Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

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Version of record first published: 20 Apr 2011.

To cite this article: E. F. Carr (1984): A Heat Switch Using Liquid Crystals in the Presence of Electric Fields, Molecular Crystals and Liquid Crystals, 111:1-2, 161-170

To link to this article: http://dx.doi.org/10.1080/00268948408082180

Mol. Cryst. Liq. Cryst. 1984, Vol. 111, pp. 161-170
0026-8941/84/1112-0161/$18.50/0

Printed in the United States of America

A HEAT SWITCH USING LIQUID CRYSTALS IN THE PRESENCE OF ELECTRIC FIELDS*

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The heat transfer through certain liquid crystals can be controlled by applying an external electric field. Because of the electrical conductivity anisotropy, space charge accumulates in certain regions of the liquid crystal when an electric field is applied. The space charge interacts with the field to produce hydrodynamic flow. It is the movement of fluid from one electrode to the other that is responsible for the changes in the heat transfer. Results show that the heat transfer in a certain liquid crystal can be changed by a factor of approximately 40 or more when a very high electric field is applied.

1. INTRODUCTION

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 can be controlled by an electric field.[1] Results have been obtained which show that the heat transfer in N-[P-methoxybenzylidene]-p-butylaniline (MBBA) can be changed by a factor of approximately 40 or more when applying a very high electric field.

Many liquid crystals of the nematic type exhibit fluid flow in the presence of dc or very low frequency electric fields. This can be easily demonstrated by placing the sample of liquid crystal in a rectangular container with the wide sides of the container serving as conducting electrodes. The short sides and the bottom of the container are made from electrically insulating material such as teflon. When a high electric field is applied between the electrodes, hydrodynamic motion can be observed. This can be easily seen by observing the movement of dust particles on the free surface of the sample with a microscope. The movement of the particles shows that there is fluid flow from one electrode to the other leading to rotational (cellular) flow as shown in Figure 1.

2. RESULTS AND DISCUSSION

2.1. Heat Transfer

The effect of an electric field on the heat transfer through a liquid crystal was demonstrated by comparing the heat transferred through a liquid crystal with the heat transferred through materials with known thermal conductivity. A schematic diagram of the experimental setup is shown in Figure 2. A copper cylinder (2 inches high and 1.5 inches in diameter) is placed above and separated from a large aluminum block by 0.2 cm of cork except for an area which served as the sample cell. A thin sheet of teflon was placed between the cork and the aluminum block to prevent electrical breakdown. The area of the sample cell was approximately 4 square cm. The copper cylinder was heated and insulated with styrofoam. Because of the insulation around the copper cylinder much of the heat from the

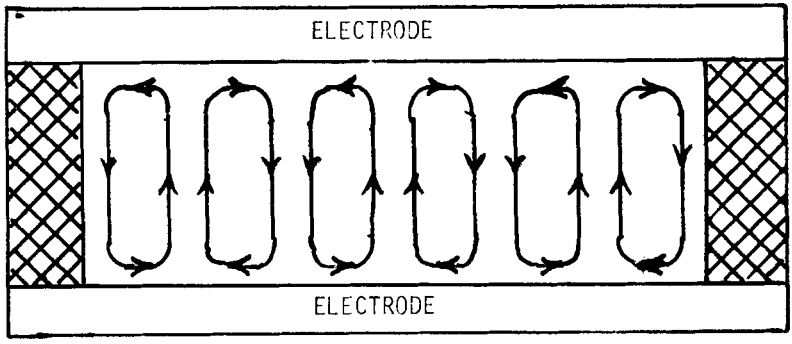

FIGURE 1 Flow pattern for a liquid crystal in an electric field at the free surface.

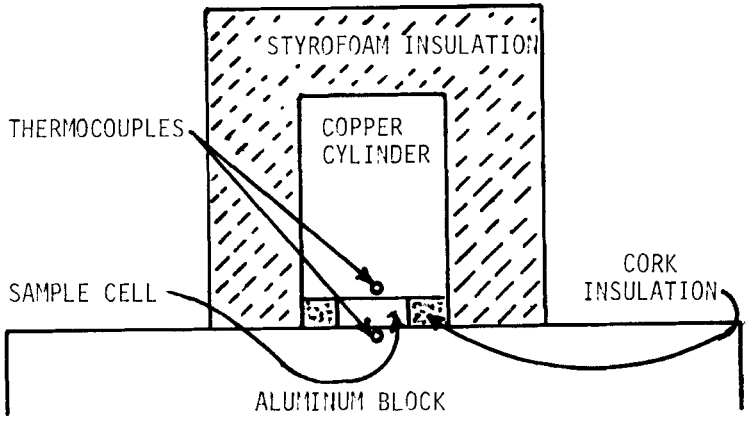

FIGURE 2 Schematic diagram for heat transfer experiment.

cylinder passed through the sample and into the large aluminum block. The large aluminum block was not insulated so it remained very close to room temperature. The bottom of the copper cylinder and the top of the aluminum block served as electrodes. The temperature differences between the copper cylinder and the aluminum block were measured in the vicinity of the cell as a function of time. The

heat lost by the copper cylinder, which did not pass through the cell, was not critical because it was the temperature difference as a function of time that was compared for the various materials. The sample was cooled from the bottom to prevent the creation of a Bernard-Rayleigh instability.

When making the necessary measurements the copper cylinder was normally heated to 8 or 10 degrees above room temperature and cooled down to about 1 or 2 degrees above room temperature. The cooling rate for MBBA with no electric field was slower than for glycerin and as slow as for castor oil. This indicates that the thermal conductivity of MBBA is comparable to that of castor oil. In a field of 37 kV/cm the cooling rate for MBBA was comparable to that of pure mercury. This indicates that the heat transfer at this field strength was comparable to the heat transferred in mercury. These results show that the heat transfer has been changed by a factor of approximately 40 when applying the high electric field. We do not have any reliable measurements giving a relationship between heat transfer and electric field intensity, but it appears to be more like an E^2 dependence than an E dependence. Even though we have used very high fields the amount of power consumed is very low and the equipment needed to produce these fields if very inexpensive.

2.2. Fluid Motion

A model[2] illustrated in Figure 3 is used to explain the flow pattern shown in Figure 1. This model depends on two unusual properties exhibited by certain liquid crystals: electrical conductivity anisotropy, and the fact that when these liquid crystals are sheared, the preferred direction

of the molecules (director) is not random, but rather is at a small angle[3] with respect to the direction of shear. Because of the conductivity anistropy charge accumulates where there is a change in direction of the director when an electric field is applied. In the case of liquid crystals this charge is due to ionic impurity.

Figure 3 illustrates a reasonably stable situation which appears to exist in liquid crystals when a high electric field is applied. Walls (defects), which are changes in the direction of the director, are formed perpendicular to the electrodes and the free surface. The charge which accumulates at these walls cannot move readily through the fluid when acted upon by the electric field, so the fluid is dragged along with the charge. Since the charges on adjacent walls are opposite in sign, the movement of the walls produces a shear. This shear maintains the alignment between the walls with the director aligning at a flow alignment angle.[3] The motion of the fluid is similar to that shown in Figure 1.

Since the motion of the fluid at the free surface has to be parallel to the surface, the walls must be perpendicular to the surface. Much below the surface the motion is not necessarily parallel to the free surface. However, if a magnetic field of a given strength is applied parallel to the electrodes, it can keep the director in a plane parallel to the free surface without preventing the fluid flow. The photograph in Figure 4a shows the effect of an 8000 Gauss magnetic field when a 5000 V/cm electric field is applied. The electric field is a 50 Hz field but it has the same effect as a dc field. This photograph was taken at the electrode-to-liquid crystal interface and about one cm below the free surface. The electrodes were made of

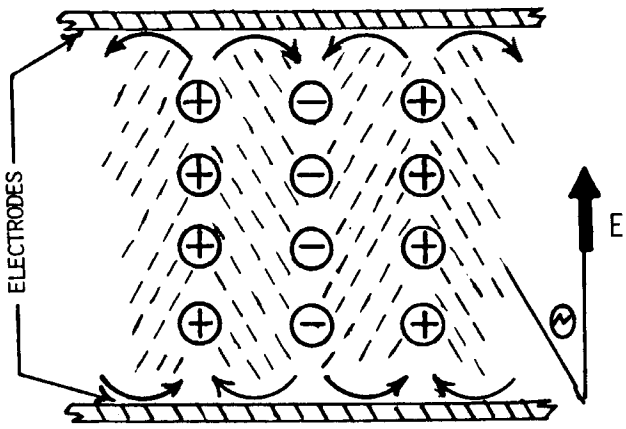

Figure 3. Model for molecular alignment and material flow due to an external electric field. Charges accumulate at the walls (defects) which are perpendicular to the electrodes and the plane of the paper. Forces due to the interaction of the electric field with the space charge at the walls (defects) 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. For further discussion see reference 2.

transparent conductive coated glass. We believe that the darker lines in this photograph represent walls that extend out from the near electrode. Between the wide dark lines there are narrow dark lines. These lines represent walls that extend out from the far electrode to a region very close to the near electrode. Adjusting the focus of the microscope indicated the walls from the far electrode did not extend to the opposite electrode. These observations are consistent with earlier observations[4] at the free surface. This previous work showed that the walls at the free

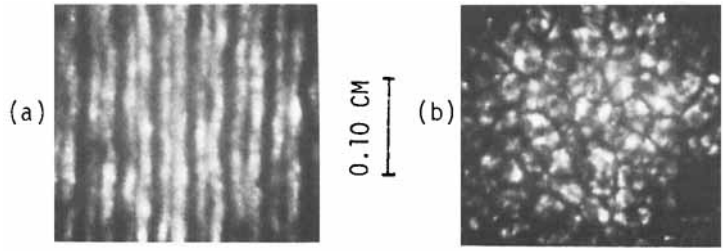

FIGURE 4 (a) Photograph of the electrode-to-liquid crystal interface with a 5 kV/cm electric field perpendicular and an 8kG magnetic field parallel to the electrodes. (b) Same as (a) except no magnetic field. The material was MBBA.

surface extended out from an electrode to more than one-half the distance to the opposite electrode. The model in Figure 3 explains the results shown in Figure 4a with the walls extending to the bottom of the sample.

In order to make the observations shown in Figure 4, a small amount of dye (much less than 1% of indephenol blue) was added to the MBBA. Previous work[5] had shown that this dye could be added without destroying the nematic properties of MBBA. With the dye the movement of the fluid along the electrode-to-liquid crystal interface could be observed. The flow pattern for the results in Figure 4a at the electrode-to-liquid crystal interface looked like rotating cylinders. The cylinders were parallel and vertical and every other cylinder was rotating in the opposite direction. The rotations showed that the fluid was moving away from the near electrode at the wide dark lines and toward the near electrode at the narrow dark lines. This provides excellent evidence in support of the model.

The explanation of the result shown in Figure 4a involves only two dimensions, but when the magnetic field

is removed the flow pattern much below the free surface becomes a three-dimensional problem. A photograph taken at the electrode-to-liquid crystal interface and about one cm below the free surface is shown in Figure 4b with no magnetic field applied. The electric field strength was 5000 V/cm. We do not have a clear explanation of the flow patterns in Figure 4b but a few comments can be made. Observations with a microscope indicated that the fluid was moving away from the near electrode at the wide dark lines. This implies that the dark lines represent walls. These walls are perpendicular to the electrodes but are at any angle relative to the free surface. The sizes of the walls vary a lot and how far they extend through the sample is not known. The results shown in Figure 4a should exhibit a reasonably defined flow alignment angle θ, whereas the flow alignment angle may not be as well defined for the results in Figure 4b. The flow alignment angle for Figure 4a is probably larger than that measured from pure shear flow because of the torque due to the magnetic field. Although Figure 4b does not appear to represent a system as well ordered as Figure 4a, previous results[6] indicated that the average flow alignment angle for the results represented in Figure 4b is less than the angle for those in Figure 4a.

3. CONCLUSION

Although we have demonstrated that the heat transfer can be changed by a factor of approximately 40 or more in a sample of thickness 0.2 cm, it should be pointed out that measurements at other thicknesses have not yet been carried out. When heating a liquid from the top surface, as was done in the experiments reported here, we do not expect much motion

of the fluid due to temperature gradients. We have not shown that there is no motion, but some evidence[1,7] is available which indicates that any motion that may exist due to temperature gradients probably has a very small effect. Liquid crystals should be good materials for the detection of fluid motion due to temperature gradients because of their anisotropic properties.

The model in Figure 3 appears to be an excellent explanation of the fluid flow when a 5000 V/cm electric and an 8 kG magnetic field act simultaneously (Fig. 4a). When the magnetic field is removed (Fig. 4b), and a two-dimensional problem has become a three-dimensional problem, we believe that the ideas associated with the model still apply. NMR experiments[8] have shown the existance of a flow alignment angle when a high electric field is applied as predicted by the model. Because of the presence of the magnetic field for these measurements we are not certain whether the NMR results correspond to the flow patterns associated with Figure 4a or 4b.

Although we do not have measurements showing the effect of electric fields on the heat transfer in thin samples (10-100 microns) there is reason to believe that there should be an appreciable effect. Observations[9] at the free surface have given some indication that the model (Fig. 3) applies to thin samples, but the best evidence indicating that this model may be involved in thin samples is presented by Igner and Fried.[10]

4. ACKNOWLEDGEMENTS

The author wishes to thank Elizabeth C. Carr for critically reading the manuscript.

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