} Sm m^{-1} for *n*-hexane, 2.05×10^{-11} for Freon and 3×10^{-8} Sm m^{-1} for diethyl ether.

3. HEAT TRANSFER RESULTS

It has been established on the basis of the experiments carried out that in the absence of electric field (Fig. 2) the experimental values of the heat transfer coefficients exceed those calculated by the Nusselt equation by 15–20% on the average. Under the action of an electric field the heat transfer rate increases substantially, with the difference between a DC and an AC (50 Hz) field being insignificant. Consequently, the mechanism of interaction (polarizational or chiefly Coulomb one) of the field with the medium is immutable for the given type of a heat agent irrespective of the applied voltage frequency.

A specific feature of heat transfer in the course of vapour condensation on an imperfect dielectric in a variable field of commercial frequency is a departure from the power law $\alpha_E \sim \Delta t_{v-w}^{-0.25}$ observed in the experiments with ether and Freon-113 [Fig. 2(a), (b)]. With increasing voltage, the exponent of Δt_{v-w} decreases in absolute magnitude. Among other possible reasons, this departure should be attributed to warming of the film due to dielectric losses at comparatively high intensities of the field. That the dielectric is heated chiefly in the variable field has been confirmed experimentally. An electric field was set up for 30 min at the initial room temperature in a small cylindrical vessel with a test fluid which entirely filled the interelectrode gap. At direct current and alternating current voltage the temperature rise amounted respectively to 0.2 and 1.6 °C for diethyl ether ($E = 20$ kV cm^{-1}), 0.1 and 0.5 °C for Freon-113 ($E = 50$ kV cm^{-1}) and below 0.1 °C in both cases for *n*-hexane ($E = 50$ kV cm^{-1}). These data testify to the fact that the alternating current voltage is energetically less expedient than the direct current one.

Comparison of the experimental data on heat transfer under the EHD effect for different fluids (Fig. 2) shows that the maximum increase in the heat transfer rate is attained with the use of a polar heat agent when a Coulomb interaction between the field and the dielectric prevails due to the availability of free charges.

Based on the investigations carried out the optimum conditions have been determined that engender the greatest increase in the heat transfer rate. These are the interelectrode space $h = 7$ mm, the working medium pressure $p > 10^5$ Pa, a high-voltage electrode in the form of a solid plate or a vertically slotted plate, a constant electric field, heat agents with the conductivity from 10^{-11} to 10^{-8} Sm m^{-1}. Adherence to the above recommendations may yield a twenty-fold increase in the heat transfer coefficient in the constant heat flow mode (Fig. 3). As the heat agent we used diethyl ether. Similar electrophysical properties are maintained by Freon-21 which offers promise as a heat carrier in low-temperature power engineering.

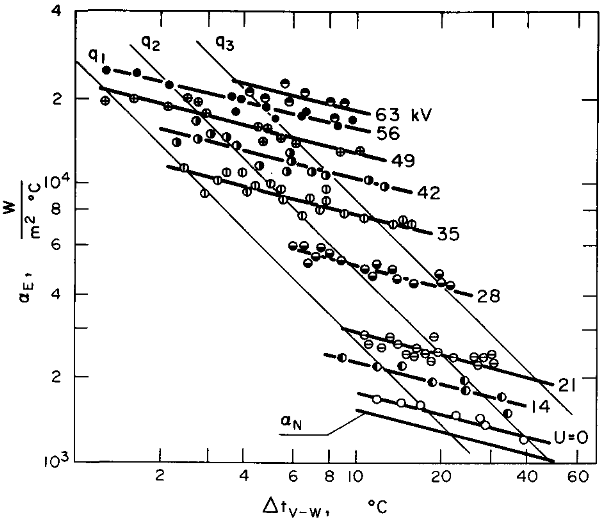

FIG. 3. Dependence of the heat transfer coefficient for diethyl ether vapour condensation on the temperature difference and voltage drop: $t_{sat} = 70$ °C ($p = 310$ kPa); $h = 7$ mm; vertically slotted electrode-plate; direct current voltage; $q_1 = 27$, $q_2 = 49$ and $q_3 = 88$ kW m^{-2}.

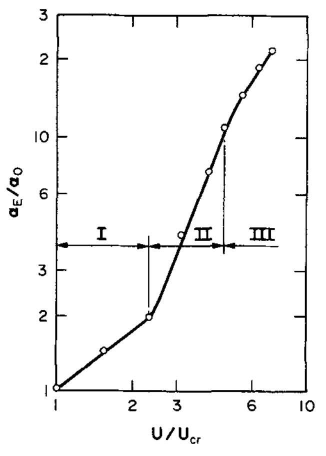

FIG. 4. Increase in the relative heat transfer coefficient as a function of the relative voltage drop; q = constant.

The lines drawn through experimental points at fixed voltage drops are parallel to the straight line corresponding to the Nusselt equation which is indicative of the validity, for the constant electric field, of the dependence $\alpha_E \sim \Delta t_{v-w}^{-0.25}$ typical of heat transfer in laminar flow of condensate film.

By analysing the nature of the α_E/α_0 vs U/U_{cr} plot (Fig. 4) based on the data of Fig. 3, we can identify three regions of the field effect on heat transfer: (1) the transient region ($U/U_{cr} < 2.3$; for ether $U_{cr} = 9$ kV) in which surface tension and viscosity impose a constraint on the electrical forces; (2) the basic region ($U/U_{cr} = 2.3 - 4.6$) when the process is chiefly controlled by the forces of electrical and gravitational fields; and (3) the region with the tendency toward saturation with increase in the heat transfer coefficient ($U/U_{cr} > 4.6$) when the transverse electric field starts to act as an obstacle to condensate evacuation from the interelectrode gap under gravity. For a horizontally slotted electrode a sharp decrease in the heat transfer rate can be observed in the third region associated with formation, when a high voltage is applied, of condensate bridges (Fig. 5 i) between the electrode and the heat transfer surface that decelerate the film flow.

In the investigations carried out a system of coaxial cylindrical electrodes was used along with a plane-parallel one. Vapour condensation then occurred in a nonuniform field on the outer surface of a vertical field's tube 300 mm high and 21 mm dia. A vertically slotted tube of 35 mm I.D. resting on Teflon insulators served as an electrode. The temperature of the outer wall of heat transfer surface was measured by a resistance thermometer.

As a result of the experiments carried out with electrodes of different geometry (inner [5] and outer [6] surfaces of tubes, a plate) it has been established that increase in the heat transfer coefficient for a particular type of the heat agent is unambiguously determined by the magnitude of E_1 at the boundary between the vapour phase and the condensate film ($E_1 = U/[R_t \ln R_e/R_t]$ or $E_1 = U/h$) and is independent of the mode of field strength variation in the vapour phase, i.e. the EHD processes in the vapour phase far from the film surface are unimportant for the enhancement of heat transfer. The result obtained is due to the fact that the temperature is identical all over the vapour phase and is equal to the saturation temperature, which is also true for the sputtered drops drawn away from the condensate film and moving in the interelectrode gap (with increase in the high voltage applied the heat transfer surface temperature measured in the experiments as well as the average temperature of the film and of the sputtered drops tend to the saturation temperature). Thus, we can conclude that volumetric condensation of vapour exposed to the EHD field plays a lesser role.

With heating in an AC field excluded from consideration, we can see from Figs. 2 and 3 that the value of α_E/α_0 in the DC field does not depend on the temperature difference Δt_{v-w}. Since the bulk electric force ($\mathbf{F} = \rho_k \mathbf{E} - \frac{1}{2}E^2\nabla\varepsilon$, where $\rho_k \mathbf{E} = \sigma E^2 \nabla\tau$) is determined by the temperature gradient in the film ($\nabla\tau = [\partial\tau/\partial t]\,\nabla t$ and $\nabla\varepsilon = [\partial\varepsilon/\partial t]\,\nabla t$), then it is possible to conclude that the EHD processes in the bulk of the condensate film are of no importance for increase in heat transfer.

The revealed dependence of the heat-transfer coefficient on, first, the film surface temperature equal to the temperature of saturation [6] and, second, on the field strength E_1 at the boundary between the vapour phase and the film makes it possible to draw a conclusion that enhancement of heat transfer depends on the EHD processes occurring at the vapour–liquid film interface.

4. HYDRODYNAMICS OF THE CONDENSATE FILM FLOW

In order to elucidate the mechanism of the electric field effect on heat transfer in film condensation the hydrodynamics of the condensate film flow has been studied. The pattern of rearrangement of waves has been revealed, the speed of disturbances on the film surface has been determined as well as the height of crests and the length of the longitudinal and transverse waves as a function of the voltage applied. These topics have been insufficiently covered in literature.

The behaviour of a horizontal surface of a stagnant isothermal liquid exposed to the EHD effect has been studied at greater length, for example, in [7, 8]. The action of a transverse electric field on the free surface of liquid flowing under gravity produces a specific loss of surface stability, viz. appearance of transverse waves at the interface. Chung-On Lee and Choi [9] studied the behaviour of the surface of an isothermal film falling down an inclined grounded plane with an electrode placed parallel to it. On application of the field, the laminar film became unstable; the waves with crests parallel to the flow appeared first downstream and, as

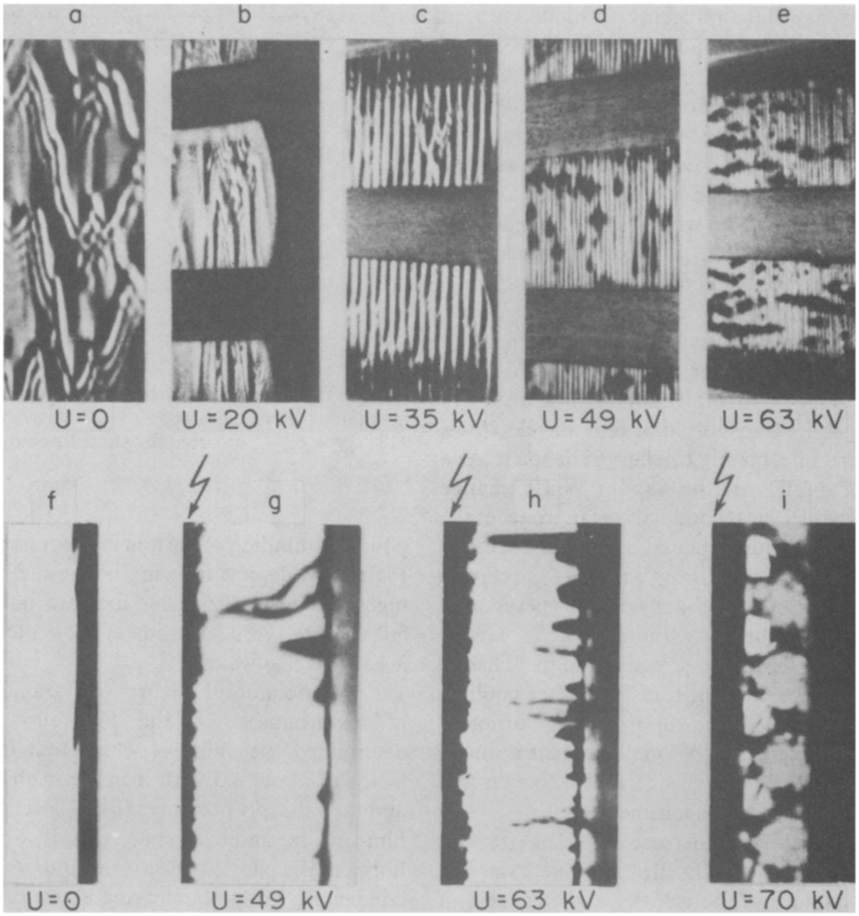

FIG. 5. Rearrangement of wave structure (a–e, view of the film surface) and condensate spraying into the electrode gap (f, g, h, i, electrode is to the left shown by arrow) under the EHD effect; Freon-113; t_{sat} = 62 °C; h = 7 mm (b–e, i, obtained with the use of a horizontally slotted electrode; g, h, electrode in the form of a narrow vertical strip).

the voltage was increased, propagated upstream of the flow. The Reynolds number varied from 0.1 to 0.47, with the transverse wavelength remaining constant and equal to $\lambda^* = 9.2$ mm. With reference to the conditions of the experiment (specifically for $Re < 1$) the stability problem was formulated. The analysis based on the three-dimensional Orr–Zommerfeld equation solved by the method of successive approximations with respect to low Reynolds numbers (for the case when Re is smaller than the non-dimensional wave number $\beta = 2\pi\delta/\lambda^*$) has shown that in the transverse electric field only those disturbances are preserved which propagate across the flow, while the longitudinal ones are damped.

The hydrodynamics of condensate film flow has been studied on an experimental setup described above (Fig. 1) with the aid of ordinary- and motion-picture photography; the working fluid was mainly Freon-113. The Reynolds number calculated from the formula $Re = \bar{q}H/r\rho\nu$ varied from 4 to 300 at the level of viewing windows installed in the midheight of the heat transfer surface; a DC field has been used in the majority of experiments.

In the absence of the electric field, disordered three-dimensional longitudinal waves 9–11 mm long were observed on the film surface (Fig. 5 a, f; $Re = 50$; the photograph in Fig. 5 f shows the film flow pattern on a cylindrical surface, the remainder, on the plane surface). On application of the field the triangular waves contract into filament-crests (Fig. 5 b–e) and instability develops in the form of transverse standing waves 3 mm long. In this case, in contrast to [9], $Re \gg 1$ and is much above the wave number β. Rearrangement of the longitudinal waves into transverse ones occurs within the range of U/U_{cr} from 1 to 2.3 which corresponds to the transition region shown in Fig. 4 (U_{cr} for Freon-113 under the present experimental conditions is equal to 16 kV). With further increase in the field strength, the length of the transverse waves is maintained, the amplitude decreases and at $U/U_{cr} \geqslant 2.5$ conical droplets appear on the film surface (Fig. 5 g, h) the growth rate of which varies between 0.04 and 0.22 m s^{-1}. Alongside the conical droplets, the condensate enters the interelectrode gap in the form of small sprayed droplets that reach the opposite electrode, recharge and, greatly reduced in size, return to the film. A portion of the condensate flows down a high-voltage electrode. It should be noted that the photographs of Fig. 5 g, h, taken when a narrow electrode was used, somewhat distort the true picture of the process because of the end effect which causes condensate influx to the zone exposed to the electric field thus increasing the number of conical droplets.

When a condensate spray enters the interelectrode gap, it converts a dry saturated vapour into a moist one causing a changeover in the mechanism of electrical conduction in the vapour phase: in a dry vapour, charges are transported by ions and electrons, while in a moist one, mainly by charged droplets. As a result, the properties of the vapour phase change drastically – the electrical conductivity approaches the conductivity of the liquid phase, a corona discharge disappears. Initiation and disappearance of the corona discharge can be observed visually on an experimental rig by creating the conditions when vapour condensation can terminate or occur due to a change in the conditions of the heat transfer surface cooling. No corona discharge in the vapour phase during its condensation is indicative of small concentration of ions in vapour and their insignificant role in the process of heat transfer enhancement.

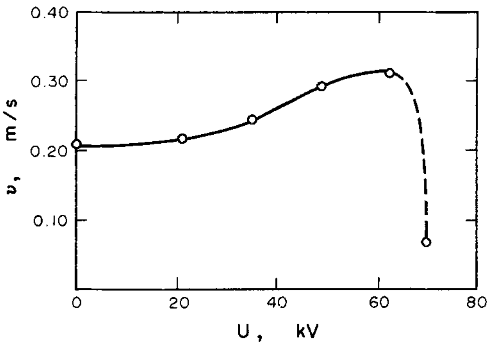

Fig. 7. The speed of disturbances on the film surface as a function of the voltage drop; $q = 2.5 \times 10^4$ W m^{-2}; Freon-113; $t_{sat} = 62$ °C, horizontally slotted electrode; $h = 7$ mm.

In order to elucidate the increase in the heat transfer rate in response to the EHD effect, it is necessary to reveal the behaviour of the velocity and thickness of the condensate film. With the use of a high-voltage electrode in the form of a narrow vertical plate, a groove can be observed on the surface of condensation (Fig. 6 a) resulting from condensate spraying which points to thinning of the film in the zone of field action. Figure 6 b depicts drawing of the dielectric into the high-voltage field zone and increase in the condensate fall velocity (vertical bands at the center of the figure are transverse waves).

From the motion pictures (600 frames/s) the speed of disturbances on the film surface has been determined the value of which first increases by a factor of about 1.5 with increase in the DC strength and then sharply decreases (Fig. 7). Retardation of the film in the interelectrode gap is observed for a horizontally slotted electrode and is attributed to condensate bridges appearing between the electrodes at high field strengths (Fig. 5 i). It should be noted that in the absence of the electric field the speed of disturbances exceeds not more than by 10–15% the liquid velocity on the film surface calculated on the

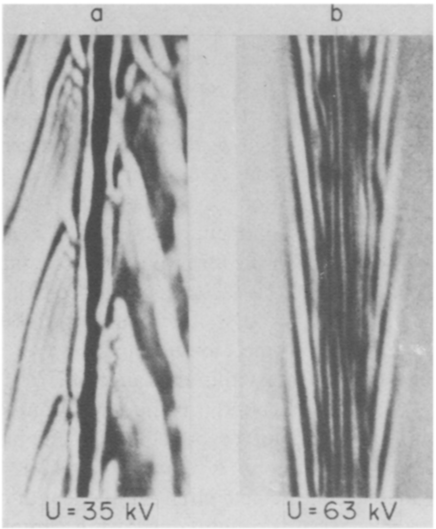

Fig. 6. The condensate film surface facing a narrow electrode: Freon-113; $t_{sat} = 62$ °C; $h = 7$ mm: (a) $U = 35$ kV; $Re = 60$; (b) $U = 63$ kV; $Re = 4$ (the values of Re are given for the segment not exposed to electric field).

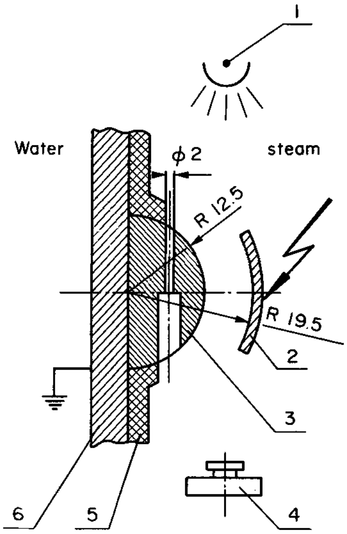

Fig. 8. Device to measure the condensate film height: 1 light source; 2 high-voltage electrode; 3 working surface; 4 camera; 5 heat insulation; 6 water-cooled plate.

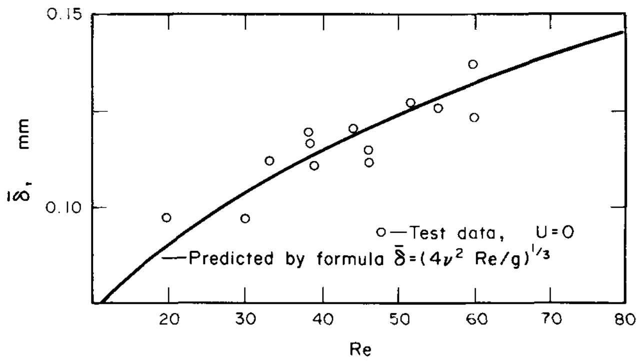

FIG. 9. A change in the mean film thickness as a function of the *Re* number, Freon-113, without electric field.

basis of the Nusselt theory for laminar flow. By comparing the behaviour of velocity with the degree of heat transfer enhancement for the same voltage drops we can draw a conclusion that an increase in the heat transfer coefficient under the EHD effect cannot be unambiguously ascribed to a change in the film flow velocity.

The height of crests of longitudinal and lateral condensate film waves δ_w was measured from photographs of a vertical cylindrical surface 25 mm dia. and 150 mm in height (Fig. 8) placed opposite the viewing windows in the condenser. Except for a stretch 15 mm wide the cylindrical surface and the plate were thoroughly insulated to preclude the possibility of condensate influx into the zone of the electric field action. Two unobstructed holes 2 mm in dia., the relative position and dimensions of which had been very carefully specified, were used to estimate the increase in the scale of pictures (by about a factor of 50) and to calculate the height of crests.

In order to verify the adopted procedures of determining δ_w at different *Re* numbers in the absence of the electric field, mean thicknesses $\bar{\delta}$ of films were determined by means of a planimeter (Fig. 9). A satisfactory agreement is obtained between the measured values of $\bar{\delta}$ and the familiar formula $\bar{\delta} = (4\,\nu^2 Re/g)^{1/3}$ for the mean thickness of the film in laminar wave flow [10].

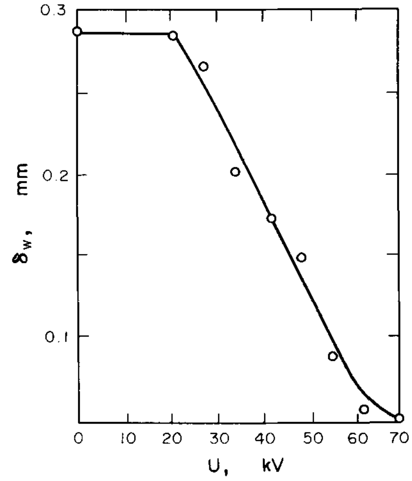

FIG. 10. Decrease in the height of crests of transverse waves with increase in the voltage drop applied; q = (5–6) × 10^4 W m^{-2}, Freon-113; t_{sat} = 62 °C.

Figure 10 shows a change in the height of wave crests as a function of the applied voltage drop in the constant heat flux mode. The upper horizontal segment corresponds to rearrangement of the wave structure with the height of crests maintained (Fig. 5 b). With increase in the voltage drop a sharp decrease in the height of crests is observed due to condensate spraying into the interelectrode gap. Such a nature of the function $\delta_w = f(U)$ is indicative of a decrease in the condensate film mean thickness in the electric field.

Thus, a conclusion can be drawn that enhancement of heat transfer under the EHD effect is a result of decrease in the film thickness and increase in the surface of condensation due to condensate spraying into the vapour phase, appearance of the structure of transverse waves and conical droplets, with the basic contribution into the enhancement of heat transfer being made by thinning of the film in the recesses between transverse waves rather than by an increase in the condensation surface since thermal resistance of wave crests and conical droplets to heat transfer is large as compared with the rest of the film.

5. NON-DIMENSIONAL RELATIONS

The experimental data on heat transfer in film condensation of the vapours of Freon-113, *n*-hexane and diethyl ether obtained under the optimal conditions of the DC field effect have been correlated by means of the similarity theory methods. Besides the similarity numbers $(\bar{\alpha}/\lambda)(\nu^2/g)^{0.33}$, *Re* and *Z*, which are used to describe the heat transfer processes, the non-dimensional groups V and Π have been used which characterize the EHD effect and which were derived earlier in [9, 11]. The group $V = \varepsilon_0\ \varepsilon_1\ E_1^2 h/S$ is the measure of the electric field forces to the surface tension ratio, the group $\Pi = \sigma h^2/\varepsilon_0 \varepsilon \nu = h^2/\tau\nu$ is the

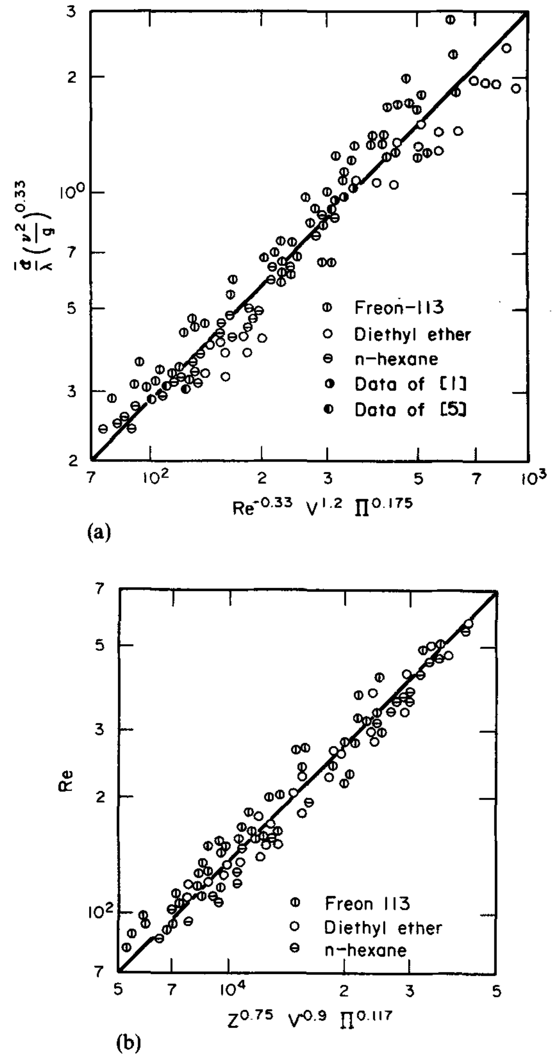

FIG. 11. Vapour film condensation heat transfer in the DC field. Given: (a) heat flux density; (b) 'vapour–wall' temperature difference.

measure of the time ratio between damping of mechanical disturbances and electric charge relaxation in the medium.

In order to calculate the mean heat-transfer coefficient at the prescribed heat flux density, a similarity equation has been derived which approximates the experimental data on heat transfer with the relative square-mean error not exceeding ±16% (Fig. 11 a):

$$\frac{\bar{\alpha}}{\lambda}\left(\frac{\nu^2}{g}\right)^{0.33} = 3 \times 10^{-3} Re^{-0.33} V^{1.2} \Pi^{0.175}. \quad (1)$$

At the prescribed 'vapour–wall' temperature difference, the similarity equation is reduced to the following form (square-mean error does not exceed ±13%, Fig. 11 b)

$$Re = 1.375 \times 10^{-2} Z^{0.75} V^{0.9} \Pi^{0.117}. \quad (2)$$

The saturation temperature has been chosen as the controlling one, since in film condensation under the EHD effect the basic part is played by the surface electric force which depends on the values of $\varepsilon = \varepsilon(t_{sat})$ and $\sigma = \sigma(t_{sat})$. The correction allowing a change in the physical properties of the condensate across the film with varying temperature is close by its magnitude to unity and can be neglected.

The similarity equations (1) and (2) describe heat transfer during film condensation of pure stagnant vapour of a dielectric liquid on vertical plane and cylindrical surfaces up to 0.3 m high exposed to a DC field in the following ranges of non-dimensional parameters: $Re = 70$–600; $Z = 50$–900; $V = 40$–400; $\Pi = 11$–4×10^5; $Pr = 3$–6.5; $E_1/E_{1cr} = 2$–6; $h/h_{opt} = 0.715$–1.00. The experimentally established optimum value for the interelectrode gap $h_{opt} = 7$ mm satisfies the conditions of obtaining the maximum degree of heat transfer enhancement at a relatively small voltage supplied. At $h < h_{opt}$, the growth of the heat transfer coefficient decreases, at $h > h_{opt}$ the supplied voltage increases while the degree of heat transfer enhancement remains almost the same (it is meant that E_1 = const throughout). The experimental data of [1, 5] are satisfactorily correlated by equation (1).

The similarity equations (1), (2) point to the fact that under the exposure to the EHD forces the heat transfer is governed by the laws of the laminar film flow regime ($Re^{-0.33}$, $Z^{0.75}$). The observed loss of film stability in the form of droplets occurs on the crests of waves where the field strength E_1 is at maximum; vapour condenses mainly in the recesses between waves where the field strength and thermal resistance to heat transfer from vapour to the cooling medium are minimal.

6. CONCLUSIONS

(1) The enhancement of heat transfer is determined by the EHD-processes at the vapour–condensate film interface; the electrohydrodynamic processes within the vapour and film volumes are of no consequence for increase in the heat transfer rate.

(2) The EHD-processes at the vapour–film interface manifesting themselves in the form of condensate spraying into the vapour phase and transverse waves, lead to an increase in the surface of condensation and decrease in the condensate film thickness. Thinning of the film in the recesses between transverse waves contributes basically to enhancement of heat transfer.

(3) Heat transfer in film condensation of stagnant vapour on short vertical surfaces exposed to the DC field obeys the laws that govern the laminar film flow.

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TRANSFERT THERMIQUE ET HYDRODYNAMIQUE LORS DE LA CONDENSATION DE VAPEUR EN FILM SOUS L'INFLUENCE D'UN CHAMP ELECTRIQUE

Résumé—On présente des résultats expérimentaux sur le transfert de chaleur et l'hydrodynamique dans la condensation en film d'une vapeur pure au repos, sur des surfaces verticales et courtes placées dans un champ électrique de différentes puissances, fréquence et uniformité. On atteint un transfert de chaleur vingt fois plus grand avec une puissance négligeable. L'accroissement du transfert sous l'effet hydrodynamique est dû à la réduction de l'épaisseur du film causée par la dispersion du condensat dans la phase vapeur et par la formation d'ondes transversales. On montre que sous l'action d'un champ électrique constant, le transfert de chaleur pendant la condensation en film obéit aux lois qui gouvernent l'écoulement laminaire. On établit à partir des relations de similitude, une coordination des résultats expérimentaux pour différents fluides.

WÄRMEÜBERGANG UND HYDRODYNAMISCHE VORGÄNGE BEI DER FILMKONDENSATION VON DAMPF UNTER DEM EINFLUSS EINES ELEKTRISCHEN FELDES

Zusammenfassung—In der Arbeit wird über experimentelle Ergebnisse zum Wärmeübergang und den Strömungsvorgängen bei Filmkondensation eines ruhenden reinen Dampfes an kurzen vertikalen Flächen in einem elektrischen Feld unterschiedlicher Stärke, Frequenz und Homogenität berichtet. Durch Anlegen eines elektrischen Feldes vergroßerte sich bei vernachlässigbarem Energieaufwand der Wärmeübergangskoeffizient um das Zwanzigfache. Die Erhöhung des Wärmeübergangs unter dem elektrohydrodynamischen Einfluß ist auf die Verkleinerung der Filmdicke durch das Sprühen von Kondensat in die Dampfphase und die Bildung querlaufender Wellen zurückzuführen. Es zeigt sich, daß unter Einwirkung eines konstanten elektrischen Feldes für den Wärmeübergang bei Filmkondensation dieselben Gesetze wie für eine laminare Filmströmung gelten. Aus der Korrelation der Versuchsergebnisse für verschiedene Fluide wurden Gleichungen in dimensionsloser Form abgeleitet.

ТЕПЛООБМЕН И ГИДРОДИНАМИКА ПРИ ПЛЕНОЧНОЙ КОНДЕНСАЦИИ ПАРА В УСЛОВИЯХ ВОЗДЕЙСТВИЯ ЭЛЕКТРИЧЕСКОГО ПОЛЯ

Аннотация — Представлены результаты экспериментального исследования теплообмена и гидродинамики при пленочной конденсации неподвижного чистого пара на вертикальных коротких поверхностях в электрическом поле различной напряженности, частоты и неоднородности. Достигнуто двадцатикратное увеличение коэффициента теплоотдачи при ничтожных затратах мощности на создание электростатического поля. Установлено, что причиной интенсификации теплообмена при электрогидродинамическом воздействии является уменьшение толщины пленки, вызванное разбрызгиванием конденсата в паровое пространство и образованием поперечных волн. Показано, что в условиях воздействия постоянного электрического поля теплообмен при пленочной конденсации подчиняется закономерностям ламинарного режима течения пленки. Проведено обобщение опытных данных для различных рабочих жидкостей в виде уравнений подобия.