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Electrohydrodynamics and the Heat Switch†

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The "heat switch" is basically a nematic liquid crystal sandwiched between two electrodes at different temperatures. When an electric field is applied convective flow cells are created which we believe control the heat transfer. The heat transfer rate does not appear to vary with the electrode separation for a given applied voltage even though the electric field intensity is inversely proportional to the electrode separation. Results are presented showing the heat transfer rate as a function of the applied voltage for samples ranging in thickness from 140 microns to 0.5 cm and in electric field intensities up to 100 kV/cm in the 140 and 300 micron samples. The results are discussed in terms of a model published earlier.

Keywords: electrohydrodynamics, heat transfer, nematic

INTRODUCTION

The "heat switch" is basically a nematic liquid crystal sandwiched between two conducting plates (electrodes). If the temperature at one electrode is greater than that of the other the heat transfer rate from one electrode to the other can be controlled by applying an electric field between the electrodes. When the electric field is applied, convective flow cells are created in the liquid crystal which we believe increases the heat transfer. A model proposed earlier[1] and illustrated in Figure 1 describes a mechanism which is likely responsible for the convective cells. The experimental method employed for the heat transfer measurements was discussed earlier[2] and the material used in the work reported here was *N*-[*p*-Methoxybenzylidene]-*p*-butylaniline (MBBA)). The electrical resistivity of the MBBA was approximately 10^9 ohm-cm.

HEAT TRANSFER

The heat transfer rate (in units of thermal conductivity) as a function of a dc voltage applied to the electrodes is shown in Figure 2 as a log-log plot for various electrode separations (L). Some of the results (L = 0.085 cm, 0.15 cm and 0.50 cm) were discussed earlier.[2] There is a small enhancement of the heat transfer rate with increased voltage at lower voltages and for voltages above 1,000 volts the heat

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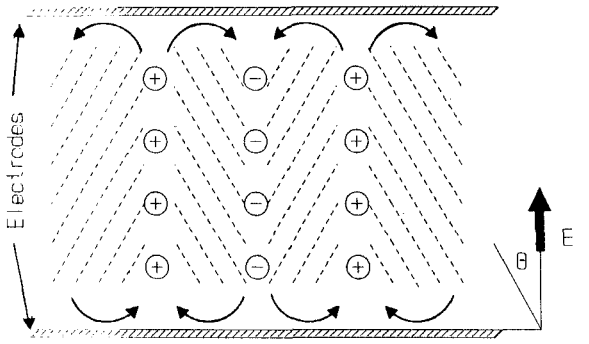

FIGURE 1 Model for molecular alignment and material flow in the presence of an external electric field. Charges due to the electrical conductivity anisotropy accumulate at the walls (defects) which are perpendicular to the electrodes and the free surface of the sample. Forces due to the interaction of the electric field with the space charge at the walls (defects) tend to shear the sample. Because of shear flow, the director associated with the sample between the walls is turned toward the electric field, giving rise to the "flow alignment angle" Θ. Although the walls should appear to be stationary, the material making up the walls is constantly changing.

transfer rate appears to be proportional to the applied voltage. The results also show that, for a given voltage, there is little if any variation with the electrode separation (L) even though the electric field intensity is inversely proportional to the separation. We do not have an explanation for this unexpected result or do we understand why the heat transfer rate is proportional to the applied voltages above 1,000 volts. Although there are some small variations in the measurements for the various electrode separations, they can not be taken seriously because of the difficulty in making measurements in the presence of very high electric fields.

The heat switch is more effective at larger electrode separations. For an electrode separation of 0.5 cm we were able to change the heat transfer rate[2] by a factor of approximately 100 when applying a voltage of 18 kV (mentioned in conclusion of Reference 2).

Some very interesting results, from Figure 2, are the measurements at the higher voltages for electrode separations of 140 and 300 microns. The linear relationship above 1,000 volts appears to apply for electric fields of up to 100,000 volts/cm which is about three times the breakdown field for air. This suggests the possibility that the mechanism primarily responsible for the heat transfer rate just above 1,000 volts is also effective at the higher fields. We do not have direct evidence that the mechanism illustrated in Figure 1 applies to electrode separations of a few hundred microns for voltages in the neighborhood of 1,000 volts, but there are results for larger samples. Earlier results[3] indicated that this mechanism was effective at 6,000 volts for electrode separations of 1.2 cm and 0.5 cm. Results will be presented indicating that the model illustrated in Figure 1 does apply to a sample thickness of 140 microns with applied voltages of 70 and 140 volts.

MOLECULAR ALIGNMENT AND MATERIAL FLOW AT 140 MICRONS

One reason for carrying out work at electrode separations in the neighborhood of 100 microns is that it allows for a comparison of results on thin samples (less than

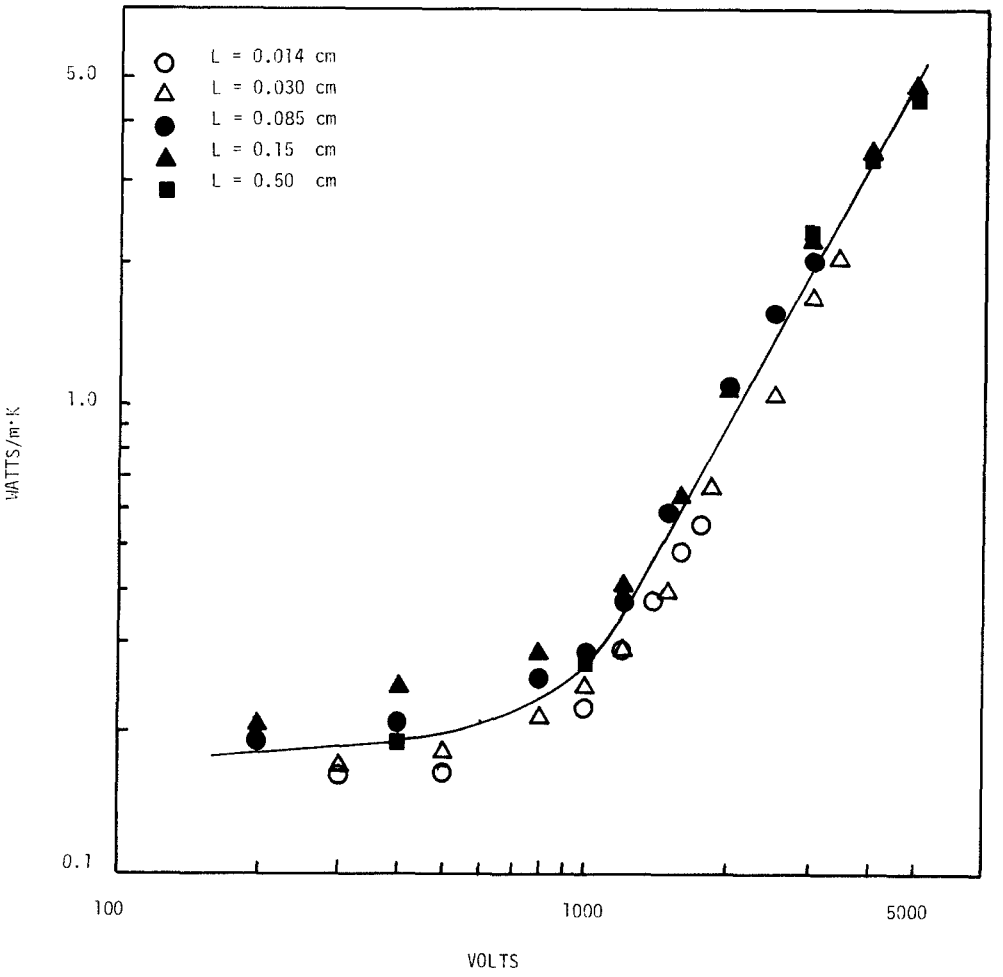

FIGURE 2 Heat transfer enhancement due to dc electric fields. A Log-Log plot for various electrode separations (L).

100 microns) with those in bulk samples. At this separation we can make observations of Williams Domains and dynamic scattering as well as observations that are consistent with those made on bulk samples.

Results[4] from NMR measurements have provided good evidence that the mechanism illustrated in Figure 1 applies for electrode separations of 0.1 cm. Other investigations[1,3,5] have provided support for larger samples. In order to provide evidence that the mechanism illustrated in Figure 1 applies to an electrode separation of 140 microns we apply some techniques used earlier for bulk samples. Figure 1 shows the molecular alignment and material flow at the free surface. If a magnetic field is applied parallel to the electrodes and the free surface, we have shown earlier[5,6] in a bulk sample that the electric field can be adjusted so the pattern shown extends to the bottom of the sample container. The magnetic field

tends to keep the molecules aligned in a plane parallel to the free surface which results in a two-dimensional rather than a three-dimensional structure.

Figure 3 shows a pattern when observing perpendicular to the electrodes for a 140 micron separation. A magnetic field of 8 kG parallel to the electrodes, and a voltage of 140 volts were applied. A careful observation looked like rotating cylinders perpendicular to the magnetic field with adjacent cylinders rotating in opposite directions. This is what was observed earlier[6] for an electrode separation of 0.15 cm which implies convective flow cells as predicted by the mechanism shown in Figure 1. The flow cell width as a function of electric field intensity for an electrode separation of 135 microns has been reported earlier,[5] even though the model in Figure 1 and the observations in Figure 3 were not available at the time of publishing. It should be pointed out that the pattern shown in Figure 3 for an electrode separation of 140 microns is not always easily obtained, but once obtained it is reproducible.

Although the results shown in Figure 3 provide good evidence for convective flow cells, they do not provide information about molecular alignment. The mechanism illustrated in Figure 1 predicts that the director for the fluid between the walls (defects) will align at the flow alignment angles[7] of $+\Theta$ or $-\Theta$ (Θ = approximately 20°). In order to investigate this alignment the sample of MBBA was doped with the dye "indophenol blue" which aligns with the liquid crystal and absorbs light polarized parallel to the director. This implies that the light directed upward and leaving the free surface between the walls (defects) should be partially

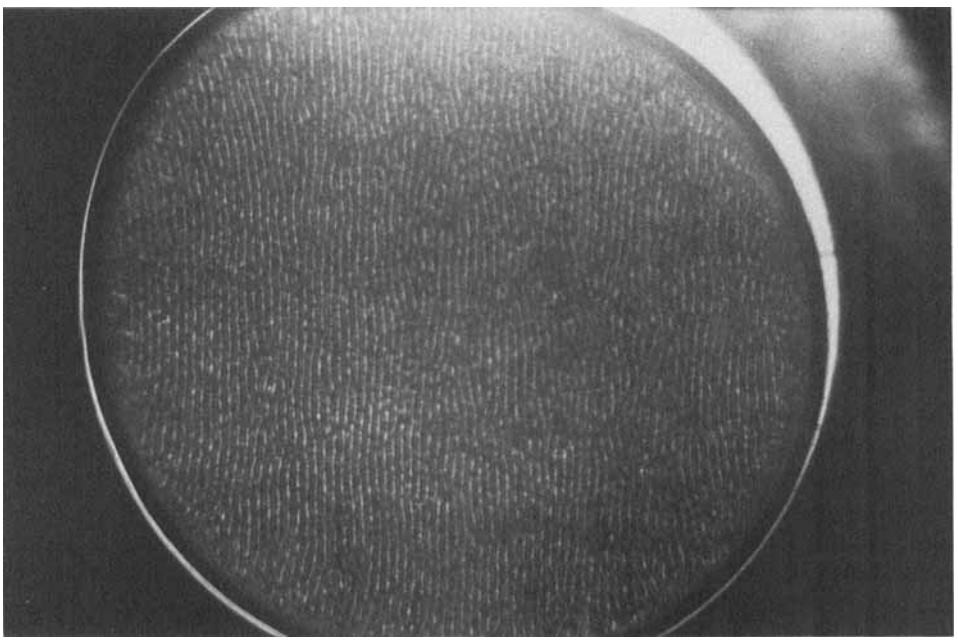

FIGURE 3 Photograph of the electrode-to-liquid crystal interface with 140 volts (50 Hz) applied to the electrodes and a 8 kG magnetic field applied parallel to the electrodes. The electrode separation was 140 microns, and the magnification was 30X.

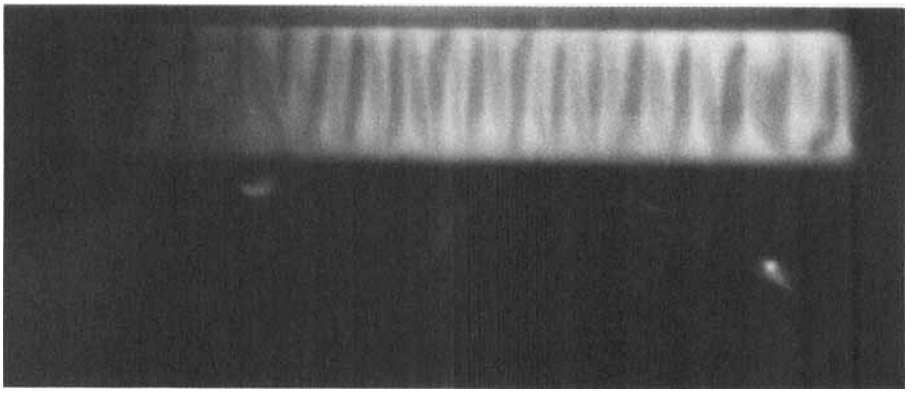

FIGURE 4 Photograph of the free surface of a sample of MBBA doped with the dye indophenol blue. A voltage of 70 volts (50 Hz) was applied to the electrodes with a separation of 140 microns and a magnetic field of 8 kg was applied parallel to the electrodes. The magnification was 100X.

polarized at angles of approximately $+70°$ or $-70°$ with respect to the direction of the electric field. For an analyzer oriented at about 20° with respect to the electric field light and dark regions should appear at the free surface. Figure 4 shows a photograph of the free surface for an analyzer setting of 20° and 70 volts (50 Hz) applied to the electrodes. An 8 kG magnetic field was applied parallel to the free surface and the electrode separation was approximately 140 microns. Dark and light regions separated by walls can be observed. When the analyzer was changed from 20° to $-20°$ the light regions became darker and the darker regions became light which provides good evidence that the molecular alignment is consistent with the mechanism illustrated in Figure 1. In order for the dye to produce partially polarized light the pattern at the free surface must extend much below the surface, which is the reason for the presence of a magnetic field. The evidence presented here in support of the Model for thin samples only applies to low electric field intensities compared to those shown in Figure 2.

CONCLUSION

We believe that the most interesting result from the work discussed here is the wide range of sample sizes and electric field intensities over which the model illustrated in Figure 1 may apply. This includes electrode separations much below 100 microns as suggested by Igner and Freed[8] as a possible explanation for their results to over 1 cm. It includes electric field intensities from 100 V/cm to approximately 100,000 V/cm in some of the thinner samples.

There is no direct evidence that the mechanism illustrated in Figure 1 is responsible for the heat transfer at the highest fields shown in Figure 2, but if we assume that the heat transfer is associated with convective flow cells, we do not have any other mechanism to suggest. If the convective cells become turbulent, as the electric field is increased, we might expect the heat transfer to decrease, but this was not observed.

Although it is not understood why the heat transfer rate does not depend on the electrode separation for a given voltage, the data presented in Figure 2 does allow for a comparison of results on bulk samples with those having electrode separations in the neighborhood of 100 microns.

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