INTENSIFICATION OF LIQUID EVAPORATION BY A LOW-CURRENT HIGH-VOLTAGE DISCHARGE

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UDC 536.423.1:537.52

Results of an experimental study of the effect of an electrical discharge on liquid evaporation are presented.

A significant intensification (by a factor of 1.5-3 times) in heat and mass exchange in capillary-porous bodies upon application of an electrical discharge has been established by many authors [1-5], but the mechanism and principles of this process have yet to be clarified, while the conclusions presented in the studies cited are to a great extent ambiguous. Therefore, a detailed study of the effect of electrical discharges on the kinetics of liquid evaporation was undertaken.

The experimental study of the physical mechanism of heat and mass exchange during liquid evaporation with action of an electrical discharge was performed by the technique described in [6], using point—ring and point—point electrode systems. The liquid was evaporated from thin glass tubes 1.6, 2.3, and 2.5 mm in diameter.

Figure 1 shows typical experimental arrangements (2-9). Depending on the position of the electrodes relative to each other and the mouth of the tube and the electrical parameters of the discharge, significantly different physical conditions for discharge action on the evaporation process were created. But in all experiments the region near the liquid meniscus was practically free of electric field action, i.e., the liquid was located outside the interelectrode space. The localization of the high voltage discharge was varied over various zones relative to the meniscus by changing the length of the discharge gap l_1 over the range 1-3 mm and the extent of the discharge-free zone above the tube section l_2 over the range 0.2-2 mm. For comparison, also shown in Fig. 1 is diagram 1, corresponding to the conditions under which the results of [1-5] were obtained, where the specimen was located in the space between point and plane electrodes.

The voltage applied to the electrodes was varied over the range 4-10 kV, with currents from 0.1 to 140 μA. Depending on the electrical parameters the discharge excited showed a clearly expressed channel, a channel with diffuse plasma region, or a corona form. In one particular regime the corona was concentrated in the form of scintillating points directly at the point of the electrode. The same apparatus was used for each electrode arrangement to perform experiments with no discharge, the electrodes being maintained in the same position and the parameters of the external medium maintained the same.

The liquids studied were distilled water, ethyl and isopropyl alcohols, acetone, kerosene, and carbon tetrachloride. These liquids differ in molecular mass, chemical bond structure, dipole moment, dielectric permittivity, specific heat, etc. In each experiment the measures necessary to ensure sterile conditions were taken.

To evaluate the effect of the electrical discharges on evaporation processes, a relative intensification factor γ was introduced, defined as the ratio of the evaporation rates under discharge and discharge-free conditions with all other conditions the same for the two cases.

The experiments revealed that a low current high voltage discharge of the corona type or its variants has a strong effect on the evaporation process, and can increase the velocity of this process by more than an order of magnitude as compared to discharge-free conditions. This effect is dependent on the character of the discharge, the electrode location, the amount by which the liquid meniscus is lowered, etc.

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0022-0841/86/5006-0671$12.50

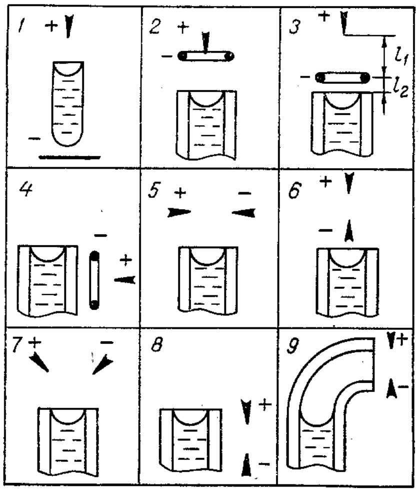

Fig. 1. Electrode configurations used for study of effect of electrical discharge on liquid evaporation processes.

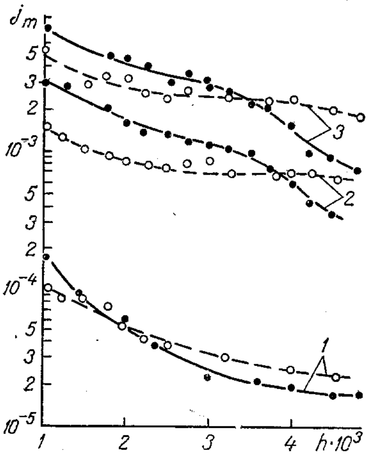

Fig. 2

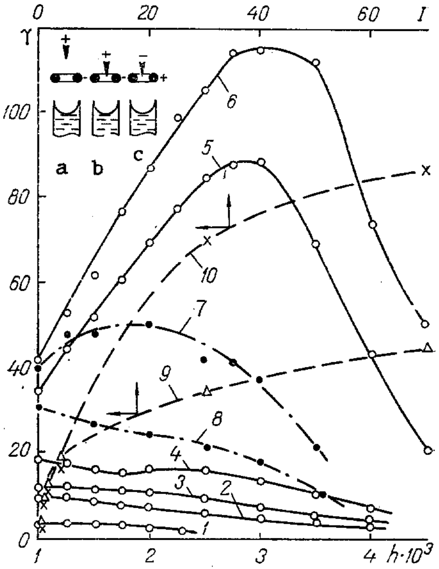

Fig. 3

Fig. 2. Water evaporation rate vs liquid meniscus height in 1.6-mm (solid lines) and 2.5-mm (dashed lines) tubes: 1) no discharge; 2, 3) discharge currents of 4 and 70 μA, respectively. j_m, kg/m^2•sec; h, m.

Fig. 3. Change in relative intensification of water evaporation process with descent of liquid meniscus (curves 1-8) and with change in discharge current I (curves 9, 10). Positive potential of electrode point (arrangement a): 1) I = 0.5; 2) 0.7; 3) 1.5; 4) 4; 5) 30; 6) 70; 7) 70 (arrangement b); 8) 70, negative electrode-point potential (arrangement c); 9, 10) change $\gamma = \gamma(I)$ with meniscus descent by 1 and 2 mm from tube mouth. I, μA.

Figure 2 shows a typical dependence of water evaporation rate on the height of the liquid meniscus h for various discharge and discharge-free conditions (I = 0). In the calculations the evaporation surface was taken equal to the area of a sphere segment. In all cases the evaporation rate was maximal when the liquid meniscus was located near the mouth of the tube. As the meniscus descends evaporation slows, this tendency intensifying with decrease in discharge current. The principles of evaporation kinetics established for the

TABLE 1. Relative Intensification of Water Evaporation from 1.6 mm Diameter Tube under Action of Electrical Discharge for Various Electrode Configurations

No.	Exptl. configuration	l_1, mm	l_2, mm	Discharge current, μA	Point electrode polarity	Rel. intensification h_1	$\gamma_{\min}$	h_2	$\gamma_{\max}$
1	2	0	1,5	0,5	+	1	7,5	2	10
2	2	0	1,5	70	+	1	40	2	50
3	2	0	1,5	70	—	3,5	11	1	31
4	3	1,0	0,2	0,5	+	1	2,3	2	6
5	3	1,0	0,2	30	+	1	2,5	4	10
6	3	1,0	0,2	70	+	1	3,5	4	22
7	3	2,0	0,5	0,5	+	1	2,4	3	3,5
8	3	2,0	0,5	30	+	1	34	3	88
9	3	2,0	0,5	70	+	1	41,5	3	115
10	5	1,6	1,5	0,5		1	3,5	1,5	4
11	5	1,6	1,5	80		3	6	1	12,5
12	6	1,6	1,5	70		1	4	3	7
13	7	1,6	1,5	60		1	16	3	24

TABLE 2. Relative Intensification of Liquid Evaporation γ for Various Electrical Discharge Regimes

Liquid	$p_0 \cdot 10^{30}$, C·m	ε	$\sigma \cdot 10^3$, N/m	Point potential: positive, $I = 10$ μA	positive, $I = 70$ μA	negative, $I = 10$ μA	negative, $I = 70$ μA
Acetone	9,5	21,1	23,7	52,6	71,2	14,2	19,5
Ethyl alcohol	5,6	25,0	22,8	31,8	70,5	14,1	20,7
Isopropyl alcohol	5,6	19,7	21,7	32,3	52,4	7,6	15,7
Water	6,1	81,0	72,8	26,3	38,9	13,3	26,6
Carbon tetrachloride	0	2,2	26,8	24,1	35,0	20,4	30,6
Kerosene	—	2,1	24,0	12,1	—	14,3	28,9

1.6-mm tube are maintained in the wider tube (Fig. 2, dashed lines), but with descent of the meniscus the rate of evaporation from the wider tubes decreases more slowly than the rate from narrow tubes. This indicates an increase in resistance to vapor escape with decrease in tube diameter.

Significant intensification of the evaporation process under the action of a low-current high-voltage discharge begins at discharge currents on the order of 0.5 μA (Fig. 3, curves 1-6). With increase in current from 0.5 to 70 μA there is a nonlinear relationship between current strength and liquid evaporation rate (curves 9, 10). For example, for a point-ring electrode system and 1.6 mm diameter tube at h = 1.0 mm and current of 0.7 μA the evaporation rate increased 10 times as compared to discharge-free conditions (from $5 \cdot 10^{-5}$ to $5 \cdot 10^{-4}$ kg/m^2•sec). Increase in current from 0.7 to 70 μA (curve 6) led to an increase in evaporation by a factor of only four — to $2 \cdot 10^{-3}$ kg/m^2•sec. The same principle of evaporation rate increase with increase in current was observed for other discharge conditions.

Table 1 presents comparative data on intensification of evaporation for various arrangements of point–ring and point–point electrodes, which indicate that the liquid evaporation rate from a thin tube also depends on the electrode form and polarity and their location relative to each other and the tube mouth. The minimum intensification of evaporation for the point–ring electrode system is in the range 2-41, with maximum intensification of 4-115 times. For the point–point system there is also a significant intensification of the evaporation process under discharge conditions, but somewhat less than for the point–ring system. Minimum intensifications lie in the range 3-16 times, with maxima of 4-24 times.

For the point–ring system the current density vector at the point was parallel to the tube axis. In experimental configuration 5 (Fig. 1) the current density vector was perpendicular to the tube axis, while in configuration 7 the current density vector formed a 45° angle to the axis, i.e., an intermediate value. In this case the intensification also takes on a value intermediate between the results of the point–ring and point–point experiments, i.e., intensification of the evaporation process also depends on the inclination of the current density vector at the electrodes to the axis of the tube from which the liquid evaporates, with the greatest effect achieved in the case where the current density vector at the point electrode coincides with the tube axis, as realized in the point–ring electrode system.

An optimum configuration exists for the point–ring electrodes, at which the relative intensification of the evaporation reaches a value of 115 (Table 1, Nos. 7-9). The same effect was achieved with configuration 3 (Fig. 1) where a sufficiently extended discharge zone and small discharge-free zone above the tube mouth are formed. The presence of such a discharge-free zone has a significant effect on the evaporation rate especially at high currents (Fig. 3: 6). Reduction in the size of the discharge zone (configuration 2, Fig. 1) leads to some suppression of the evaporation process (Fig. 3, curve 7), although as before the evaporation rate significantly exceeds that found under discharge-free conditions.

For a fixed electrode configuration relative to the tube mouth intensification of the evaporation process depends on the polarity of the point electrode (Fig. 3, curves 7, 8). Oscillograms of the discharge show that for a negative point potential the current has only a constant component over a wide range of values, becoming impulsive only in the prebreakdown range, while for positive point potential there were almost always current pulses on the background of the constant component. The frequency of these pulses and their character depend on the voltage across the discharge gap. The duration of the pulses varies over the range 30–70 μsec, with amplitudes in the range 10–50 μA. The low current range (to 25 μA) corresponds to a pulsating corona discharge. With increase in current, spark closure of the corona sets in, accompanied by an abrupt increase in the frequency of current pulsations. It should be noted that upon transition from one type of discharge to another the dependence of evaporation rate on current strength remains continuous. The pulsating corona discharge has a greater effect on the evaporation process, with γ being larger, the higher the frequency of these pulses.

The intensification of evaporation by the electrical discharge depends on the physical properties of the evaporating liquid.

Experiments on evaporation of six different liquids were performed under discharge-free conditions ($I = 0$) and for a point–ring electrode system at currents of 10 and 70 μA with both electrode polarities. The liquids were evaporated from a 2.3 mm tube. Distance between the electrodes along the system axis was 1.5 mm, while the distance from the ring electrode to the tube section was 1 mm. Under discharge-free conditions the evaporation rates of the selected liquids differed by more than an order of magnitude and decreased for all liquids with descent of the meniscus. Because of the high volatility of some of the liquids studied the value of the relative intensification of evaporation γ upon discharge action was determined from the average value of the evaporation rate over a segment Δh beginning at the tube section, identical for all liquids. Each experiment was repeated 2–3 times and the mean of several measurements was taken as the evaporation rate. Results of the experiments are presented in Table 2, from which it is evident that depending on polarity of the point electrode the electrical discharge affects the liquids studied in different manners. For positive point electrode potential and the polar liquids acetone, ethyl, and isopropyl alcohols, having practically identical surface tension coefficients, the values of γ vary as the liquid molecule dipole moment p_0. Thus, the highest relative intensification of the evaporation process is observed in acetone, the dipole moment of which is higher than that of the remaining liquids studied. Of the alcohols, which have identical dipole moments, for $I = 70$ μA γ is higher in ethanol than in isopropanol, but the ethanol has a higher dielectric permittivity ε. At $I = 10$ μA the intensification of evaporation by the discharge in both types of alcohol is the same. Water, with dielectric permittivity and dipole moment greater than the alcohols, but also with a surface tension coefficient σ three times larger, has a γ value lower than that of acetone and the alcohols. The nonpolar carbon tetrachloride and kerosene, with the lowest dielectric permittivities, have a γ less than that of the polar liquids.

Change in polarity of the point electrode to negative immediately changes the effect of the discharge on evaporation. The highest intensification is found for CCl_4 and the lowest, for the alcohols and acetone.

Analyzing the results of these experiments, we can conclude that in the action of an electrical discharge upon evaporation of liquids change in polarity of the point electrode has an insignificant effect on the nonpolar liquid CCl_4 and kerosene and a very intense effect on polar liquids, probably due to their electrical properties and the effect of the discharge on the surface layer.

The hypothesis that intensification of evaporation under the action of a discharge is produced by attraction of the liquid film along the capillary walls [3-5] was not confirmed in our experiments for evaporation of liquids from glass tubes 1.6-2.5 mm in diameter. This hypothesis was subjected to further testing in experiments upon evaporation of a liquid droplet, performed by the method described in [6], with similar conditions for discharge action on evaporation kinetics. In this case increase in the evaporation area due to attraction of a thin liquid film is excluded, and intensification of the evaporation process in all experiments remained at the same level as in evaporation from thin tubes.

Comparison of the results obtained with the data from the literature shows that with organization of the process with the configurations presented herein, where the discharge is excited above the liquid surface and the liquid itself remains outside the interelectrode gap, intensification of the evaporation process is an order of magnitude greater than observed in [1-5], and that this phenomenon can be considered a physical effect of the action of the electrical discharge on evaporation kinetics. Analysis of the experimental data indicates the existence of two mechanisms for intensification of evaporation under discharge conditions: 1) thermal action of the discharge on the liquid; 2) participation of liquid vapors in the discharge process and convective mixing of the vapor—gas mixture due to an electrogasdynamic flow accompanying electrical discharges in gases [7, 8].

With periodic application and removal of the discharge at defined time intervals the rate of evaporation is quite sensitive to creation and suppression of discharge conditions with insignificant inertia, which indicates the surface character of discharge energy absorption on the phase boundary. Thus, for application of a discharge current of 70 μA over a period of time less than 1 min the evaporation rate of water increased 4-5 times. A similar pattern was observed for switchoff of the discharge current for any repetition rate of a train of impulsive discharges.

When a discharge is excited not above the mouth of the tube, but on the outside along the side wall of the tube at the level of the meniscus (configurations 4 and 8, Fig. 1) in general no intensification of the evaporation process was observed. The expected thermal effect, related not only to thermal conductivity, but also to radiation, was not observed. In addition, under the conditions described the other proposed intensification mechanism cannot develop either. In experiments where the discharge was localized in the mouth of a curved tube (configuration 9, Fig. 1) there was a significant intensification of evaporation characteristic of discharge conditions, despite the fact that the thermal action of the discharge on the liquid was suppressed significantly. Thus, at $I = 70$ μA $\gamma = 3\text{-}4$, and at $I = 110$ μA $\gamma = 10\text{-}15$.

Qualitative analysis of these results indicates that the volume thermal effect is not the main factor determining intensification of evaporation under the action of a discharge, since in the latter case transient processes would be of greater duration.

Thus it follows that the mechanism "responsible" for intensification of liquid evaporation under discharge conditions is the action of the discharge on the surface layer of the liquid and attraction of liquid vapor into the discharge processes, which are accompanied by extraction of these vapors from the mouth of the tube (i.e., there is an action similar to that of a pump). This mechanism can be controlled by various physical factors:

1) The inhomogeneous electric field of the discharge can attract liquid molecules in the vapor phase as dipole systems into the discharge zone.

2) Attraction of liquid vapor into the discharge zone may be related to ionization of the former. It is known that upon excitation of an electrical discharge a large quantity of positive and negative ions and electrons is formed about the corona electrode, with mainly negative ions being formed when the point electrode is negative due to "adhesion" of free

electrons to neutral molecules. The possibility and speed of such "adhesion" are determined by the electron affinity to the molecule of the evaporating liquid. The large quantity of negative ions formed affects the properties of the electrical discharge, with the discharge showing a characteristic instability and a change in its current-voltage characteristic [9]. For example, for CCl_4 the vapor flux density during evaporation and the negative ion formation rate are very high [9] and it can be assumed that negative CCl_4 ions are formed sufficiently rapidly and in large quantity for both negative and positive potentials of the point electrode, which has an effect on the character of the discharge, so that change in electrode polarity has little effect on intensification of the evaporation process.

If the dominant ion type is positive, which is characteristic for positive potential of the point electrode, then the flux of ionized gas has a high energy capacity as compared to a flux of electrons and negative ions [10] and its effect on evaporation processes will probably be more significant.

3) The surface of the liquid is drafted by gas dynamic jets (the electrical wind of [7, 8]), formed in the interelectrode space due to directed motion of gas ions, the sign of which coincides with that of the corona electrode. Upon collision the ions transfer their energy to neutral molecules, initiating a flow of gas from the corona point electrode to the second electrode, which intensifies heat liberation by a factor of more than two times [7].

An approximate evaluation of the speed of the gas dynamic flow was performed experimentally using the comparison method. The point—ring electrode system of configuration 3 (Fig. 1) was installed above a water-filled cup 5 mm from the liquid surface as was a vertical tube with inner diameter of 1 mm, connected through a type RS-3A rotameter to a compressed gas cylinder. Upon excitation of a discharge, under the action of the electrical wind a crater with depth dependent on the discharge current forms on the liquid surface. By selecting the air flow rate through the tube such that the crater in the liquid surface was of the same depth as under discharge conditions, and determining this flow rate with the rotameter, the velocity of the gas jet can be calculated. Experiments showed that for change in discharge current from 10 to 70 μA the speed of the gas dynamic flow changes from 6 to 13 m/sec.

The flow normal to the evaporation surface insures transverse mixing of the vapor—gas mixture, which intensifies heat exchange and enables a significant reduction in partial vapor pressure along the evaporation surface. This is confirmed by the fact that the greatest intensification of the evaporation process was found in experiments where the current density vector at the point electrode was parallel to the tube axis and a small discharge-free zone was formed above the tube mouth.

Thus, on the basis of the experiments performed it can be proposed that entrance of the surrounding gas and liquid vapor into discharge processes is accompanied by formation of high energy gas dynamic flows at the electrodes, which in their action on the liquid insure significant liberation of energy at the boundary with excitation of intense evaporation and effective turbulent removal of vapor from the evaporation surface. The high energy capacity of these flows is specifically related to the discharge since the latter generates such high energy particles as ions, excited neutral atoms, and molecules, which can enter the composition of the gas dynamic flow and transfer their energy to the liquid surfaces.

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HYDRODYNAMICS OF THE FILTRATION PROCESS OF DRYING

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UDC 66.047

The results of investigations and a capillary model of the hydrodynamics of the drying of gas-permeable sheet materials by filtration are presented.

The interest of investigators has recently been attracted by the process of drying of gas-permeable materials by filtration. The essence of this method is that the heat-transfer agent under the action of a pressure difference passes through pores and capillaries of the material, imparts heat to it, and, becoming saturated with moisture, is drawn out of it. As was established in [1-4], the filtration drying of gas-permeable materials occurs dozens of times more intensely than ordinary convective drying. The mechanism of filtration heat and mass exchange, as well as the factors causing its intensification, are described in detail in [5, 6].

In an investigation of filtration drying, it is important to study the hydrodynamics of the process. Filtration heat and mass exchange is a nonsteady process. The hydraulic resistance of a material in the process of drying is a variable quantity; it decreases from a maximum value at the start of drying, when the material has a moisture content $W = W_0$, to a minimum when the moisture content is $W = W_{eq}$.

The rate of filtration of the heat-transfer agent through the material increases with a decrease in its moisture content. The only constant hydrodynamic characteristic of the material is the dependence of the hydraulic resistance on the rate of air movement through the pores and capillaries, when the material is in a dry state.

To obtain the analytic dependence between the hydrodynamic parameters ΔP_m and Q_m of the material in the dry state and the current values ΔP and Q, varying in the process of drying, we present a capillary model below. The occurrence of both the mass-exchange and the hydromechanical processes has a very complicated character, and the proposed model reflects the true picture of these phenomena only in a first approximation.

The structure of a porous solid, all the capillaries of which are of cylindrical shape, pass through it, and are partly filled with moisture, is represented in simplified form in Fig. 1. If a heat-transfer agent moves through such a solid, then the current value of the hydraulic resistance, equal to $\Delta P = P_1 - P_2$, corresponds to a velocity of the heat-transfer agent of

$$w = \frac{4Q}{NF\pi d_c^2}. \qquad (1)$$

Lenin Komsomol Polytechnic Institute, Lvov. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 6, pp. 959-963, June, 1986. Original article submitted February 25, 1985.

0022-0841/86/5006-0677$12.50