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EFFECT OF VARIABLE ELECTRIC FIELDS ON THE THERMAL CONDUCTIVITY OF DIELECTRIC LIQUIDS

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We give a description of the apparatus, procedure, and experimental results of an investigation of the effects of variable electric fields on the thermal conductivity of dielectric liquids.

The results of many investigations indicate an intensifying effect of constant and variable electric fields of low and high frequencies on heat exchange in dielectric liquids [1-4]. However, the nature of the phenomenon and the mechanism of the processes taking place when the heat exchange in dielectric liquids is affected by an electric field have not been sufficiently clarified. Up to now, therefore, there is no general method for calculating the heat exchange in an electric field.

The authors of studies devoted to this problem attribute the intensification of the heat exchange to the occurrence of electroconvection, i.e., the macroscopic motion of the liquid under the action of electric-field forces. They usually disregard the question of the thermophysical properties of the medium in the field, assuming that they cannot change or that they are negligibly small.

Attempts at the experimental investigation of the effect of electrical fields on the thermal conductivity of liquids have been carried out in [5-7]. The results of these studies did not confirm the assumptions concerning the effect of constant and variable low-frequency (∿50 Hz) fields on the thermal conductivity of liquids. There are no data at all on the effect of high-frequency electric fields on the thermal conductivity of liquids.

The purpose of the present study is to investigate experimentally the effect of electric fields with frequencies of $3 \cdot 10^5$ to $6 \cdot 10^5$ Hz on the thermal conductivity of dielectric liquids. The thermal conductivities were measured by a relative method using a plane layer in combination with an interference method for determining the temperature difference in a

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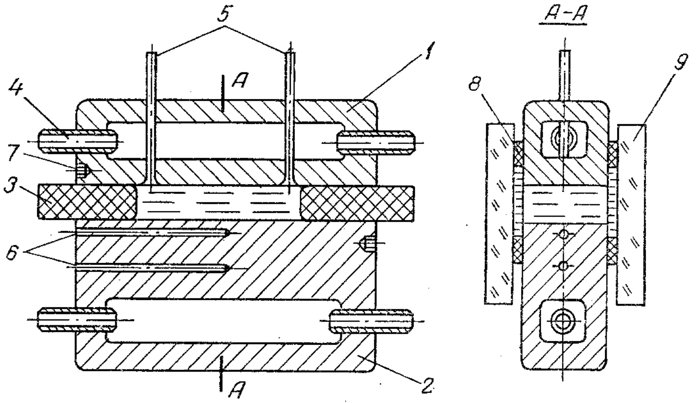

Fig. 1. Diagram of the measuring cell.

layer of the liquid under investigation. The latter made it possible to demonstrate clearly that there was no convection in the liquid.

The experiments were carried out on an apparatus whose basic elements were a measuring cell with a thermostating system, an electrical generator, and an optical apparatus. A diagram of the measuring cell is given in Fig. 1. The cell consisted of two hollow flat plates of stainless steel, 1 and 2. The liquid 8 being investigated was placed in the closed volume between two fluoroplastic spacers 3, the optical glass blocks 9 and the plates 1 and 2, which acted as the electrodes of a capacitor. The upper plate was fed with the voltage from the electrical generator, and the lower plate was grounded. The openings 7 were used for connecting the electrical contacts. The plates had fittings 4 for the entry and exit of the thermostating liquid and fittings 5 for pouring in the liquid under investigation. The grounded lower plate acted as the calibrating layer. The holes 6 were drilled in the end wall of the plate in a direction parallel to the working surface. Into these holes we placed the junctions of a differential thermocouple, the vertical distance between which was $14 \cdot 10^{-3}$ m, and determined the thickness of the calibrating layer. The electromotive force of the thermocouple was measured by an R348 potentiometer with an accuracy of 0.002. The distance between plates 1 and 2 (the thickness of the liquid layer) was $8 \cdot 10^{-3}$ m.

The cell was placed in a metal vacuum chamber, which served as an insulator and a shield to exclude the effect of extraneous fields on the process under study.

The high-frequency electric field applied to the measuring cell may be a source of significant parasitic emfs induced in the thermocouple circuit and distorting the results of the measurements. In order to prevent the rise of such parasitic emfs, the thermocouple wires, for their entire length from the surface of the cell plate to the potentiometer, were encased in a grounded metal shield. Metallic contact was established between the thermocouple shield and the body of the plate. For insulation from the metal shield and the body of the cell plate, the thermocouple wires were placed in a fluoroplastic cambric.

The upper hole 6 for the thermocouple was placed at a depth of 2.5 mm from the surface of the plate. This is certainly greater than the depth of penetration of the electric field, which for the material of the plate — 1Kh18N9T steel — and the field frequencies of up to $6 \cdot 10^5$ Hz that were used, is 0.54 mm. Therefore, there was no electric field in the region of thermocouple placement.

In addition, if the external electric field had induced parasitic emfs, then the thermocouple readings would have had to change almost instantaneously at the moment when the field was turned on. However, as the experiments showed, the changes in the thermocouple readings began some time after the field was turned on and came to an end after 5-15 min, depending on the experimental conditions. This was an indication that the variations in the thermocouple emf were due to thermal processes and not to the direct action of the electric field on the thermocouple.

The thermostating system consisted of two thermostats which fed transformer oil onto each plate of the cell in order to maintain the specified temperature on the plates.

The high-voltage source used was an L3-13 generator. The oscillatory loop of the generator was assembled according to a circuit which ensured stepwise variation of the voltage and frequency at the outlet ranging from 0 to 4 kV and from $3 \cdot 10^5$ to $6 \cdot 10^5$ Hz, respectively.

The optical apparatus was a variant of the double-beam interferometer. The light source used was an LG-36 optical quantum generator. The interferometer enabled us to observe the temperature field in the liquid layer, i.e., to judge the nature of the heat exchange (molecular or convective) and to make quantitative calculations of the temperature drop in the layer. The possibility of using an interferometer in the experimental determination of the thermal conductivity of liquids was explained in [8].

The experiments were carried out in the following sequence: we determined the thermal conductivities of the liquid without an electric field, λ_{liq}, and in an electric field, λ_{liq}^{el}; from the relative change in the thermal conductivity, $\lambda_{liq}^{el}/\lambda_{liq}$, we could judge the effect produced by the field on the thermal conductivity of the liquid under investigation.

The values of the parameters of the electric field were the following: intensity $E = 110, 150, 200, 250$ kV/m; frequency $\nu = 3 \cdot 10^5, 5 \cdot 10^5, 6 \cdot 10^5$ Hz.

The average temperature of the liquid layer in the experiments varied between 290 and 294°K. The temperature difference in the liquid layer varied between 1.5 and 4°K.

We investigated the effect of the electric field on the thermal conductivities of chlorobenzene, toluene, carbon tetrachloride, and benzene, whose molecules have dipole moments of 1.56, 0.50, 0, and 0 D, respectively.

In conducting the experiments, we paid special attention to the purity of the liquids being investigated. The liquids were dehumidified with potassium chloride, filtered, and distilled at the appropriate boiling temperatures. The purity of the liquids after this was monitored by measuring the index of refraction with an IRF-22 refractometer.

The thermal conductivities were measured by the relative plane-layer method. This method is based on the fact that the heat flux passing successively through two plane layers — a layer of the liquid under investigation and a layer of a calibrating material — creates on the boundaries of the layers temperature differences proportional to their thermal resistances. Thus, for a stationary regime in the absence of an electric field

$$q = (1/R_{liq})\,\Delta T_{liq} = (1/R)\,\Delta T, \tag{1}$$

for a stationary regime in an electric field

$$q^{el} = (1/R_{liq}^{el})\,\Delta T_{liq}^{el} = (1/R)\,\Delta T^{el}. \tag{2}$$

Here $R_{liq} = l_{liq}/\lambda_{liq}$ and $R_{liq}^{el} = l_{liq}/\lambda_{liq}^{el}$ are the thermal resistances of the layer of liquid being investigated without an electric field and in an electric field, respectively. The thermal resistance of the calibrating layer of metal, R, was determined by a relative method using a calibrating liquid and found to be $R = 0.761 \cdot 10^{-3}$ $(m^2 \cdot {}^\circ K)/W$. It should also be noted that in our experiments we excluded the possibility of the electric field's affecting the thermal conductivity of the metal, and consequently $R = \text{const}$.

From (1) and (2), after substituting the values of R_{liq} and R_{liq}^{el}, we obtain the following expressions for the thermal conductivities:

$$\lambda_{liq} = (1/R)\,l_{liq}\,(\Delta T/\Delta T_{liq}), \tag{3}$$

$$\lambda_{liq}^{el} = (1/R)\,l_{liq}(\Delta T^{el}/\Delta T_{liq}^{el}). \tag{4}$$

l_{liq} and R are known constants. Thus, the problem of determining λ_{liq} and λ_{liq}^{el} reduces to the measurement of the temperature drops in the liquid layer, ΔT_{liq}, ΔT_{liq}^{el}, and in the calibrating layer, ΔT and ΔT^{el}.

The temperature drop in the calibrating layer was determined from the readings of a potentiometer included in the thermocouple circuit, and the pressure drop in the liquid layer was determined from the number of interference bands, according to the equations

$$\Delta T_{liq} = \frac{m\overset{0}{\lambda}}{S\,(dn/dT)}, \quad \Delta T_{liq}^{el} = \frac{m^{el}\overset{0}{\lambda}}{S\,(dn/dT)}. \tag{5}$$

Here S, dn/dT, and $\overset{0}{\lambda}$ are known constants, and therefore in order to determine ΔT_{liq} and ΔT_{liq}^{el} we must know the number of interference bands in the image of the liquid layer with

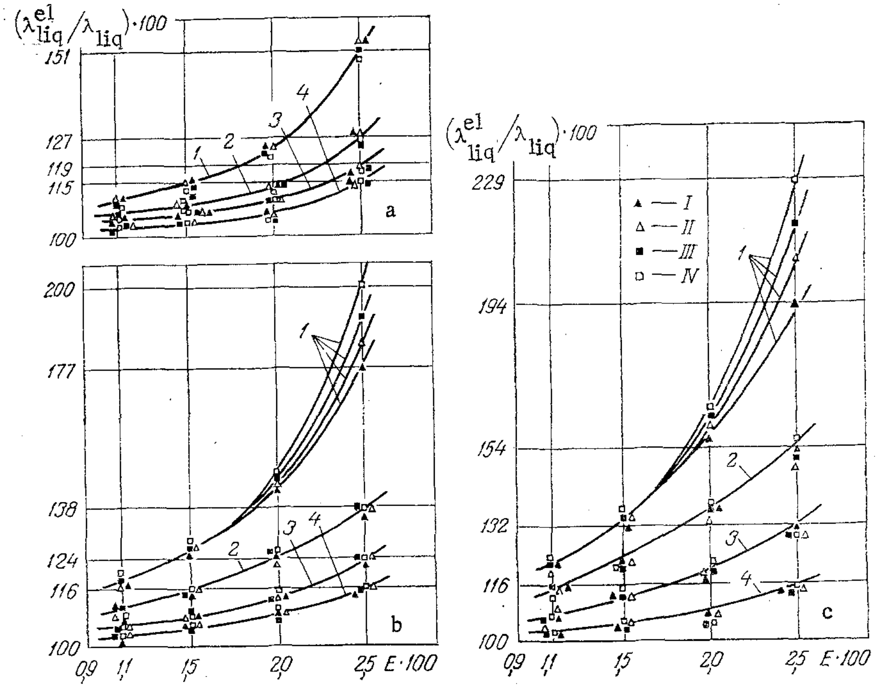

Fig. 2. Variation of $(\lambda_{liq}^{el}/\lambda_{liq})\cdot 100$ (%) as a function of E (kV/m) for values of ν (Hz) equal to: a) $3\cdot 10^5$; b) $5\cdot 10^5$; c) $6\cdot 10^5$: 1) chlorobenzene (I) $T_{av} = 292.95$°K; II) 293.15; III) 293.65; IV) 294.05); 2) toluene (I) $T_{av} = 292.65$°K; II) 292.95; III) 293.65; IV) 294.05); 3) carbon tetrachloride (I) $T_{av} = 292.65$°K; II) 293.15; III) 293.65; IV) 293.95); 4) benzene (I) $T_{av} = 291.65$ K; II) 292.15; III) 292.65; IV) 292.95).

and without an electric field — m and m^{el}, respectively. In order to determine the number of bands, the observed interference picture was recorded on photographic film, from which we then obtained microphotographs by means of an IFO-451 microphotometer. The values of the thermal conductivities were referred to the average temperature of the liquid layer, $T_{av} = T_2 + \Delta T_{liq}/2$, where T_2 is the temperature of the lower plate, which was kept in the 290-292.5°K range.

The values of the thermal conductivities of chlorobenzene, toluene, carbon tetrachloride, and benzene measured without an electric field differed from the literature data [9] by no more than 1%. This confirmed the satisfactory accuracy of the measurement method and the reliability of the measured values of λ_{liq}.

In variable electric fields in the range of frequencies we used, it is possible that the metal of the plates and the dielectric liquids will become heated. Estimating and taking account of such factors superimposed on the basic heat-conduction process under study constitute one of the necessary conditions for obtaining reliable results in the λ_{liq} measurements. However, the calculation of the electric-field power losses for heating the metal of the plates and the dielectric liquids is a complicated problem which can be solved only approximately. For this reason, before measuring the thermal conductivity in the field, we conducted special experiments.

Over the entire range of the parameters ν and E of the electric field, we measured the values of the temperature drops in the calibrating layer, δT_1^{el} and δT_2^{el}, corresponding to the heat fluxes q_1^{el} and q_2^{el}, resulting from the heating of the metal of the plates and the liquids under investigation. In determining the values of δT_1^{el}, a cell free of liquid was thermostated for the case of identical temperatures at the upper and lower plates: $T = T_1 = T_2$, i.e., $\Delta T = 0$. In our determination of the values of δT_2^{el}, the cell filled with the liquid under investigation was also thermostated for the case $T = T_1 = T_2$, i.e., $\Delta T = 0$ and $\Delta T_{liq} = 0$. Such experiments were carried out for different temperatures T over the entire range of variation from 290 to 294°K. In the range of field parameters we used, the dielectric heating of toluene, carbon tetrachloride, and benzene was negligibly small and could not be sensed by our measuring instruments. For chlorobenzene we observed slight dielectric losses and corresponding temperature drops in the calibrating layer, δT_2^{el}. As the experiments showed, the quantities δT_1^{el} and δT_2^{el} depended on the field parameters ν and E were independent of the values of the absolute temperatures T in the range under investigation.

In our measurement of the thermal conductivity in the case of an applied electric field, the temperature drop in the calibrating layer increased, $\Delta T_{liq}^{el} > \Delta T$, which indicated an increase in the heat flux through the lower plate. This can take place, on the one hand, as a result of a variation in the thermal conductivity of the liquid in the field and, on the other hand, as a result of the generation of heat because of electrical-energy losses in the metal of the plate and in the liquid. Consequently, the total heat flux density passing through the layer of calibrating liquid is

$$q_{tot}^{el} = q^{el} + q_1^{el} + q_2^{el}, \tag{6}$$

from which we obtain an expression for the component of the heat flux q^{el} that characterizes the assumed effect of the increase in the thermal conductivity of the liquid in the field:

$$q^{el} = q_{tot}^{el} - (q_1^{el} + q_2^{el}). \tag{7}$$

From (7), taking account of the fact that $R = \text{const}$; $q^{el} = (1/R)\Delta T^{el}$; $q_{tot}{}^{el} = (1/R)\Delta T_{tot}{}^{el}$; $q_1{}^{el} = (1/R)\delta T_1^{el}$, and $q_2^{el} = (1/R)\delta T_2^{el}$, we find

$$\Delta T^{el} = \Delta T_{tot}^{el} - (\delta T_1^{el} + \delta T_2^{el}). \tag{8}$$

In determining ΔT^{el} from the values of $\Delta T_{tot}{}^{el}$ measured for given field parameters ν and E, we calculated the values of δT_1^{el} and $\delta T_2{}^{el}$, determined for the given liquid at the same values of ν and E in the preliminary experiments. As indicated above, the values of $\delta T_1{}^{el}$ and $\delta T_2{}^{el}$ were independent of the values of absolute temperature in the 290-294°K range. This gives reason to assume that the results of the preliminary experiments, carried at $\Delta T = 0$ and $\Delta T_{liq} = 0$, remain valid when we have temperature differences in the 1.5-4.0°K range.

The increments in the temperature drops in the calibrating layer, $\delta T_1^{el} + \delta T_2^{el}$, corresponding to the heating of the metal of the plates and of the liquid in the field, amounted to 2-12% of the corresponding values of $\Delta T_{tot}{}^{el}$.

The reliability of the measured values of λ_{liq} and λ_{liq}^{el} depends largely on the absence of thermal and electrical convection in the liquid. Therefore during the entire experiment, both without an electric field and after the field was turned on, we maintained visual observation and took photographic images of the liquid layer. The criterion of stationary of the thermal state and absence of convection was the maintenance of constant readings on the thermocouple, stability of the interference picture, rectilinear shape of the interference picture, rectilinear shape of the interference bands, and equal numbers of interference bands on microphotographs corresponding to the photographs taken at different instants of time after the onset of the stationary state. As the experimental results showed, for all the electric-field parameters used in the liquids we investigated, there was no electroconvection.

When convection was found, we took no measurements.

In accordance with the results of [10] on measuring cells identical with those used in our experiments, for the liquids we investigated and the temperature range we used, the maximum value of the radiant component of the thermal conductivity is 2-7%, which does not exceed the limits of error of our experiments. Therefore, the radiant component of the thermal conductivity was not taken into consideration, and we assumed that the heat transfer in the liquid took place by pure conduction.

A more detailed description of the method used in carrying out the experiments is given in [11].

The maximum relative error in the measurements was 9%. An average of 50% of the total number of λ_{liq}^{el} measurements were tested for reproducibility. Individual experimental points were reproduced 3-5 times. The variation of the results of individual measurements did not exceed 4%.

The results of the experiments for the liquids investigated are shown in Figs. 2a, b, and c in the form of curves of the relative change in thermal conductivity, $(\lambda_{liq}^{el}/\lambda_{liq})\cdot 100$ (%), as a function of the electric field intensity. As can be seen from Fig. 2, in a variable electric field there is an increase in the thermal conductivities both of chlorobenzene, a polar liquid, and of toluene, carbon tetrachloride, and benzene, which are nonpolar liquids. The effect of an increase in thermal conductivity becomes greater with increased value of the dipole moment of the liquid molecules for all the field parameters ν and E that we used.

Both in polar and in nonpolar liquids we observe an increase in the effect produced by the field on the thermal conductivity as the field intensity increases.

For benzene the magnitude of the increase in thermal conductivity is independent of the frequency of the electric field. For chlorobenzene, toluene, and carbon tetrachloride we see a dependence of the effect on the frequency of the field. Thus, for a maximum field intensity and an increase in frequency from $3\cdot 10^5$ to $6\cdot 10^5$ Hz the values of $(\lambda_{liq}^{el}/\lambda_{liq})\cdot 100$ (%) increase for chlorobenzene from 151 to 229, for toluene from 128 to 154, and for carbon tetrachloride from 119 to 132, while for benzene they remain equal to ∿116.

The phenomenon we have discovered is an indication that when a liquid is acted upon by a variable electric field, there may be not only electroconvection but also an intensification of molecular heat transfer as a result of the increase in thermal conductivity. Evidently, both of these factors may contribute to the total effect of intensifying the heat exchange in the electric field.

NOTATION

λ, thermal conductivity, W/m·K; E, electric field intensity, kV/m; ν, frequency of the electric field, Hz; q, heat flux density, W/m; T, temperature, °K; ΔT, temperature drop, °K; R, thermal resistance, (m·K)/W; l, height of the layer, m; m, number of interference bands; $\overset{\circ}{\lambda} = 6328$, wavelength of the light source, Å; $S = 2.8\cdot 10^{-3}$, layer length in the direction of the beam, m; dn/dT, temperature coefficient of the index of refraction of the liquid. The subscript liq indicates the parameters of the liquid; the superscript el indicates the values of the parameters in the electric field.

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