HEAT TRANSFER IN A DIELECTRIC LIQUID

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We have investigated heat transfer between two electrodes immersed in a liquid dielectric. The upper electrode was heated. The interference pattern in the interelectrode space was photographed, and simultaneously a noncontacting measurement was made of the temperature of the thin layer of liquid above the lower electrode. It was shown that the time from the instant the field was turned on to the appearance of the temperature jump above the lower electrode was the same as the time for the advance of the heated region of the oil between the electrodes as obtained from the photographs. The conclusion is that the basic mechanism responsible for the increased heat transfer in a liquid when the field is turned on is the turbulent hydrodynamic flow between the electrodes.

Investigations of heat transfer between conducting bodies immersed in a dielectric fluid and maintained at different potentials have been reported in a number of papers [1-8] and can be of practical importance [5, 7].

I. E. Balygin observed a sharp increase in the thermal conductivity of transformer oil between two electrodes maintained at a constant potential difference when the difference in temperatures of the oil measured by two thermometers, one close to the heated upper electrode and the other near the lower electrode, fell rapidly after the electric field was turned on [3] (also cited in [9,10]). The author estimated that heat transfer by charged particles giving rise to a conduction current in the oil is many orders of magnitude smaller than the observed value. Therefore, to interpret the experimental results the author made some questionable assumptions about the formation of a large number of weakly bound ionic complexes in the oil, which dissociate in an electric field E of the order of a few kV/cm and are responsible for the increase in the thermal conductivity but do not take part in the production of the conduction current.

It is known [3, 9, 10] that a liquid dielectric between electrodes is set into motion when a potential difference is applied between the electrodes [4-6, 11, 12]. In qualitative experiments G. A. Ustoumov [11] observed that a steady electric field produced a flow from the upper heated electrode downward and then toward the walls and upward, i.e., opposite the direction of natural convection. In another paper [13] Ustoumov presented theoretical estimates of the role of electrohydrodynamic processes and showed that a mobile medium cannot remain at rest in an electric field, and that the velocity of the liquid is proportional to E^2 for weak fields and increases linearly with E for strong fields.

It therefore appears more plausible to assume that the increase in heat transfer rate in a liquid dielectric in an electric field [1-8] is due mainly to an intensive electrohydrodynamic intermixing of liquid rather than to a flow of charged particles.

Our purpose is to test this assumption for heat transfer in transformer oil.

The experimental arrangement is shown schematically in Fig. 1. The Teflon vessel 1 with plane-parallel glass windows is filled with transformer oil and placed in one arm of a Michelson interferometer. The upper grounded copper electrode 2 is 40 mm square, has a radius of curvature of 200 mm, and can be heated by coil 3. The temperature of the electrode is measured with the miniature thermocouple 4.

The lower high-voltage electrode 5, placed 10-20 mm from the upper, has a window 6 of a single crystal of germanium which is transparent to wavelengths $\lambda > 2\mu$ [14] and transmits the infrared radiation from the oil. At room temperature germanium has a resistivity of ~ 50 ohm/cm [15], which is eleven orders of

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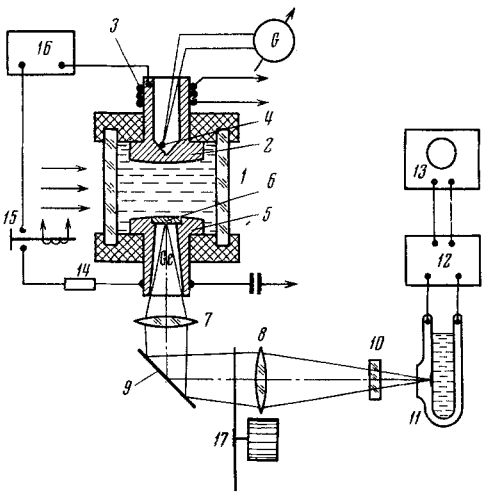

Fig. 1

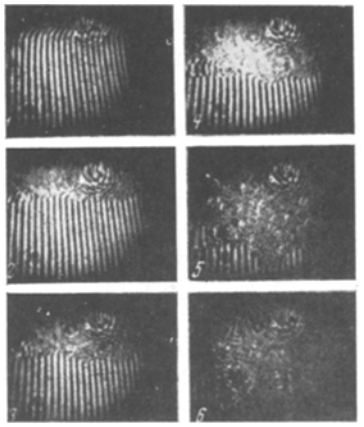

Fig. 2

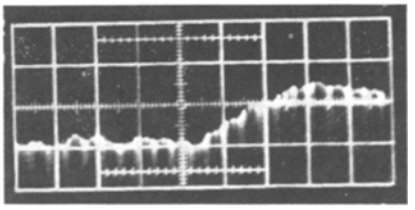

Fig. 3

magnitude smaller than the resistivity of the oil, and hence the distortion of the electric field near the electrode due to the presence of this window can be completely neglected.

Since the oil absorbs strongly in the infrared region of the spectrum, its temperature can be determined from the intensity of the thermal radiation in a thin layer (~ 0.5 mm) in direct contact with the surface of the germanium window. The infrared optical system consists of two lenses 7 and 8 made of CaF_2 [14], a deflecting mirror 9, and a light filter 10 which transmits the absorption band of the oil. A light signal modulated with a 400 GHz frequency by a rotating sector interrupter 17 [16] is recorded by a liquid nitrogen cooled infrared receiver 11 (InSb photovoltaic regime [17]), amplified by a selective amplifier 12 (U2-6), and recorded on the C1-29 oscilloscope screen 13. The potential of the high-voltage electrode is applied through the protective resistance 14 ($R = 25\,k\Omega$) and relay 15 from a Tesla Bs 222 variable high-voltage rectifier 16. The interelectrode space is photographed by the light of a helium–neon laser (0.63 μ) by a Pentazet-16 camera.

Thus the equipment permitted the simultaneous photographing of the interference pattern in the interelectrode space and the recording of the temperature of the liquid close to the surface of the lower electrode.

The measurements were performed in the following way. As rapidly as possible, in a time of the order of 10 sec, the massive upper electrode was heated, the heater was turned off, the motion-picture camera was started, and the electric field was turned on. A differentiated pulse from the lower electrode simultaneously started up the oscilloscope sweep and the time markings on the motion-picture camera, so that the start of the process was fixed precisely on the film.

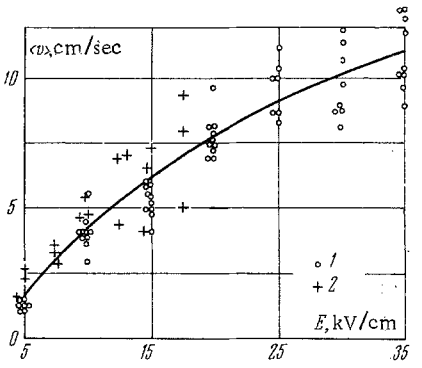

Fig. 4

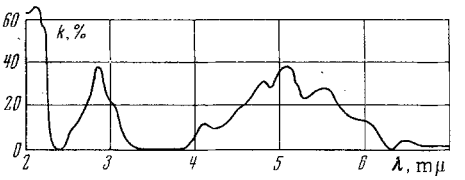

Fig. 5

The main purpose of the experiment was to show that when the upper layer of oil is heated ($20°C < T < 100°C$) and the electric field ($0 < E < 25$ kV/cm) is turned on, i.e., when all the conditions of the experiments in [3] are satisfied, there is no increase in the thermal conductivity and heat transfer until the upper layer of heated oil approaches the surface of the lower electrode as a result of electrohydrodynamic flow.

From a large number of measurements it was established that the jump in temperature of the oil above the surface of the lower electrode, determined by the infrared signal, does not occur immediately after turning on the electric field, but only after a rather long time, and that this delay time τ coincides with the time for the downward propagation of the boundary of the heated region of the oil as shown in the photographs. When the upper electrode was heated slowly, similar results were obtained, but the accuracy of determining τ was decreased since a large region of liquid was heated and the leading edge of the buildup of the infrared signal became more gently sloping.

No significant dependence of the phenomenon on the polarity of the voltage applied to the electrodes was observed. Since the upper electrode was rather massive, the experiment could be repeated several times without further heating if one to two minutes was allowed between turning off the field from one experiment and turning it on for the next to establish a temperature gradient in the vessel. The temperature jump became smaller each time since the upper electrode cooled off and the average temperature of the oil increased.

When the field remained turned on all the time, the infrared signal fell for about 10 minutes while the upper electrode and the container were cooling. In this case an intensive turbulent motion of the liquid was observed at all times, downward in some parts and upward in others. This pattern remained qualitatively the same if the upper electrode was heated only 1-2°, which was enough to make the flow visible.

Figure 2 shows photographs of the moving boundary of the heated region of the oil when the field was first turned on, obtained with the interferometer. Frames 1-6 correspond to times ϑ after turning on the field; $\vartheta = 50$, 140, 170, 190, 235, and 260 msec. The potential difference between the electrodes $U = 35$ kV and the distance between electrodes $L = 2$ cm. Figure 3 shows a typical oscillogram of the signal, proportional to the radiation of the liquid over the surface of the lower electrode. $U = 35$ kV, $L = 1$ cm, $T \approx 35°C$, and the time scale is 20 msec/cm.

The average velocity of the boundary $\langle v \rangle = L/\tau$, where L is the distance between the electrodes, calculated from the photographs and oscillograms for $L = 1$ cm and $T = 40°C$, is shown in Fig. 4 where points 1 were obtained from the infrared signal and points 2 from the photographs. The initial temperature of the oil was 20°C.

Analysis of this figure shows that the experimental relation obtained for $\langle v(E) \rangle$ agrees qualitatively with theoretical estimates of the characteristic velocity of turbulent motion [13]. The numerical values of the velocity in the latter case, estimated by Eq. (20) of [13], agree in order of magnitude with the measured values.

The graph of $\langle v(E) \rangle$ is similar to the graphs given in a number of papers [4-6, 8] for the effectiveness of the electric field or the relative increase in heat transfer in a liquid dielectric as a function of E. Intensive growth begins with a field intensity $E = 2.5$ kV/cm; at this value a rapid increase in the heat transfer coefficient is observed. According to [5, 6, 8], these values lie in the 0.7-2 kV/cm range.

The value of $< v(E) >$ increases with increasing initial temperature of the upper electrode. The effectiveness of heat transfer also increases with an increase in the temperature drop in the liquid [4, 6, 8]. This coincidence is clearly not fortuitous but arises from the fact that in the range of E and T values considered, at least in liquid dielectrics, heat transfer between conductors between which a potential difference is maintained does not occur as a result of a flow of charged particles but because of the turbulent motion of the liquid between the electrodes, i.e., as a result of its intensive intermixing.

The fact that no appreciable dissociation of ionic complexes occurs in the range of E and T values considered is confirmed by the measurements of the infrared transmission spectrum of the transformer oil. To measure the transmission spectrum, a special flat container with plane-parallel NaCl windows was constructed [14] with a heating system and two parallel high-voltage electrodes with the space between them filled with oil. The transmission spectrum of a 1-mm layer of oil was taken on an infrared spectrometer at various temperatures and voltages. For $20°C < T < 100°C$ and $0 < E < 12$ kV/cm the transmission spectrum was the same as the room temperature spectrum with the field turned off (Fig. 5). This confirms the absence of significant changes in the oil at the molecular level, since such changes would have affected the transmission spectrum.

Thus the results obtained lead to the conclusion that the effect on a liquid dielectric of the temperature and electric field in the range considered does not produce a sharp increase in the thermal conductivity of the liquid nor an appreciable change in its structure at the molecular level. The increase in heat transfer in a dielectric liquid is due to intensive turbulent motion of the medium between the electrodes.

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