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Convective flow in the liquid crystal heat switch

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The 'heat switch' is based on the fact that in some liquid crystal (LC) materials heat transfer depends on the voltage applied between two parallel electrodes containing the sample. The rate of heat transfer depends on the voltage rather than the electric field intensity, but is not understood. Since the heat switch can involve electric field intensities up to at least the breakdown field of air, it is important to understand the mechanism responsible for heat transfer. Results are presented indicating that a mechanism described earlier is involved. A proposal for a refrigerator using LC heat switches is also made.

1. Introduction

Since the 'liquid crystal heat switch' can involve very high electric fields, the primary objective of this article is to improve understanding of the mechanism responsible for the large changes in heat transfer rate. Results will be presented indicating that convective flow in the liquid crystal (LC) is present when high electric fields are applied. It is suggested that the convective flow is primarily responsible for changes in the heat transfer rate. The basic idea for the LC heat switch (US Patent 4 515 206) involves a LC layer sandwiched between two parallel electrodes. If one electrode is at a higher temperature than the other and a voltage is applied across the electrodes, the heat transfer rate in the LC will increase. This effect was first discovered in 1983 [1]. Results were later published [2–4] showing the relationship between the heat transfer rate and the voltage applied to the electrodes. In one case [3, 4] a voltage of 18 kV applied to a LC sample 0.5 cm thick with electrode area 2.8 cm^2 changed the heat transfer rate by a factor of about 100. Although high voltages were used (creating electric fields up to the breakdown field of air) the current was very low (less than 2×10^{-4} A). The high voltage source used in this work was an unregulated d.c. source, but an a.c. source should also work. It may be mentioned that Biggers *et al.* [5] have studied *Heat Transport through MBBA Due to Induced Electrohydrodynamic Motion*. US patents 5 188 171 and 5 222 548 are related to this work. It should also be mentioned that work by Wan *et al.* [6] supports the idea of convective flow.

A model to explain what has often been described as anomalous alignment has been proposed previously [7]. A specific objective of this article is to provide evidence that this model can be applied to the heat switch involving very high electric fields. A possible application for the heat switch involving a refrigerator is suggested.

The model explaining the molecular alignment and material flow in d.c. or very low frequency electric fields is illustrated in figure 1. It involves convective flow cells as shown in figure 1(*a*). Convective flow cells were involved in work by Helfrich [8] to explain 'Williams Domains'. This work provided an excellent explanation for the existence of Williams Domains, but does not explain material flow and molecular alignment involved in the heat switch.

Figure 1(*a*) shows a flow pattern often observed in a horizontal electric field at the free surface (air to liquid crystal interface). Motion at the free surface must be parallel to the surface, but below the free surface it can be three dimensional. The application of a magnetic field of sufficient strength, and parallel to the electrodes and the free surface, tends to reduce the flow pattern to two dimensions throughout the sample. This does not occur for all values of the magnetic and electric fields, but appropriate values can be chosen to secure a two dimensional pattern [7]. The direction of flow and the director tend to align in a plane as shown in figure 1(*b*). Earlier work [7], for certain values of the electric and magnetic field, has shown that the motion can be two dimensional, and clearly showed the existence of convective flow cells.

The mechanism illustrated in figure 1(*b*) involves a flow-alignment angle [8, 9]. When a nematic liquid crystal is sheared by the movements of two parallel plates in opposite directions, the sample between the plates aligns at a flow alignment angle θ (angle between the director and the plates). In this model the plates are replaced with wall defects perpendicular to the electrodes and the free surface. Charge accumulates at the defects due to changes in the electrical conductivity. Changes in the electrical conductivity are due to changes of the

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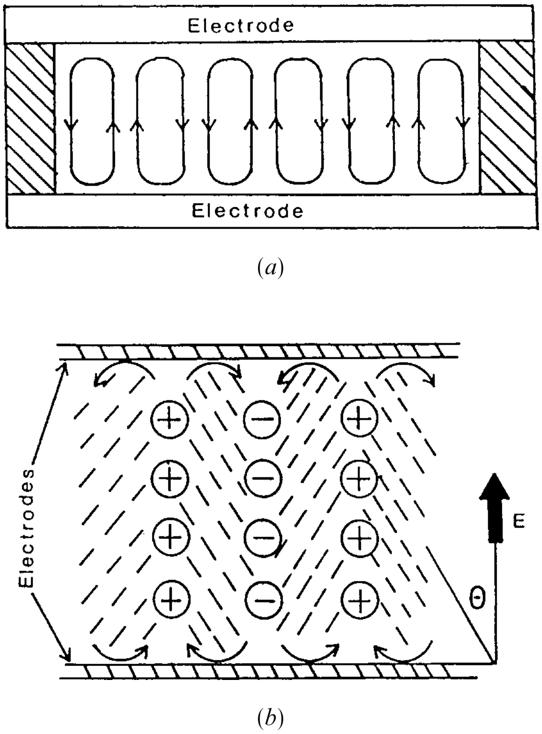


Figure 1. (*a*) Flow pattern at the free surface of a liquid crystal due to an electric field. (*b*) Model for molecular alignment and material flow due to an external electric field. Charges accumulate at the walls (defects) which are perpendicular to the electrodes and the plane of the paper. Forces 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.

director. The flow alignment angle has been observed in MBBA using NMR [10] techniques and investigated as a function of temperature. Igner and Fried [11] have presented excellent evidence that the flow alignment angle can exist for a sample thickness of less than 100 microns. Results have also been published [4] in support of the model involving the flow alignment angle for a sample thickness of 140 microns.

The samples for the work reported here were of *N*-(*p*-methoxybenzylidene)-*p*-butylaniline (MBBA). Only d.c. electric fields were used, but low frequency fields should be adequate.

2. Results

The experimental set-up shown in figure 2 was used to produce the results illustrated in figure 3. A beam of white light was directed upward and the microscope was located just above the centre of the sample, (position A) or above the edge of the sample (position B).

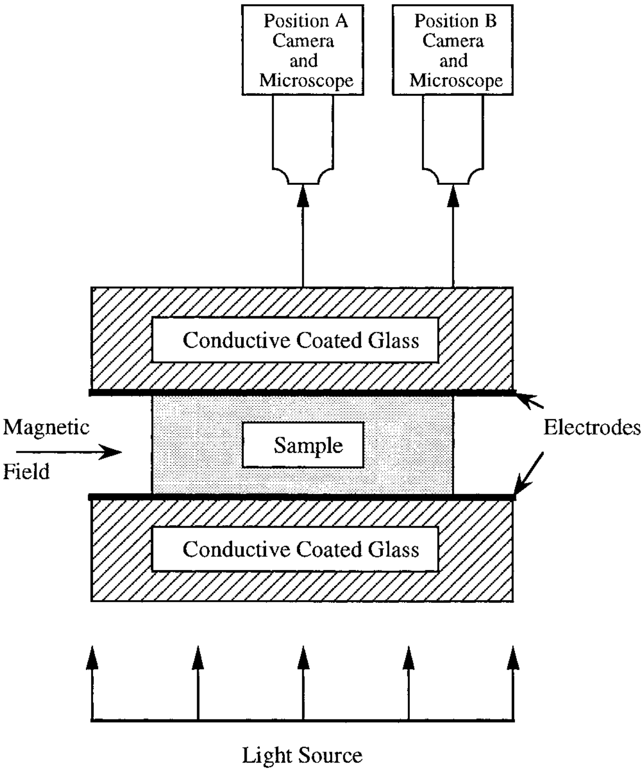
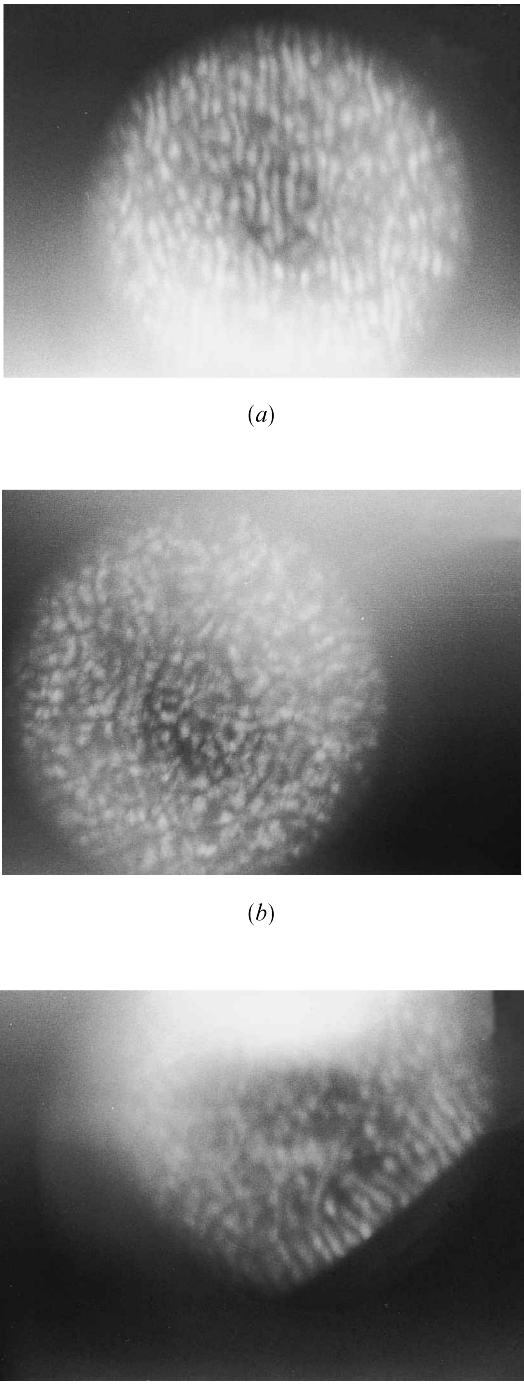


Figure 2. Experimental set-up used to obtain the results shown in figure 3. The electrode separation was 300 microns, with the electrodes perpendicular to the plane of the diagram.

The photograph shown in figure 3 (*a*) was obtained with the microscope located at position A. A 300 V source was applied to the electrodes and a 6000 G magnetic field applied parallel to the electrodes. This pattern was similar to others [7] reported earlier and can be explained using the two dimensional model shown in figure 1 (*b*).

The experimental set-up for the photograph shown in figure 3 (*b*) is identical to that used for figure 3 (*a*) except that the magnetic field was removed ($B = 0$). This pattern appears to indicate that the sample is very turbulent, but evidence will be presented showing that the model in figure 1 (*b*) appears to be involved. The experimental set-up for obtaining the photograph in figure 3 (*c*) was the same as that used for figure 3 (*b*) except that the microscope was located at the edge of the sample (microscope at position B). One can observe that the pattern shown in much of figure 3 (*c*) is similar to that in figure 3 (*b*) except near the edge of the sample (microscope at position B). The pattern shown near the edge of the sample appears to be similar to that shown in figure 3 (*a*). The patterns in figure 3 (*a*) and near the edge of the sample in figure 3 (*c*) indicate the possibility of convective flow cells in both cases. Because of changes in the index of refraction and defects in the sample,



(*a*)

(*b*)

(*c*)

Figure 3. Patterns due to a LC in a direction parallel to the electric field as shown in figure 2. The separation of the electrodes was 300 microns and a voltage of 300 V was applied to the electrodes: diameter of field of view was 0.1 cm. (*a*) A magnetic field of 6000 G applied parallel to the electrodes and the microscope located at position A in figure 2. (*b*) Conditions the same as in (*a*) except for no magnetic field. (*c*) Conditions the same as in (*b*) except that the microscope was located at position B.

movement of the sample can be detected. The movement near the edge of the sample in figure 3 (*c*) and in figure 3 (*a*) is consistent with the presence of convective flow cells. Movement of the fluid in figure 3 (*b*) also showed evidence of convective flow cells. The flow cells were similar to those in figure 3 (*a*) but appeared like long cells that were broken up and oriented at random.

The presence of a magnetic field, for the results shown in figure 3 (*a*), produces a torque on the sample that favours the director being oriented in a plane perpendicular to the electrodes. This tends to change a pattern shown in 3 (*b*), which is three dimensional, into a two dimensional pattern as illustrated in figure 1 (*b*).

In figure 3 (*c*) the flow velocity at the free surface (air to liquid crystal interface) and perpendicular to it must be zero. Therefore, the three dimensional pattern becomes two dimensional near the free surface which indicates that the model in figure 1 (*b*) could be involved. In both patterns—in figure 3 (*a*) and near the free surface in figure 3 (*c*)—the dark lines represent the wall defects which are moving toward or away from the observer. The wall defects appear to be stationary but the fluid making up the defects is constantly changing and moving toward or away from the observer. The results presented here indicate that a magnetic field and a surface have similar effects on the molecular alignment. The alignment due to the free surface does not extend great distances into the sample, but this is expected.

As one moves from the edge of the sample toward the centre in figure 3 (*c*), changes in the pattern are not abrupt. This also suggests that the mechanism primarily responsible for the pattern in the centre of the sample is similar to that near the edge.

Reference [4] discusses the heat transfer rate as a function of voltage for five separations of the electrodes. These results show that the heat transfer rate is a function of voltage instead of electric field intensity, which is not understood. The results also indicate that changes in the neighbourhood of 1000 V may indicate changes in the mechanism responsible for the heat transfer rate. The results at 300 V for a separation of 300 microns indicate that the model in figure 1 (*b*) is involved for a voltage of less than 1000 V.

The experimental set-up for the photograph in figure 4 was the same as that used in obtaining figure 3 (*c*) except for the following changes. The separation of the electrodes was 0.078 cm and a 2000 V d.c. source was applied to the electrodes.

Figure 4 shows evidence of wall defects perpendicular to the free surface. They are much shorter than those in figure 3 (*c*), and do not extend as far into the bulk of the sample, but this is to be expected because of the higher voltage. This evidence does suggest the presence of

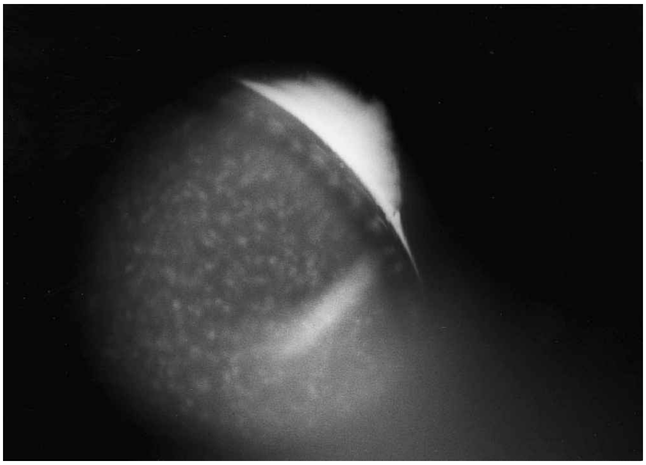


Figure 4. Pattern from an experimental set-up identical to that used for figure 3 (*c*), except that the electrode separation was changed to 0.078 cm and the electrode voltage was 2000 V.

convective flow cells which implies that the mechanism primarily responsible for the heat transfer above and below 1000 V is the same.

In order to extend this investigation to higher voltages, the experimental set-up was changed as shown in figure 5. Here the observer is looking in a direction parallel to the electrodes whereas in figure 2 the observer was looking in a direction perpendicular to the electrodes. For the use of higher voltages the thickness of the sample had to be increased to avoid exceeding the dielectric strength of air. Since the heat transfer rate appears to be a function of the voltage, changing the experimental set-up should not appreciably affect the results.

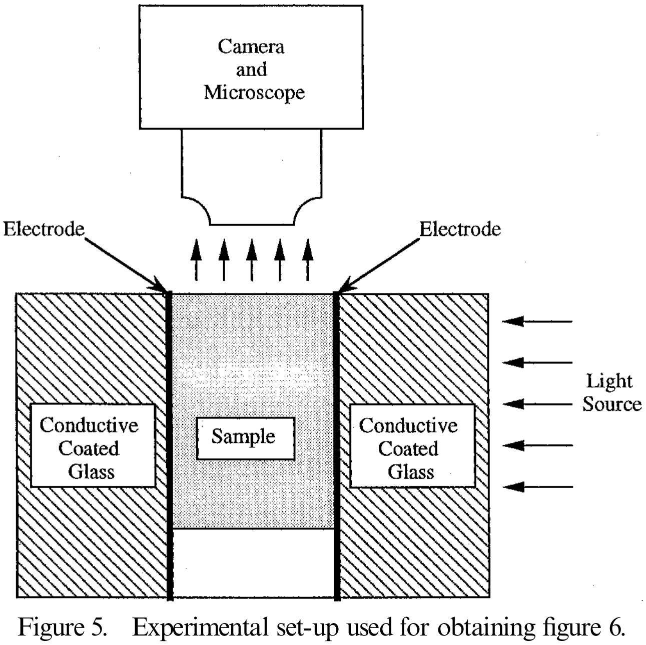


Figure 5. Experimental set-up used for obtaining figure 6.

The figure 5 set-up was used to produce figure 6. The electrode separation was 0.15 cm and a 4000 V source was applied to the electrodes. The microscope was focused at the free surface and the light lines in figure 6 represent wall defects. It can be easily seen that the fluid in adjacent wall defects is moving in opposite directions which creates flow cells similar to those illustrated in figure 1 (*a*).

It has now been shown that convective flow cells at voltages of 300, 2000 and 4000 V appear to be formed in the heat switch.

3. A refrigerator using a liquid crystal

An idea for a refrigerator using a liquid crystal was suggested earlier [12]. A simple illustration of how a refrigerator might operate is shown in figure 7. It would require a gas container, plunger and two heat switches as shown. The inner electrodes for the heat switches would serve as two walls of the container. The plunger, the bottom of the container and the other two walls of the container would be made of insulating material.

The outer electrode of one heat switch would face the reservoir (atmosphere) at temperature T_2, and the outer electrode of the other heat switch would face the cold region of the refrigerator at temperature T_1. When gas is compressed, heat switch A would be on and switch B off, so heat could be transferred to the atmosphere. After the gas has expanded, heat switch B would be on and heat switch A off, so heat would be transferred from the cold reservoir of the refrigerator to the expanding gas.

Results presented in [4] clearly indicate that a refrigerator using a liquid crystal would operate, but information as to how efficient or competitive the

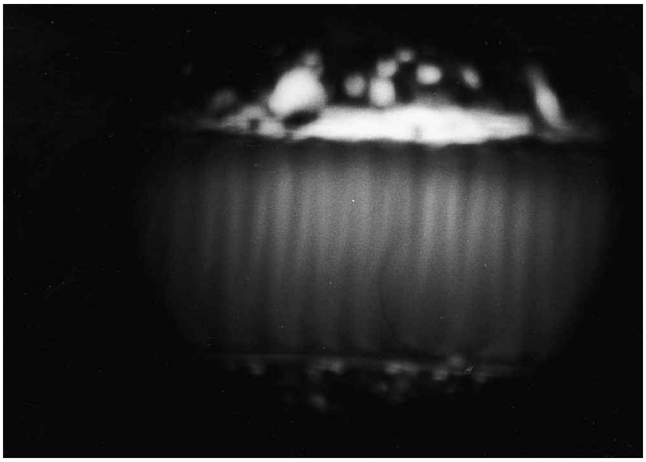


Figure 6. Pattern for an electrode separation of 0.15 cm and a voltage of 4000 V applied to the electrodes. The experimental set-up is shown in figure 5: diameter of field of view was 0.3 cm.

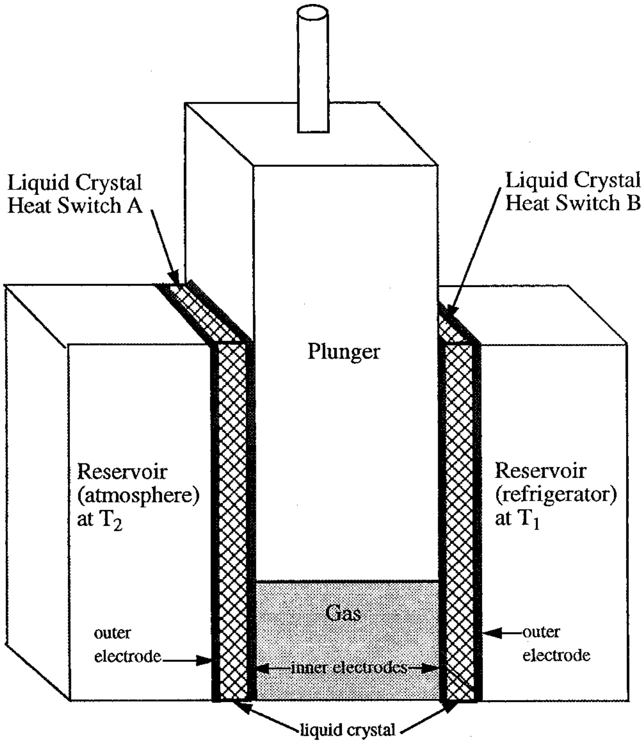


Figure 7. A schematic diagram for the operation of a liquid crystal refrigerator.

refrigerator would be is not available. This refrigerator would require no hazardous materials.

4. Conclusion

The experimental set-up [1–4] previously used to obtain the heat transfer rate as a function of voltage for the heat switch did not allow for observations of material flow. Using conductive coated glass electrodes it has been possible to have experimental set-ups comparable to those used in the study of the heat switch. These set-ups allowed for observations of flow patterns and provided information about material flow in the heat switch. Since the heat transfer rate depends primarily on the voltage applied to the electrodes, results at 300, 2000 and 4000 V were obtained. Patterns consistent with convective flow for all values of the voltage were obtained. At 300 and 4000 V direct observations of the motion of the fluid indicated the presence of convective flow cells as shown in figure 1 (*a*).

Most of the early work, involving electric field effects in LCs, used samples of thickness much less than 100 microns. Results in figure 3 (*b*) correspond to what was often referred to as dynamic scattering in very thin samples. The samples in the dynamic scattering mode seemed very turbulent, but for a separation of 300 microns movement in the sample could be detected. This movement in the sample indicated the presence of short convective flow cells oriented at random.

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References

[1] Carr, E. F., 1983, *Mol. Cryst. liq. Cryst. Lett.*, **92,** 165.
[2] Carr, E. F., 1984, *Mol. Cryst. liq. Cryst.*, **111,** 161.
[3] Hwalek, J., and Carr, E. F., 1987, *Heat transfer Eng.*, **8,** 36.
[4] Carr, E. F., 1991, *Mol. Cryst. liq. Cryst.*, **202,** 1.
[5] Biggers, R. R., Rish II, J. W., and Fullers, R., 1993, *Mol. Cryst. liq. Cryst.*, **237,** 351.
[6] Wan, C., Noble, R. D., and Clark, N. A., *J. Mebrane Sci.*, **74,** 223.
[7] Carr, E. F., 1978, *Liquid Crystals and Ordered Fluids III*, edited by J. F. Johnson and R. S. Porter (Plenum Press), p. 165.
[8] Ericksen, J. L., 1966, *Arch. ration. mech. Anal.*, **4,** 231.
[9] Leslie, F. M., 1968, *Arch, ration. mech. Anal.*, **28,** 265.
[10] Tarr, C. E., and Carr, E. F., 1980, *Solid State Commun.*, **33,** 459.
[11] Igner, D., and Freed, J. H., 1982, *J. chem. Phys.*, **76,** 6095; Igner, D., and Freed, J. H., 1983, *Mol. Cryst. liq. Cryst.*, **101,** 301.
[12] Carr, E. F., 1997, *Inside R and D*, Vol. 26, No. 44, p. 5.