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REGULATION OF HEAT TRANSFER USING LIQUID CRYSTALS IN THE PRESENCE OF ELECTRIC FIELDS

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Abstract. The heat transfer through a fluid depends both on the thermal conductivity and the motion of the fluid. When the fluid is a certain type of liquid crystal, the motion of the fluid can be controlled by an electric field. Results presented here show that the rate of heat transfer increased by at least a factor of ten when a high field was applied. Results are reported showing how a model proposed earlier can be used to explain the fluid's motion which started at the instant the field was applied.

The ability of a sample of liquid crystal to transfer heat depends both on the thermal conducitivity and the motion of the fluid. An electric field can be used to control the motion of certain liquid crystals, and it is reported here that in the presence of high fields the rate of heat transfer is primarily dependent on the field intensity. The experimental setup for demonstrating the effect of an electric field on the heat transfer in a liquid crystal is shown in Fig. 1. The copper block (cross-sectional area = 7.0 cm^2 and 6.5 cm high) was heated to about 70°C before placing it in the setup. As the copper block was cooled, the temperature difference between the copper and aluminum blocks in the vicinity of the cell were measured as a function of time. Because of the low thermal conductivity of styrofoam and

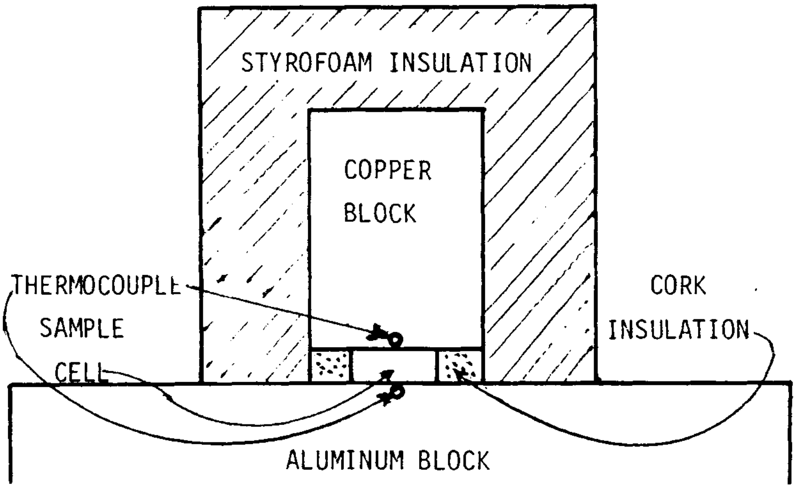
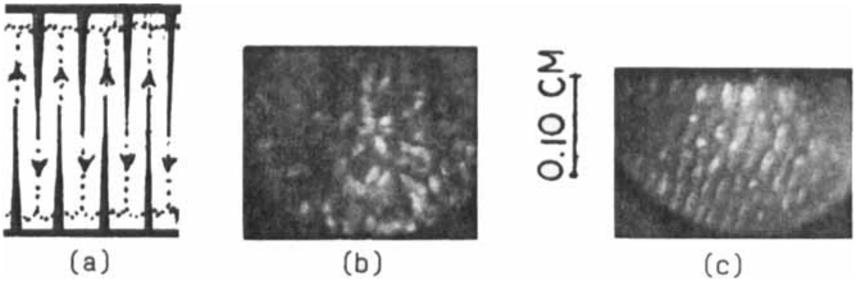


FIGURE 1. Schematic diagram for heat transfer experiment



(a) (b) (c)

Figure 2. (a) Schematic diagram for material flow at the free surface of a liquid crystal in a 5 kV/cm electric field.(b) Photograph of the electrode-to-liquid crystal interface with a 5 kV/cm electric field applied perpendicular to the electrodes.(c) Same as (b) except an 8 kG magnetic field is applied parallel to the electrodes and the free surface.

cork much of the heat was transferred through the sample. The large aluminum block was maintained at a temperature of 22°C and the copper block was cooled down to a temperature of approximately 30°C. The cooling range or the exact temperature of the aluminum block was not critical because it was the temperature difference as a function of time which was compared for the various materials. Although this method did not provide a direct measurement of the heat transfer, comparisons could be made between the liquid crystal and materials with known thermal conductivities. Even though there was heat lost through the cork (thickness = 0.2 cm) and styrofoam (thickness = 1 inch), comparisons were made in such a manner that it did not affect the results appreciably. The cold reservoir was placed at the bottom of the cell to prevent the creation of a Benard-Rayleigh instability. The absence of this instability was checked by using another experimental setup with a piece of glass as the upper surface. Motion of the sample was not observed when cooled from below. The electric field was applied by applying a voltage across the copper and aluminum blocks since the blocks served as electrodes for the sample cell.

Since the experimental setup did not provide a direct measurement of heat transfer, it was necessary to replace the liquid crystal with other liquids so that a comparison could be made. In the absence of any electric field, the cooling rate using the liquid crystal was slightly slower than that of glycerin, indicating a thermal conductivity less than glycerin. In the presence of a 25 kV/cm (dc) electric field the cooling rate was a little lower that for mercury. However, when the cross-sectional area of the sample cell was reduced from 1.5 cm^2 to 0.75 cm^2 for mercury, the cooling rate was comparable to that of the liquid crystal ($E = 25$ kV/cm) in a sample cell of 1.5 cm^2 cross-sectional area. This observation indicates that the rate of heat transfer at this field strength was approximately one-half that of mercury. These observations imply that an electric field can alter the rate of heat transfer by at least a factor of ten. It should also be emphasized that the rate of heat transfer was very dependent on the strength of the applied field.

The material used for the heat transfer measurements was a nematic liquid crystal (nematic range -5°C to 75°C) with a resistivity of about 10^9 ohm-cm and was purchased from EM Chemicals (nematic mixture 5A). MBBA was used for some of the optical observations because it represented a continuation of work published earlier in which in which MBBA was used.

In order to better understand the motion of the liquid crystal we refer to a model, which was proposed earlier[1], to explain molecular alignment and material flow due to electric fields in nematic liquid crystals. Because of the conductivity anisotropy, space charge accumulates at distortions in the alignment when a dc electric field is applied. The interaction of the electric field with the space charge causes movement of the fluid which leads to the formation of walls (defects) perpendicular to the electrodes (for further discussion see reference 1). Photographs of the air-to-liquid crystal interface (free surface) in the presence of a 5 kV/cm dc electric field have been reported[2] which show that the walls (defects) extend out from the electrodes to more than one-half the distance to the opposite electrode. These walls are illustrated in Fig. 2a where the broken lines indicate the direction of fluid flow. Although the life time of the walls may be several seconds the fluid making up the walls is constantly changing. It is the accumulation of space charge at the walls that interacts with the electric field to keep the fluid moving.

A photograph of the electrode-to-liquid crystal interface in the presence of a 5 kV/cm dc electric field is shown in Fig. 2b. The cell was constructed from two pieces of transparent conductive coated glass separated by a teflon spacer (0.15 cm thickness). The light source was a laser directed horizontally through the sample. A careful observation (Fig. 2b) near the free surface (top of the photograph) reveals that there is a tendency for walls to form perpendicular to the free surface, but at greater depths, the walls appear to be broken up. The dark lines represent the walls.

A photograph of the electrode-to-liquid crystal interface, with a 5 kV/cm electric field applied perpendicular to the electrodes and an 8 kG magnetic field applied parallel to both the electrodes and the free surface, is shown in Fig. 2c. In this case the walls tend to be perpendicular to both the free surface and the electrodes and they extend to the bottom of the sample cell. The function of the magnetic field is to keep the director in a plane parallel to both the electric and magnetic fields (or the free surface).

In order to photograph the patterns shown in Figures 2b and 2c, it was necessary to add a small amount of dye (much less than 1% of indephenol blue) to MBBA. Previous work[3] has shown that this dye could be added to MBBA without destroying its nematic properties. Not only did the patterns become much clearer but motion of the liquid crystal could be observed. In Fig. 2c the fluid at the electrode-to-liquid crystal interface was moving horizontally toward the dark vertical lines from both directions. From this observation we concluded that the dark lines represented walls, extending out from the electrodes, with the fluid moving away from the electrode at the walls and toward the electrode in between the walls. By refocusing the microscope so one could observe further into the sample, evidence of walls was observed in which the fluid was moving toward the electrode. These walls were in between the walls shown in Fig. 2c. At this position of the microscope, the pattern looked like a line of vertical cylinders that were all rotating with every other cylinder rotating in the opposite direction. This indicates that the maximum fluid velocity toward the electrode was at the walls which originated at the opposite electrodes and terminated very close to the near electrode.

The results shown in Figure 2c imply that the flow pattern is very similar to that discussed earlier[1] and much of the sample would be aligned at the flow alignment angle. In the earlier work electric fields of low intensity were applied to samples that were initially well aligned and the photographs were taken shortly after the field was applied. In the absence of a magnetic field the results in Fig. 2b along with earlier work[2] indicate that walls at the free surface extend to more than one-half the distance to the opposite electrode, but below the free surface the walls are broken up and are oriented at any angle with the free surface although they tend to be perpendicular to the electrodes. At depths much below the free surface the walls may only extend to the center of the sample.

Observations similar to those shown in Figures 2b and 2c were seen using the nematic mixture 5A although they were not as clear as those with MBBA. These observations were made for both vertical and horizontal positions of the electrodes. This implies that the model which was suggested to explain the flow for MBBA probably applies to the heat transfer measurements using the nematic mixture 5A.

Although the work reported here involves bulk samples it should be pointed out that there is also good evidence that the ideas discussed here are involved in thin samples (10 - 100 microns) of liquid crystals. Some observation[4] at a free surface indicated that the model[1] discussed here is involved in thin samples. The best observations in support of this model for certain cases in thin samples appear to be those of Igner and Freed[5] who viewed the sample in a direction perpendicular to the electrodes.

The observation[2] that the walls do not extend to the opposite electrodes is consistent with the observations of Igner and Freed[5] using thin samples. They stated that "there is a region close to one of the plates in which the wall does not penetrate or is broad". Photo 5 of plate 8 in their work indicates that adjacent walls are not exactly in focus for the same position of the microscope. This should be the case if adjacent walls were extended out from opposite electrodes.

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