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Electric-field-induced enhancement of vapour condensation heat transfer in the presence of a non-condensable gas

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Abstract—This paper presents the results of an experimental investigation of heat transfer in film vapour condensation from a vapour–gas mixture on a vertical plate under the influence of an electric field. It is shown that with a gas concentration in vapour below 10% a uniform electric field should be applied, and at higher concentrations a corona discharge should be used. The heat transfer augmentation is found to be determined by the electric hydrodynamic processes just as on the surface of a condensate film in the form of a rearranging wave structure and condensate splashing, that decrease the condensate film thickness, so over the volume of the vapour–gas mixture which is stirred by condensate droplets and, to a greater extent, by the corona discharge electric wind. The effects of gas concentration in vapour, of medium pressure, temperature difference between a vapour–gas mixture and a wall, difference of potentials, electric current strength, physical properties of a liquid phase and of a vapour–gas mixture on the degree of heat transfer enhancement are investigated. A seven-fold increase of the relative heat transfer coefficient in the conditions of corona discharge effect is obtained the development of which is favoured by the maximum gas concentration and minimum temperature differences.

1. INTRODUCTION

IN DIFFERENT areas of engineering, for example, radioelectronics, chemical and refrigeration technologies, use is often made of the processes of vapour condensation of organic liquids that exhibit low heat conduction, and correspondingly heat transfer, coefficients. Moreover, the conditions of heat transfer are considerably impaired in the presence of a non-condensable gas in vapour. Therefore, the pressing need for refining the available, and substantiating and using the new, methods of heat transfer augmentation is dictated not only by research aspects, but also by the requirements of practice. At present, along with the traditional methods such as the rotation of a heat transfer surface, vapour–gas mixture velocity increase, condensate film and mixture suction, greater attention is paid to the use of electric and magnetic fields. As a rule, organic coolants offer high resistance to the flow of electric current, thus favouring the application of the effect of electric fields. Investigations undertaken by the present authors and those described in refs. [1–3] proved the advisability of the use of the electrohydrodynamic (EHD) effect on film condensation heat transfer in the case of a pure vapour with whose aid certain advances were made in the study of the mechanism as well as the trends of heat transfer and a 10–20-fold enhancement of heat transfer was achieved [4, 5]. Investigation of heat transfer with vapour condensation in the presence of a non-condensable gas under the conditions of an electric field effect has shown [3] that the effect decreases monotonously with an increasing gas concentration in vapour. Moreover, a relatively small degree of enhancement (about 60%) in the case of a pure vapour testifies to the fact that the conditions chosen for an electric field effect are far from being optimal.

The present work is an extension of earlier studies [5] and contains the results on the elucidation of the mechanism of the electric field effect on the process of vapour condensation from vapour–gas mixtures and the determination of the optimal conditions for heat transfer enhancement.

2. EXPERIMENTAL FACILITY

Vapour condensation from a vapour–gas mixture took place on a grounded 200 mm high and 120 mm wide copper plate which served as one of the electrodes. A high-voltage electrode was positioned in a vapour–gas volume parallel to the condensation surface. In experiments, plate electrodes with slits for vapour passage and wire electrodes (parallel 0.18 mm diameter wires spaced 5 mm apart) were used. A more detailed description of the instrumentation can be found elsewhere [5]. Some improvements in the setup were made to provide better mixing of vapour with a lighter gas. For this purpose, a vapour–gas mixture was fed into the upper part of the condenser. Moreover, outside the limits of the electrode gap in the condenser volume additional thermocouples were installed at different heights to measure the medium temperature. As shown by the verification tests of the measuring procedure, the electric field does not affect the thermocouple readings.

The heat transfer agents used were R-113 and hex-

NOMENCLATURE

a	thermal diffusivity [$m^2 s^{-1}$]
C_g	relative volumetric concentration of component, $(P_{mix} - P)/P_{mix}$
D	coefficient of molecular diffusion [$m^2 s^{-1}$]
f	condensation surface area [m^2]
F	condenser cross-sectional area [m^2]
H	height of condensation surface [m]
i	electric current density [$A\ m^{-2}$]
I	current strength [A]
k	charge mobility [$m^2 V^{-1} s^{-1}$]
l	electrode spacing [m]
M	molecular mass
P	pressure [Pa]
q	heat flux density [$W\ m^{-2}$]
r	heat of phase change [$J\ kg^{-1}$]
R	gas constant [$J\ kg^{-1} K^{-1}$]
t	temperature [K]
Δt	difference of vapour–gas mixture and wall temperatures [K]
U	difference of potentials between electrodes [V]
U_{cr}	difference of potentials corresponding to the onset of heat transfer augmentation [V]
w	medium flow velocity [$m\ s^{-1}$]
W	electric power [W]

Greek symbols

α_E, α_0	mean heat transfer coefficient for vapour condensation from a vapour–gas mixture with and without exposure to electric field [$W\ m^{-2} K^{-1}$]
α_N	mean heat transfer coefficient for pure vapour condensation calculated from Nusselt's equation with correction for wave formation [$W\ m^{-2} K^{-1}$]
ε	dielectric permeability of medium
ε_0	8.85×10^{-12}
Φ/M	constant
ν	kinematic viscosity [$m^2 s^{-1}$]
ρ	medium density [$kg\ m^{-3}$]
σ	coefficient of surface tension at the vapour–gas mixture–liquid interface [$N\ m^{-1}$].

Subscripts

g	gas
mix	vapour–gas mixture
v	vapour

Liquid phase parameters do not carry affices.

Dimensionless groups

Re	$qH/r\rho\nu$
Re_{mix}	$w_{mix}H/\nu_{mix}$
Sc_{mix}	ν_{mix}/D_{mix}
Pr	ν/a
Re_e	$il^3/k_{mix}\rho_{mix}\nu_{mix}^2$
V	$\varepsilon_0\varepsilon_v U^2/\sigma l$
K_E	α_E/α_0
K_0	α_0/α_N.

ane in the presence of non-condensable gases: air, helium or carbon dioxide. The main parameters of the process varied in the following ranges: volumetric gas concentration 0–47%, working medium pressure 0.1–0.25 MPa, heat flux density 8×10^2–3.5×10^4 W m^{-2}, constant high voltage 0–56 kV. The main series of experiments was carried out with a pressure in the condenser somewhat exceeding the atmospheric one, 0.12 ± 0.02 MPa.

3. RESULTS OF HEAT TRANSFER INVESTIGATIONS AND THEIR ANALYSIS

First, a series of experiments was carried out in the absence of an electric field, and a satisfactory agreement was obtained between the results accumulated, Nusselt's relation, with wave formation taken into account in the case of pure vapour condensation, and the experimental data of ref. [6] in the case of R-113–air mixture condensation.

Having imposed a high voltage, an electric field of different degrees of inhomogeneity, including a corona discharge, was created in the gap between the condensation surface and the high-voltage electrode. It was found in the process of investigations that in the presence of a vapour–gas medium the initiation of a corona discharge was due not only to the geometry of the high-voltage electrode, but also to the amount of non-condensable gas.

It is known [7] that it is difficult to initiate a corona discharge in the process of pure vapour condensation without applying special electrodes. Other trends are noted when there is a non-condensable gas in the mixture. In particular, Fig. 1 shows the results of heat transfer investigations in an R-114 vapour–air mixture condensation using a wire electrode. To the right of the '0' curve, experimental relations 1–3 are given for a pure vapour which are characterized by a small increment of the relative heat transfer coefficient K_E, to the left relations 2*–5* for which the EHD effect is most effective, while the magnitudes of the voltage imposed are minimal. It should be noted that a portion of the relations on the right- and left-hand sides were obtained at the same gas concentration in a mixture and the difference is only in the presence of a corona discharge. The heat transfer intensification described by curves 0–3 is due to the effect of a uniform (more precisely, quasi-uniform) electric field;

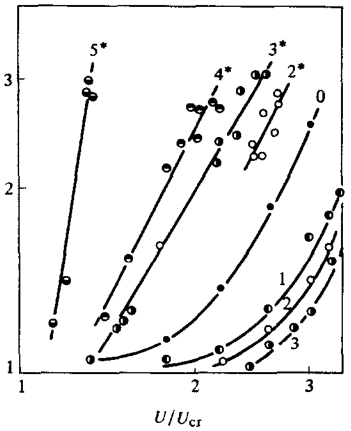

FIG. 1. Heat transfer enhancement depending on the relative potential difference and volumetric air concentration in the R-113 vapour (wire electrode). C_g(%): 1, 7; 2, 2*, 12; 3, 3*, 23; 4*, 33; 5*, 41. Here and hereafter $l = 7$ mm.

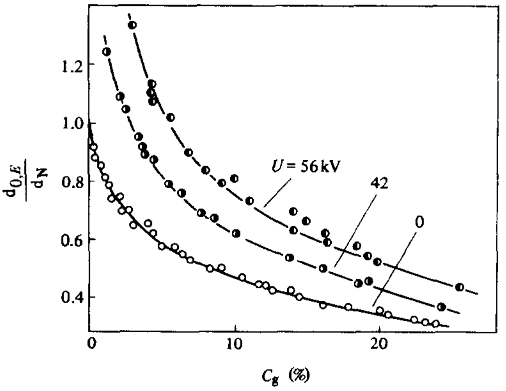

FIG. 2. Dependence of the relative heat transfer coefficient on air concentration in the R-113 vapour and electric field voltage (plate electrode).

the magnitude of the current in the circuit of condensation surface grounding is less than a microampere; the wire electrode is fully covered with condensate and, when high voltages are imposed, condensate bridges may originate between the electrode and the film surface. Typical of relations 2*–5* are the values of the corona discharge current from 2 to 700 μA; a small amount of condensate or its absence on the high-voltage electrode is noted. In the process of vapour condensation from a vapour–gas mixture at low volumetric gas concentrations (< 10%) the corona discharge is unstable and frequently dies out. Conversely, for high gas concentrations (> 30%) the EHD effect shows up as a corona discharge. Whenever the wire electrodes are replaced by those in the form of plates, the results on heat transfer in the range of gas concentrations from 7 to 23% are similar to relations 1–3.

The experimental data on R-113–air mixture condensation heat transfer presented traditionally as $\alpha_{0,E}/\alpha_N - C_g$ (Fig. 2) testify to the persistence, in the presence of an electric field, of the character of curves for which a monotonous decrease with an increasing gas concentration is typical. It is known that similar $\alpha_0/\alpha_N - C_g$ relations for a 'steam–air' mixture fall off very steeply, and the diffusional thermal resistance dominates substantially over its other constituents starting from the air concentration $C_g > 1\%$. It has been estimated that for a mixture of gases with organic liquid vapours the thermal resistance of a condensate film becomes smaller than the diffusional one only when $C_g > 6\%$, nevertheless remaining significant at higher gas concentrations, thus making it necessary to take into account the processes in both a vapour–gas mixture and a film.

In the case of a uniform electric field the EHD effects on heat transfer are characterized by the difference in potentials applied to the electrodes and, in the case of a corona discharge, by the magnitude of the electric current. The experimental data on heat transfer in the case of R-113 vapour condensation from a mixture with air, presented as a function of the corona current (Fig. 3), are approximated by the curve with a standard deviation of ±13% irrespective of gas concentrations and supplied voltage polarity. Here three regions of the effect of corona discharge on heat transfer can be distinguished: the first, in the range of current variation up to 20 μA, the second to 220 μA, the third region at higher currents. The first and third regions are self-similar, while the second region, the most extended one, is characterized by the power-law dependence of K_E on the current. The exponent for the R-113–helium mixture is 0.26, for the R-113–air mixtures it is 0.3, and for the hexane–carbon dioxide mixture it is 0.49. The extension of the above regions and the corresponding magnitude of current are also different for different mixtures.

To explain the EHD effect on the heat transfer process, it is necessary to pay attention to a change in the film flow hydrodynamics in an electric field. Visual observations showed that in the case of vapour condensation from a vapour–gas mixture, just as in the case of a pure vapour [5], the disordered three-dimensional longitudinal waves are replaced, in the presence of an electric field, by standing waves the length and amplitude of which decrease several fold. In the space between the electrodes the condensate droplets, splashed from the film surface, start to move toward the high-voltage electrode, where a portion of them flows down it and a portion, having been recharged, returns to the film.

Thus, in an electric field there occurs, on the one hand, a decrease in the thermal resistance of a condensate film due to its thinning because of the wave structure rearrangement and condensate splashing and, on the other hand, a decrease in the diffusional thermal resistance due to the boundary vapour–gas layer mixing by moving droplets replacing the process of molecular diffusion by electric convection.

Besides the above factors, the corona discharge causes the appearance of an electric wind from the corona-forming electrode, and a more efficient

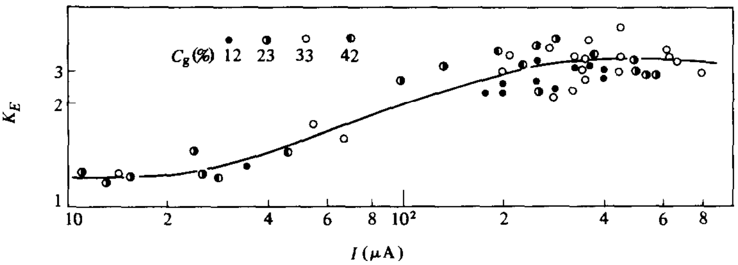

FIG. 3. Enhancement of heat transfer in the case of a corona discharge in an R-113–air mixture (wire electrode).

destruction of the boundary layer of the mixture than by moving condensate droplets. It should also be noted that under certain conditions of the corona discharge at elevated difference of potentials there occurs an intensive motion of condensate droplets from the film surface outside the interelectrode gap causing the agitation of a vapour–gas mixture in the condenser volume.

Because of the different mechanisms underlying the effects of uniform and non-uniform electric fields on the diffusional thermal resistance to heat transfer it should be expected that heat transfer effects will also depend differently on the physical properties of the working medium and operational parameters of the process. To determine the optimal conditions for the highest enhancement of heat transfer, investigations were carried out in wide ranges of vapour–gas mixture composition, pressure in a condenser, and temperature differences between the vapour–gas mixture and the wall.

It is known [6] that in the absence of an electric field the heat transfer in vapour condensation from compositionally different mixtures is determined by the relationship between the molecular masses of vapour and gas, by the magnitude of the molecular diffusion coefficient of the mixture and by the direction of vapour supply towards the working surface. Depending on the combination of these factors, either homogeneous or stratified, over the condenser height, vapour–gas mixture is formed, with the highest condensation heat transfer coefficients corresponding to the stratified mixture.

The experimental results on heat transfer in the absence of an electric field for compositionally different vapour–gas mixtures show (Fig. 4) that the highest relative heat transfer coefficients are obtained for the R-113–helium mixture and the smallest for the 'hexane–carbon dioxide' mixture. Comparison of these results with the relationship between the molecular masses of vapour and gas and the diffusion coefficient for each composition (see, e.g. compositions 1 and 2 in Table 1) shows that the main factor that determines the heat transfer intensity is the difference between the molecular masses of vapour and gas—the greater this difference, the higher the effect. The mixture stratification was inferred from the readings of thermocouples positioned at different heights in the condenser volume. On exposure of the mixture to a uniform electric field, the heat transfer, besides being affected by the high voltage, is also influenced by mixture stratification which depends on the relationship between the molecular masses of vapour and gas. For this reason, the highest relative heat transfer coefficients were again obtained for the R-113–helium mixture (Fig. 5), while for the mixtures of R-113 with air and carbon dioxide the effects were similar.

The corona discharge exerted another effect on heat transfer in the conditions of vapour condensation from a mixture with different non-condensable gases as compared with a uniform electric field, namely, the

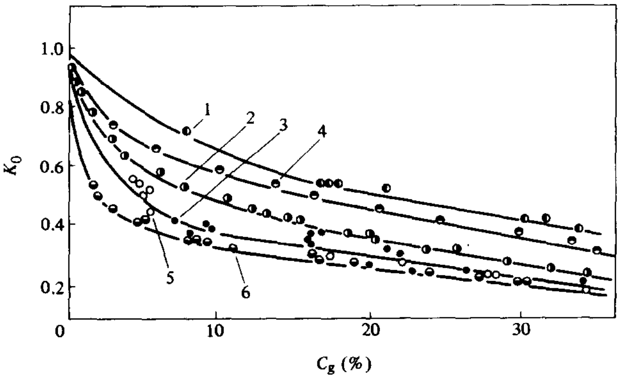

FIG. 4. Variation of the relative heat transfer coefficient with gas concentration and mixture composition in the absence of an electric field: 1–3, R-113–helium, air carbon dioxide; 4–6, hexane–helium, air, carbon dioxide.

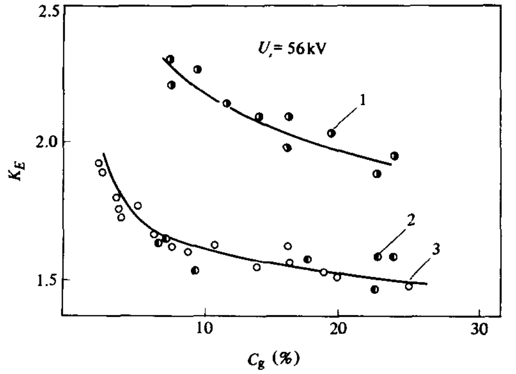

FIG. 5. The effect of a uniform electric field on heat transfer in the case of different mixture compositions (plate electrode).

greatest enhancement of heat transfer was observed for mixtures with nearly the same molecular masses of vapour and gas. The relative heat transfer coefficients increased as follows: by a factor of 1.8 for the R-113–helium mixture, 2.6 for the R-113–air mixture (Fig. 3), 3 for the R-113–carbon dioxide mixture and, finally, 5 for the 'hexane–carbon dioxide' mixture.

The explanation for this is that the corona discharge electric wind intensity, which determines the growth of the heat transfer coefficients, attains a maximum value for gases and their mixtures that have the greatest molecular mass and smallest mobility of charges, with the main part being played by the former factor which coincides in our case with a decrease in the difference between the molecular masses of vapour and gas. The independence of the heat transfer effect of the mixture stratification indicates that in corona discharge the diffusion thermal resistance decreases more substantially than in a uniform electric field.

It is known that without an electric field the heat transfer in the presence of film condensation of a pure vapour or of a vapour–gas mixture is independent of the magnitude of the pressure when the latter varies in the range of a few atmospheres and higher. Another behaviour was observed in the case of pure vapour condensation in the conditions of EHD effect [7]. The working medium pressure and, consequently, the saturation temperature may favour the enhancement of heat transfer due to a change in the electric conductivity and breakdown voltage of the working medium. Analogous results were obtained for vapour condensation from a vapour–gas mixture, but here to some specific features were noted. In a uniform electric field the K_E–P_{mix} relations (Fig. 6) increase monotonously with pressure and pass into the self-similar region. With an increasing gas concentration the effect of pressure on K_E decreases. In corona discharge, the character of the K_E–P_{mix} dependence (Fig. 7) is analogous to that obtained for pure vapour condensation [7]: a weak dependence of K_E on pressure at relatively low values of the latter, a further sharp increase of K_E and, finally, the self-similar region. As compared with a uniform field, higher heat transfer effects were achieved with a weak dependence of K_E on gas concentration. Emphasis should be placed on a distinctive feature of vapour condensation from a mixture in corona discharge, when intensive dispersion of a condensate film with the ejection of droplets outside the high-voltage electrode originates at elevated potential differences. This mode is insensitive to gas concentration and vapour–gas mixture composition and is characterized by the highest relative heat transfer coefficients (Fig. 7, curve 1).

In the case of vapour condensation from a vapour–gas mixture, of special interest is the region of small temperature differences between the vapour–gas mixture and the wall (the region of small heat fluxes) since it is encountered in such important practical problems as the thermostatic protection of different objects. The specific feature of the region of small temperature differences is conditioned, on the one hand, by the hydrodynamics of laminar condensate flow with low Reynolds numbers and, on the other hand, by the heat transfer being dependent on the diffusional thermal resistance, since, according to the Nusselt theory, the thermal resistance of the film is small in this case.

In experiments with an R-113–air mixture in the absence of an electric field a sharp decrease of the relative heat transfer coefficient is observed with a decrease of the temperature drop from 5 to 1 K. This decrease is more substantial with an increase of the gas concentration: by a factor of two for $C_g = 17\%$ and $\Delta t = 2$–5 K.

In an electric field, created by a plate electrode, the detected decrease becomes smaller, while at a greater potential difference of 56 kV, a substantial increase of the relative heat transfer coefficient with a decrease of the temperature difference was obtained. In the latter case a corona discharge develops in the interelectrode

Table 1. Relationship between the gas and vapour molecular masses and diffusion coefficients of mixtures

No.	Mixture composition	M_g/M_v	$D_{\text{mix}} \times 10^6$ m^2 s^{-1} for $t = 50$ K
1	R-113–helium	0.0214	24.9
2	Hexane–helium	0.0464	32.1
3	R-113–air	0.155	7.0
4	R-113–carbon dioxide	0.235	5.5
5	Hexane–air	0.336	9.25
6	Hexane–carbon dioxide	0.51	7.45

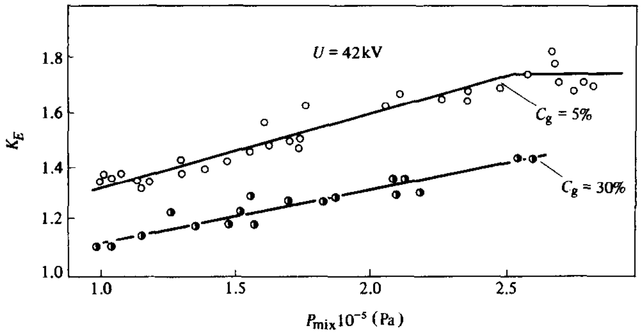

FIG. 6. Heat transfer enhancement in a uniform electric field depending on mixture pressure and air concentration in the R-113 vapour.

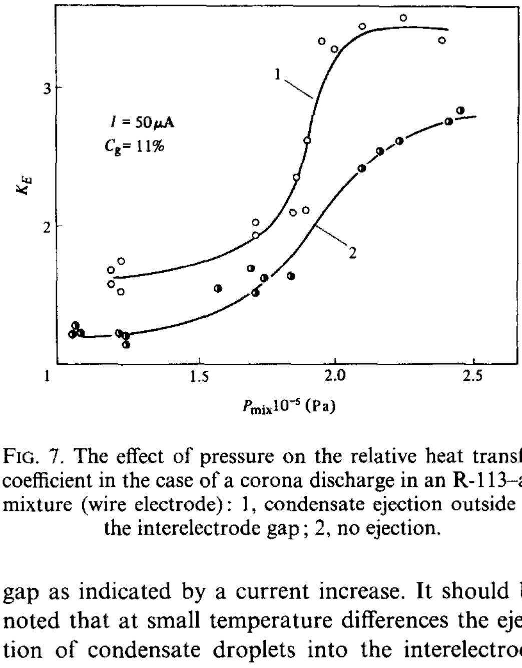

FIG. 7. The effect of pressure on the relative heat transfer coefficient in the case of a corona discharge in an R-113–air mixture (wire electrode): 1, condensate ejection outside of the interelectrode gap; 2, no ejection.

gap as indicated by a current increase. It should be noted that at small temperature differences the ejection of condensate droplets into the interelectrode gap is insignificant because of a small quantity of condensate on the heat transfer surface, and usually the electrode is not covered with the condensate, which, having a high electric resistance, insulates the electrode and prevents the development of corona discharge. The combination of small temperature differences with high gas concentrations provides the most favourable conditions for a corona discharge and highest heat transfer augmentation (Fig. 8, curve $\Delta t = 1$ K). In the absence of a corona discharge, the electric field yields a smaller effect, so that the rest curves decrease first sharply and then monotonously with an increase in the gas concentration and temperature difference (Fig. 8).

When, on using a wire electrode, a corona discharge is sustained throughout the entire range of temperature differences, then the curves will have the character as shown in Fig. 9: a marked increase in K_E in the range of small temperature differences, with the heat transfer rate being determined by the magnitude of the corona current.

As regards the power expenditure for the creation of the field

$$W = J \cdot U \text{ [W]} \tag{1}$$

the following can be noted.

For a uniform field the current did not exceed 1 μA and at the greatest potential difference of 56 kV the maximum power spent amounted to 0.056 W indicating a high efficiency of its application.

In the case of a corona discharge the current magnitude is much higher and in some of the experiments it was nearly 10^{-3} A. When bearing in mind that, on applying the corona discharge for heat transfer intensification it is advisable, when selecting the conditions for the process, to limit ourselves only to the second region in the K_E–J relation (Fig. 3), then the maximum current will amount to 500 μA (R-113–carbon dioxide mixture) and, at the greatest potential difference of 30 kV, the power expenditures will constitute 15 kW. In this case the heat flux transferred through the working surface attained 170 W. Thus, the expenditures amounted to 8.8% of the heat flux transferred. For the hexane–carbon dioxide mixture this value did not exceed 1%, for the R-113–air or helium mixture it was equal to 3–3.5%. It can be concluded that, when confining the operation of heat exchangers with the EHD effect to the second region of the K_E–J relation, the application of a corona discharge can be regarded as economically justifiable.

4. COMPUTATIONAL RELATIONS

The experimental data on heat transfer in the case of a film condensation of R-113 vapour from mixtures with carbon dioxide, helium, air and in the case of hexane vapour condensation from mixtures with carbon dioxide and helium, obtained for the optimum conditions of constant electric field effect, are presented by empirical relations. Along with the familiar similarity numbers the complexes are used that characterize the EHD effect in a uniform field (V) and in the case of corona discharge (Re_e). The complex V represents the measure of the relationship between the

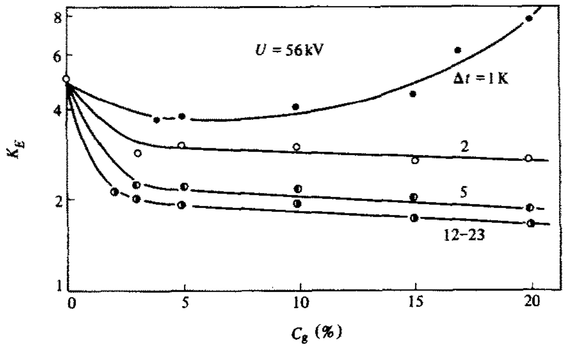

FIG. 8. Dependence of the relative heat transfer coefficient on air concentration in the R-113 vapour and temperature difference (plate electrode).

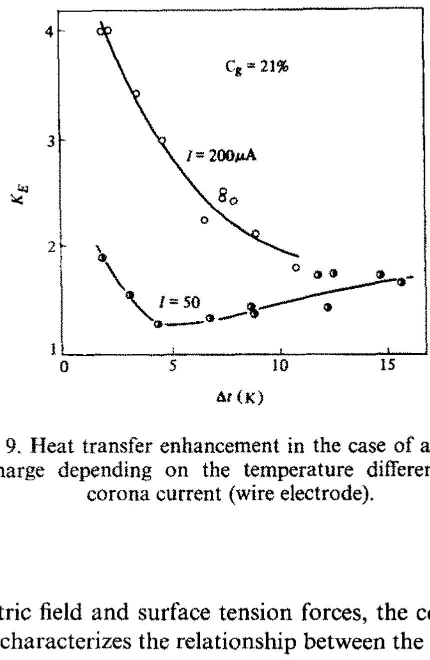

FIG. 9. Heat transfer enhancement in the case of a corona discharge depending on the temperature difference and corona current (wire electrode).

electric field and surface tension forces, the complex Re_e characterizes the relationship between the electric and viscous forces and is a modified hydrodynamic Reynolds number in which the electric wind speed is expressed in terms of electric quantities—current and mobility of charges. The physical parameters of a vapour–gas mixture, that enter into the complexes, were calculated as recommended in ref. [8].

To calculate the mean condensation heat transfer coefficient based on the difference between the vapour–gas mixture volume and the wall temperatures, the following equations were derived:

(a) in the absence of an electric field (Fig. 10(a))

$$K_0 = 0.023 Re^{-0.4} Re_{\text{mix}}^{0.52} Sc_{\text{mix}}^{-0.42} C_g^{-0.24} \qquad (2)$$

at $Re = 1.7\text{–}73$, $Re_{\text{mix}} = 2.5\text{–}860$, $Sc_{\text{mix}} = 0.068\text{–}0.46$, $C_g = 0.4\text{–}46\%$;

(b) in the conditions of the uniform electric field effect (Fig. 10(b))

$$K_E = 1.89 Pr^{-0.56} V^{0.12} \quad \text{at} \quad V = 27.5\text{–}200 \qquad (3)$$

$$K_E = 0.33 Pr^{-0.56} V^{0.45} \quad \text{at} \quad V = 200\text{–}605 \qquad (4)$$

when $Pr = 4.2\text{–}7.3$, $Re = 1.3\text{–}130$, $Re_{\text{mix}} = 19\text{–}1090$, $Sc_{\text{mix}} = 0.068\text{–}0.46$, $C_g = 0.7\text{–}47\%$;

(c) in the case of a corona discharge (Fig. 10(c))

$$K_E = 0.786 Pr^{-0.7} (R_v/R_g)^{0.1} Re_e^{0.24} \qquad (5)$$

when $Pr = 4.2\text{–}7.3$, $R_v/R_g = 0.0214\text{–}0.51$, $Re_e = 2.5 \times 10^5\text{–}2.8 \times 10^7$, $Re = 4.4\text{–}118$, $Re_{\text{mix}} = 50\text{–}950$, $Sc_{\text{mix}} = 0.078\text{–}0.485$, $C_g = 8\text{–}44\%$.

Equation (2) approximates the experimental data on heat transfer within ±15%, the other equations within ±20%. The physical parameters of the vapour–gas mixture, of vapour and gas were determined at a distance from the condensation surface; the physical properties of the liquid phase and the phase conversion heat were related to the condensate film surface temperature. The correction which takes into account the variation of the physical properties of a condensate over the film thickness with temperature is close to unity and was ignored in this work.

Equations (2)–(5) describe the heat transfer in film condensation of a dielectric liquid vapour from a vapour–gas mixture on vertical surfaces up to 0.22 m high in the absence, equation (2), and presence of a uniform, equations (3) and (4), and strongly non-uniform, equation (5), electric fields with the inter-electrode gap of 7 mm when the mixture pressure varies within the range of 0.1–0.25 MPa and the temperature difference from 2 to 23 K. The analysis of equations (3)–(5) shows that the degree of heat transfer enhancement in a uniform electric field is determined by the potential difference and by the physical properties of the liquid phase, and in the case of a corona discharge by the electric current magnitude, physical properties of the vapour–gas mixture and of the liquid phase. The role of the diffusion coefficient does not show up in the electric field.

5. CONCLUSIONS

The heat transfer augmentation is determined by the EHD processes both on the condensate film surface in the form of originating waves of a new type and

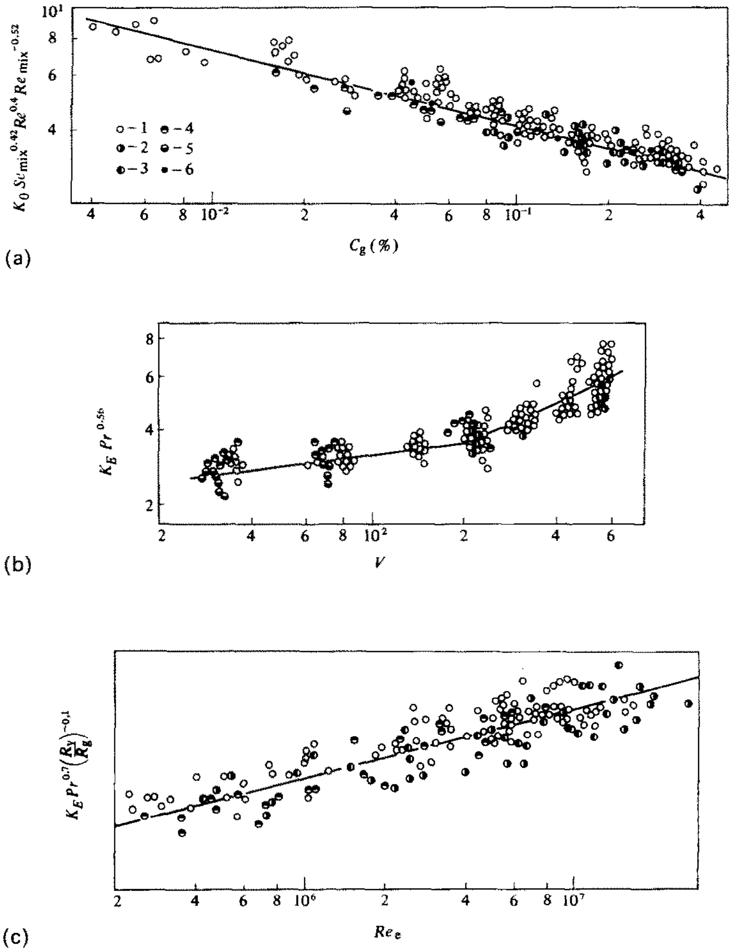

FIG. 10. Heat transfer in film vapour condensation from a vapour–gas mixture on a vertical plate: 1–3, R-113–air, carbon dioxide, helium; 4–6, hexane–carbon dioxide, helium, air; (a) in the absence of an electric field; (b) a uniform electric field; (c) a corona discharge.

condensate splashing that decrease the film thickness, and in the vapour–gas mixture volume in the form of its mixing by moving condensate droplets and, to a much greater extent, by the electric wind of a corona discharge.

Depending on the magnitude of the non-condensable gas concentration it is advisable to apply electric fields of different degrees of non-uniformity: a uniform field for $C_g < 10\%$ and a corona discharge for higher C_g.

In the case of vapour condensation from a vapour–gas mixture, the appearance of a corona discharge is conditioned by the magnitude of gas concentration and the presence of a condensate film on the electrode, rather than by the geometry of the electrode.

The maximum heat transfer augmentation equal to a seven-fold increase of K_E was obtained in the conditions which are most favourable for corona discharge development: at maximum gas concentrations and minimum temperature differences.

In the conditions of EHD effect an increased pressure serves as a factor of heat transfer enhancement.

The determining factor of heat transfer enhancement in a uniform electric field and in the case of its absence is the relationship between the molecular masses of vapour and gas that causes the mixture stratification. In the case of a corona discharge such factors are the magnitude of the mixture molecular mass and the mobility of charges.

The analysis of equations has shown that the degree of heat transfer enhancement is determined in a uniform electric field by the magnitude of the potential difference and by the physical properties of a liquid phase, and in the case of a corona discharge by the magnitude of the electric current, physical properties of a vapour–gas mixture and of a liquid phase; the role of the diffusion coefficient does not show up in electric fields.

The expenditures of power for corona discharge production are several orders of magnitude higher than for a uniform electric field, but nevertheless its application can be regarded as worthwhile.

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AMELIORATION DU TRANSFERT THERMIQUE AVEC CONDENSATION DE VAPEUR PAR CHAMP ELECTRIQUE, EN PRESENCE D'UN GAZ INCONDENSABLE

Résumé—On présente les résultats d'une recherche expérimentale sur le transfert thermique avec condensation en film d'un mélange vapeur–gaz sur une plaque verticale, sous l'influence d'un champ électrique. On montre qu'avec une concentration en gaz inférieure à 10% un champ électrique uniforme peut être appliqué et qu'à des concentrations supérieures on doit utiliser une décharge corona. L'augmentation de transfert thermique par le procédé électrique est semblable à ce qui est obtenu par une structure d'onde en réorganisation et une impaction de condensat, ce qui diminue l'épaisseur du film de condensat, en agissant sur le volume du mélange vapeur–gaz, lequel est brassé par les gouttelettes de condensat et, à un plus fort degré, par le vent électrique de la décharge corona. On étudie les effets de la concentration en gaz dans la vapeur, de la pression, de la différence de température entre le mélange vapeur–gaz et la paroi, de la différence de potentiel, de l'intensité du courant électrique, des propriétés physiques de la phase liquide et du mélange vapeur–gaz, sur le degré d'accroissement du transfert thermique. Une augmentation du transfert de l'ordre de sept fois, dans les conditions de la décharge corona, est obtenue dans le cas de la concentration maximale en gaz et de différences de température minimales.

DIE VERBESSERUNG DES WÄRMEÜBERGANGS BEI DER KONDENSATION VON DAMPF IN ANWESENHEIT EINES NICHTKONDENSIERBAREN GASES DURCH EIN ELEKTRISCHES FELD

Zusammenfassung—Die Ergebnisse einer experimentellen Untersuchung des Wärmeübergangs bei der Filmkondensation aus einem Dampf–Gas-Gemisch an einer senkrechten Platte unter dem Einfluß eines elektrischen Feldes werden vorgelegt. Es wird gezeigt, daß bei einer Gaskonzentration von unter 10% im Dampf ein einheitliches elektrisches Feld, bei höheren Konzentrationen eine Sprühenladung angewandt werden sollte. Der Anstieg des Wärmeübergangs, so zeigt sich, wird durch die elektrisch-hydrodynamischen Vorgänge bestimmt, durch die in dem gesamten Bereich des Dampf–Gas–Gemisches Kondensat-Tröpfchen versprüht werden bzw. ein elektrischer Wind der Sprühentladung auftritt. Dadurch wird die Kondensatfilmdicke verringert. Untersucht wurden die Einflüsse der Gaskonzentration im Dampf, des Druckes, der Temperaturdifferenz zwischen Gemisch und Wand, der Potentialdifferenzen, der elektrischen Stromstärke, der physikalischen Eigenschaften der flüssigen und der gasförmigen Phase und der Grad der Erhöhung des Wärmeüberganges. Ein siebenfacher Anstieg des relativen Wärmeübergangskoeffizienten wird unter den Bedingungen der Sprühentladung erhalten, die sich bei der maximalen Gaskonzentration und den kleinsten Temperaturdifferenzen bevorzugt entwickelt.

ИНТЕНСИФИКАЦИЯ ТЕПЛООБМЕНА ПРИ КОНДЕНСАЦИИ ПАРА В ПРИСУТСТВИИ НЕКОНДЕНСИРУЮЩЕГОСЯ ГАЗА ЭЛЕКТРИЧЕСКИМ ПОЛЕМ

Аннотация—Представлены результаты экспериментального исследования теплообмена при пленочной конденсации пара из парогазовой смеси на вертикальной пластине в условиях воздействия электрического поля. Показано, что при концентрации газа в паре меньше 10% следует применять однородное электрическое поле, а при больших значениях–коронный разряд. Установлено, что интенсификация теплообмена определяется ЭГД-процессами как на поверхности конденсатной пленки в виде перестройки волновой структуры и разбрызгивания конденсата, уменьшающих толщину пленки, так и в объеме парогазовой смеси, которая перемешивается каплями конденсата и в более значительной степени электрическим ветром коронного разряда. Исследовано влияние на степень интенсификации концентрации газа в паре, давления среды, температурного перепада «парогазовая смесь–стенка», разности потенциалов, электрического тока, физических свойств жидкой фазы и парогазовой смеси. Получено семикратное увеличение относительного коэффициента теплоотдачи в условиях действия коронного разряда, развитию которого способствуют максимальные концентрации газа и минимальные температурные перепады.