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Gas flow-field induced director alignment in polymer dispersed liquid crystal microdroplets deposited on a glass substrate

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Polymer dispersed liquid crystal thin films have been deposited on glass substrates by the processes of polymerization and solvent evaporation induced phase separation. The electron and the optical polarization microscopies of the films reveal that PDLC microdroplets formed during the process of phase separation near the top surface of the film remain exposed and respond to shear stress due to air or gas flow on the surface. Optical response of the film to an air flow-induced shear stress input on the free surface has been measured. Director orientation in the droplets changes with the applied shear stress leading to time varying transmitted light intensity. Director dynamics of the droplet for an applied step shear stress has been discussed from free energy considerations. Results on the measurement of light transmission as a function of the gas flow parameter unambiguously demonstrate the potential of these systems for use as boundary layer and gas flow sensors.

1. Introduction

Study of polymer dispersed liquid crystal (PDLC) thin films has been the subject of recent interest because of their potential for applications in electro-optic devices such as large area displays and electrically controllable light shutters [1–4]. PDLC thin films are formed by the processes of phase separation induced by polymerization, thermal quenching or solvent evaporation [5] and consist of liquid crystal microdroplets ($\sim 0{\cdot}1$–$10\,\mu$m) whose size distribution is controlled, among other factors, mainly by the liquid crystal concentration and the rate of phase separation [6, 7]. The kinetics of the phase separation process leaves the liquid crystal (a birefringent material of birefringence $\Delta n = n_e - n_o$, n_e and n_o being the extraordinary and the ordinary refractive indices, respectively) microdroplets dispersed randomly in the polymer matrix (an isotropic medium of refractive index n_p). For the conventional mode of electro-optic operation, the liquid crystal is also a material of positive dielectric anisotropy ($\Delta\epsilon > 0$). In the normal off state (in the absence of the external electric field), there is a strong scattering of the incident light from the PDLC thin film resulting in its cloudy appearance. The film becomes transparent ($n_p = n_o$) on the application of a sufficiently high electric field through transparent electrodes deposited on the film (the on state). The transparency, a function of the applied electric field, is maximum when the refractive indices of the polymer, the liquid crystal and the transparent substrate (n_s) are matched ($n_p = n_s = n_o$).

The microscopic texture and the morphology of droplet formation in PDLC thin films have been widely [8–10] studied. Whereas the typically observed director

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configurations in nematic droplets are the radial, the axial, the bipolar and the concentric, electron microscopy results on the thin film reveal both the ball and the reverse (or swiss cheese) morphologies.

In the present paper, a new operational mode in which an external shear stress on a free surface of the PDLC thin film, instead of an electric field on a sandwich cell, has been described. In the present case of the PDLC operation, nematic liquid crystal microdroplets fill the randomly distributed microvoids in a rigid continuous polymer matrix leading to a swiss cheese morphology of the PDLC thin film free surface. In such a configuration, the liquid crystal microdroplets on the top surface of the thin film are only partially entrapped in the polymer matrix resulting in a unique PDLC morphology. The microdroplets are surrounded by the rigid polymer matrix from all sides except from the top, thus providing a direct liquid crystal–air interface. Such a PDLC free surface, when exposed directly to an air flow, responds by director reorientations in the partially exposed polymer dispersed liquid crystal (PEPDLC) microdroplets. These director reorientations are manifested in an optical response observed when the PEPDLC thin film is viewed in transmission under crossed polarizers. In this paper, we report the results of the optical polarization and the electron microscopic studies on the PEPDLC microdroplet textures. We also report the observation and the measurement of the optical response of the PEPDLC thin films deposited on glass substrates for a gas or air flow on its free surface. The optical transmission characteristics of the PEPDLC microdroplets in relation to their director configurations in this new morphology of the PDLC thin films are discussed.

2. Experimental

The PEPDLC thin films are deposited on glass substrates by the method of solvent evaporation-induced phase separation. Polystyrene is dissolved in methyl ethyl ketone (1 : 1) and a nematic liquid crystal (E38, EM Industries, U.S.A.) is mixed with the polymer solution in the concentration ratio 1 : 1. The polymer solution—liquid crystal mixture is sprayed on a glass substrate to provide a dry film thickness of ~ 10–25 μm. As the solvent evaporates, the liquid crystal tends to become insoluble and starts phase separating from the polymer matrix in the form of microdroplets. After a period of about an hour, the solvent completely evaporates leaving a PEPDLC thin film–glass substrate system which on being viewed in transmission in a polarizing microscope with crossed polarizers produces a typical texture (liquid crystal microdroplets dispersed in a rigid polymer matrix), shown in figure 1 for a film thickness of ~25 μm. There are three particularly interesting and unique features of the texture in figure 1: (i) the microdroplets have a size (diameter) distribution of ~2–10 μm, (ii) there are droplets, as at A, which are covered completely by the polymer matrix and there are also droplets, as at B, which are only partially covered, i.e. covered from all sides leaving the top (partially exposed), and (iii) the droplets in general have a distribution of concentric (as at C) and bipolar (as at D) director configurations [8] seen more clearly for the partially exposed droplets. Clusters of the partially exposed droplets are also seen making some of the droplets appear non-spherical in shape and with sizes larger than 10 μm.

Electron microscopy of the PEPDLC thin film surface, shown in figure 2, reveals a swiss cheese morphology with the microvoids on the top surface filled by the liquid crystal. Whereas the partially exposed microdroplets respond to the air flow on the surface of the film, the droplets lying deeper in the bulk of the PDLC film, being covered

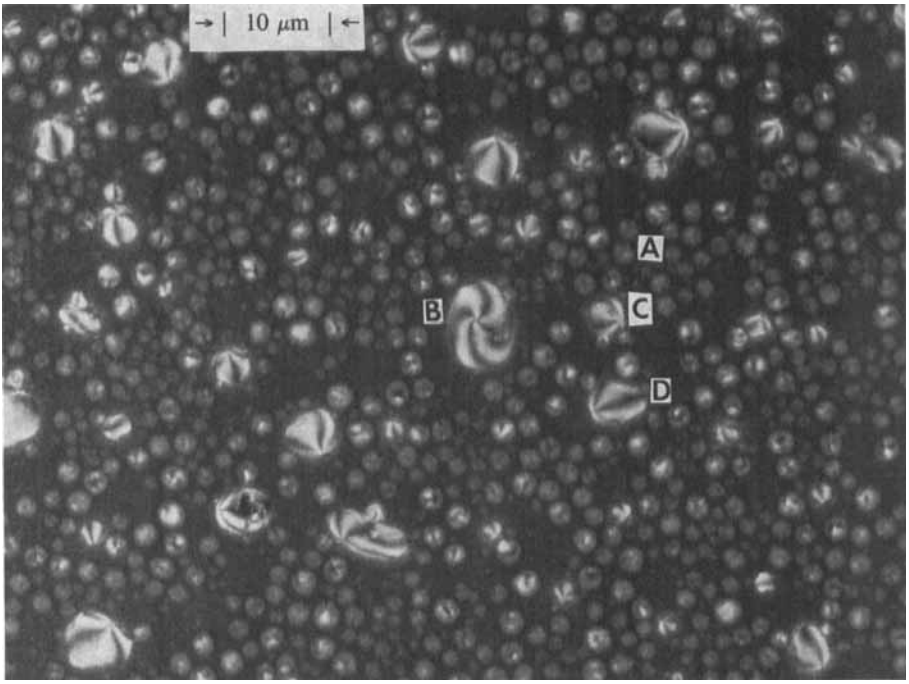


Figure 1. Size distribution of the nematic droplets on the exposed surface of the PDLC thin film.

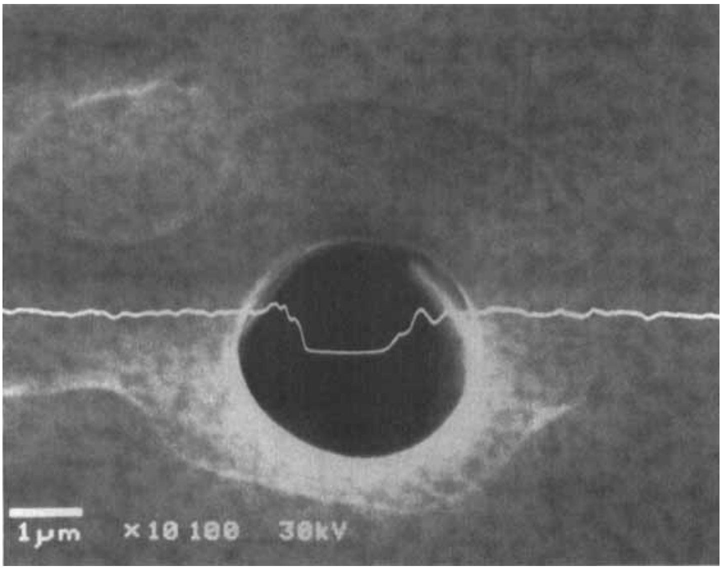


Figure 2. Electron micrograph of the PEPDLC droplet environment.

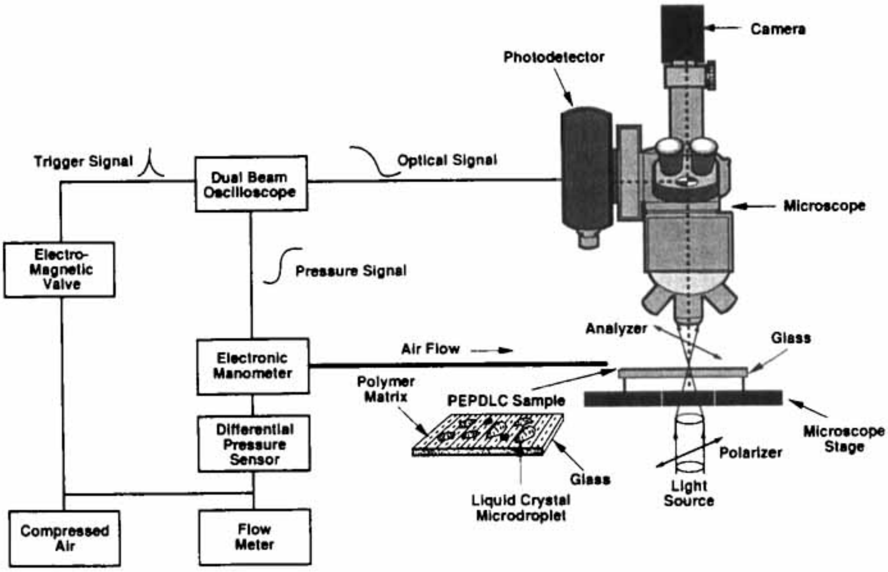


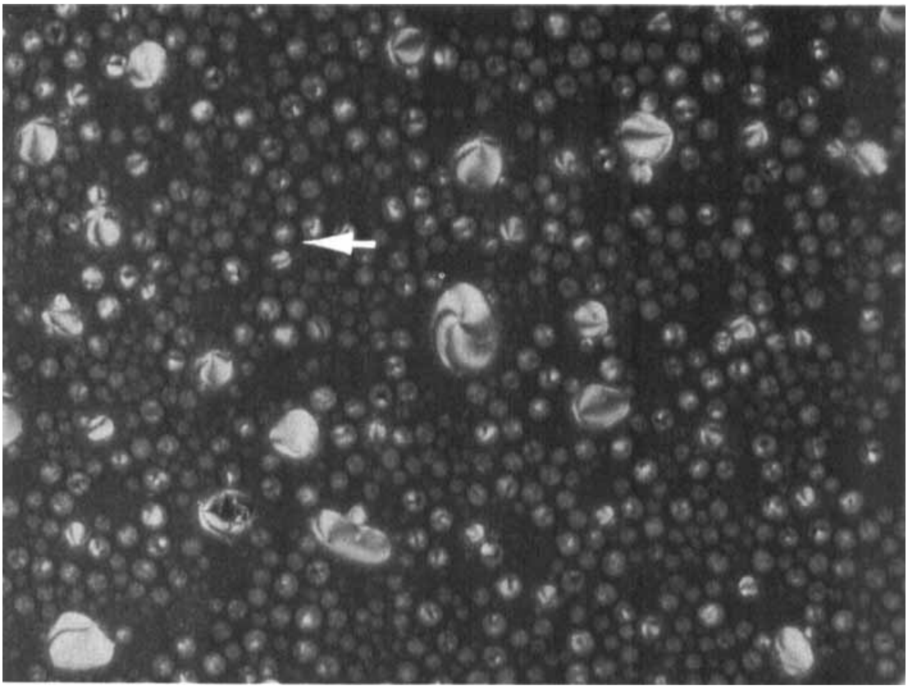
Figure 3. Schematic diagram of the experimental set-up.

from all sides including the top by the rigid polymer matrix, remain largely unaffected by the air flow. Also, some of the droplets formed on the top surface of the thin film are completely free from the polymer matrix and do not hold to the surface under shear stress. They are washed out easily by the wind flow within the first few seconds of starting the experiment. The results reported here do not include the response of the droplets which are washed out.

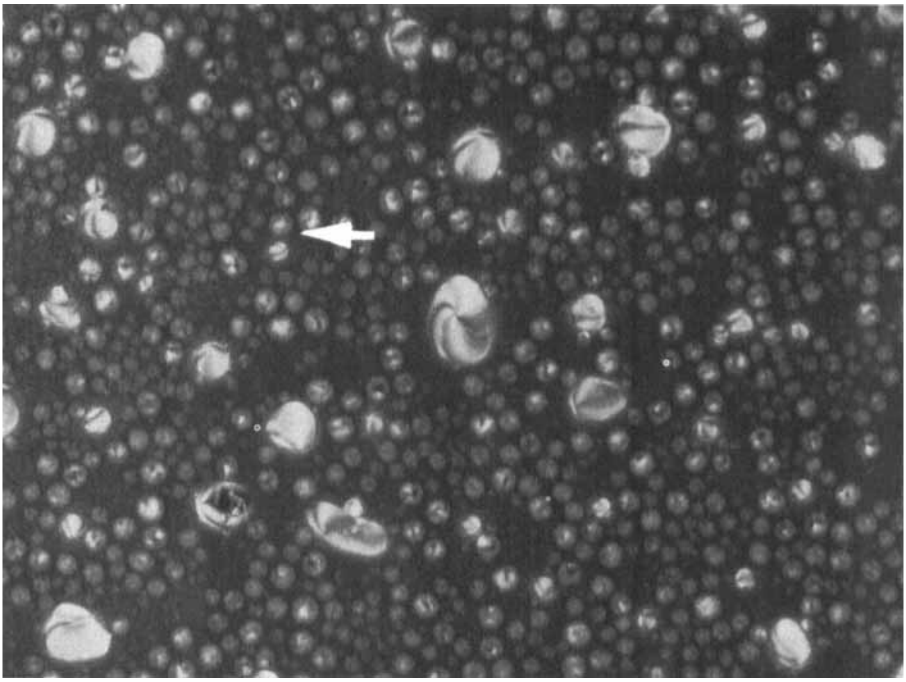
The experimental arrangement to study the transmission of light through the PEPDLC thin film under shear stress (further details in [11]) is shown schematically in figure 3. The PEPDLC sample is mounted on a polarizing microscope (Nikon, Optihot-Pol). Compressed air is blown horizontally over the sample and a flow measuring system consisting of a flow meter, a differential pressure sensor, an electronic manometer and an electromagnetic valve are used to control and measure the flow conditions. On releasing the air, the electromagnetic valve triggers the oscilloscope and the time dependence of the transmitted light intensity from the instant of switching on of the flow is recorded with the help of a photodetector attached to the microscope.

3. Results

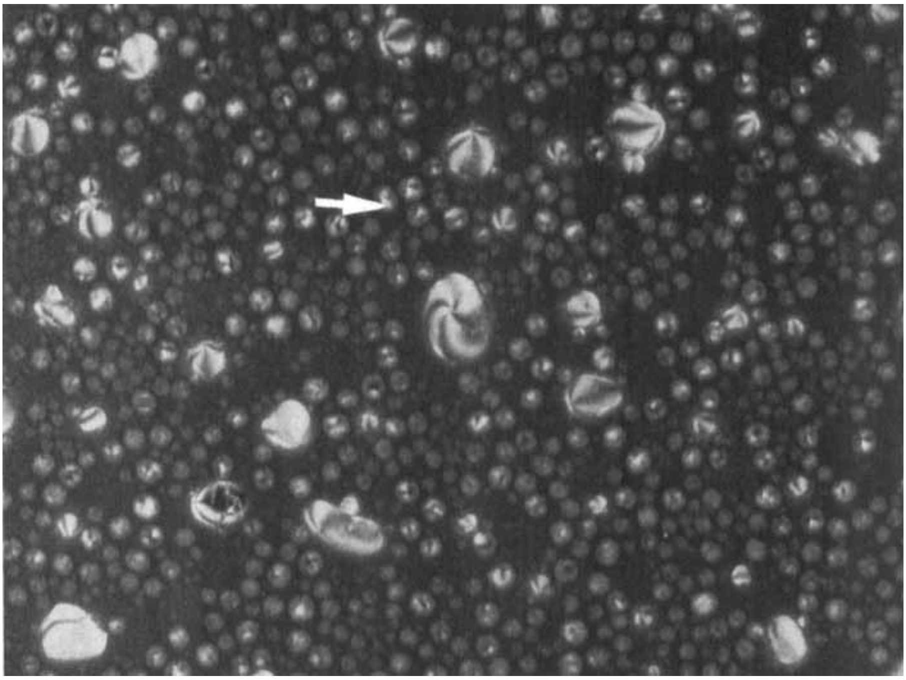
When an air flow impinges on the exposed surface of the PEPDLC thin film, the intensity of the light transmitted through the droplets changes with the air flow differential pressure. Figures 4(*a*) and (*b*) illustrate the increase in the intensity of the transmitted light for differential pressures Δp of 1·7 and 2·5 T, respectively. The increase in intensity is clearly a function of Δp (for example the droplets B, C and D in figures 4(*a*) and (*b*) are brighter in comparison to their counterparts in figure 1). Similar changes are observed when the direction of the air flow is reversed as shown in figures 4(*c*) and (*d*) for $\Delta p = 2{\cdot}2$ and 3·8 T, respectively. There are several other interesting aspects of the director field distribution of figure 1 and its deformation as a result of the



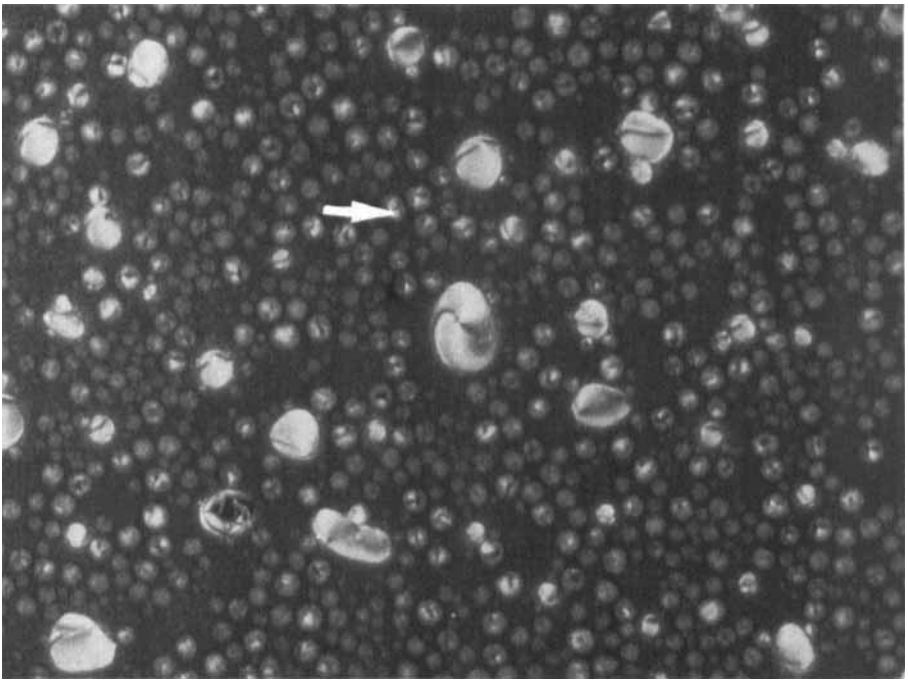
(*a*)



(*b*)



(c)



(d)

Figure 4. Droplets in figure 1 get brighter for air flow in the direction of the arrow; Δp: (a) 1·7 T, (b) 2·5 T. Reversing the direction of the air flow has the same effects; Δp: (c) 2·2 T, (d) 3·8 T.

air flow in figures 4 (*a*)–(*d*). In the PEPDLC droplet size distribution of figure 1, three specific features of the director field configuration are clearly noticed: (i) the director field, in general, is radial [8] for small (like droplet D) and large (like droplet B) droplets, and (ii) the topographical point defect hedgehog is not necessarily at the centre of the droplet (this observation is in disagreement with the previous experimental [12] results and the theoretical [13] predictions), and (iii) in smaller droplets, the appearance of boojum defects is common (as at C and D). This suggests that the anchoring at the droplet–polymer matrix interface, although strong, is not necessarily normal in the PEPDLC configuration.

The air flow induces director field reorientation and the director **n** tends to align in the direction of the flow. If the director field in absence of the air flow is radial, its reorientation due to air flow in the direction of the arrow results in a line defect shown in figure 5 for $\Delta p = 24{\cdot}6\,\mathrm{T}$. In figure 5, the droplet is the same as B in figure 1, but represented on a magnified scale. The shape and the position of the line defect depends on the initial configuration of the director field and the magnitude and the direction of the air flow. This change in the director field configuration due to shear stress resulting in a line defect has been reported by us recently [11]. An increase in the transmitted light intensity through the droplet is also seen as a result of the air flow. Further increase in the air flow increases the intensity of the transmitted light through each droplet. It may be noted that the line defect always originates from the hedgehog point defect at the centre. Similarly in the droplets with a boojum defect, one end of the air flow-created line defect is always at the boojum. Additionally, multiple line defects appear as a result of the non-centricity of the hedgehog defect. The dynamics of the line defect as a function of the air flow rate are under current investigation.

It is further observed that with the appearance of the line defect in a droplet, a secondary point defect resembling a tiny droplet on the exposed surface of the

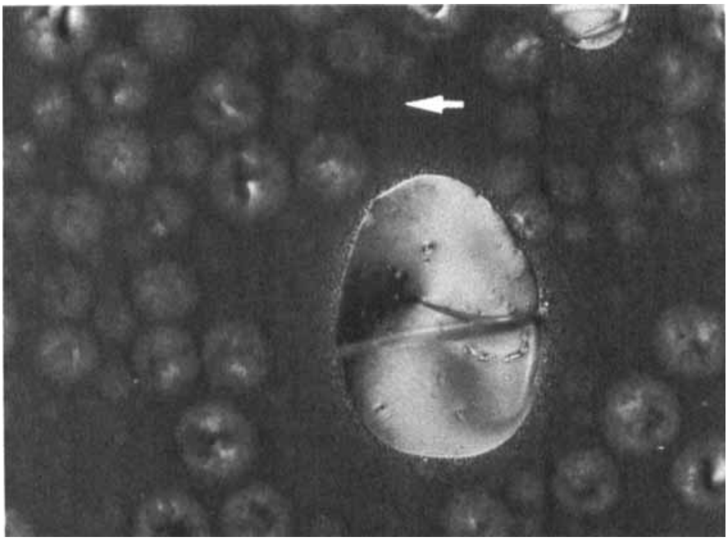


Figure 5. Topological defects appear as a result of the air flow shear stress ($\Delta p = 24{\cdot}6\,\mathrm{T}$). Droplet B from the droplet texture of figure 1 is shown on a magnified scale. A line defect appears in the direction of the air flow as a result of the director field reorientation.

microdroplet also appears. The secondary point defect, unlike the hedgehog, oscillates along the direction of the air flow. The frequency of oscillation of this defect is a function of Δp as shown in figure 6.

The variation of the transmitted light intensity, $\Delta I = I_s - I_0$ (I_s and I_0 being respectively the intensities in the presence and the absence of the air flow), as a function of Δp is shown in figure 7. Such a variation can be explained from considerations of the Jones matrix formulation for the propagation of light through a birefringent (liquid

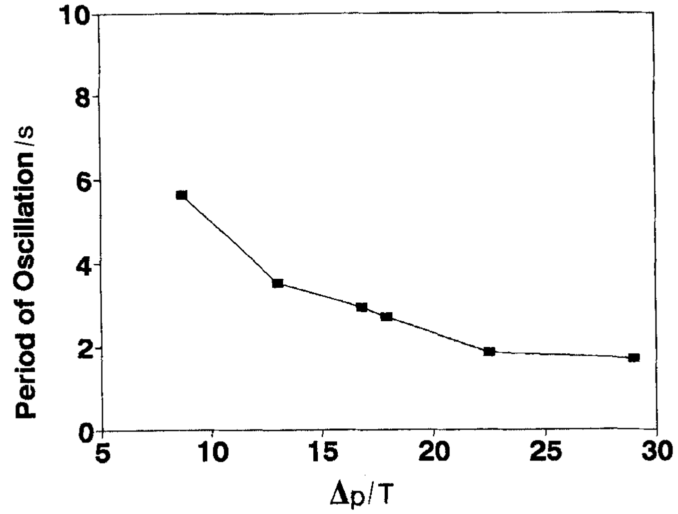


Figure 6. The variation of the frequency of oscillation of the secondary point defect with Δp.

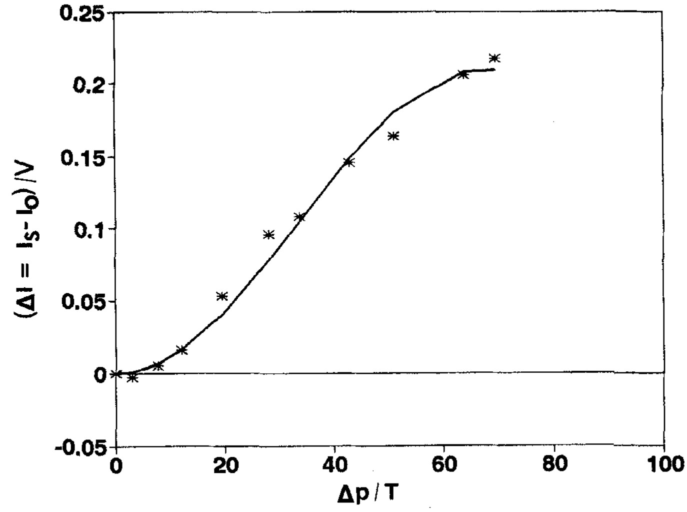


Figure 7. Variation of the intensity of the transmitted light with Δp. The solid line is a fit from equation (1).

crystal) medium sandwiched between crossed polarizers. These calculations under the assumption of a linear relation of the director reorientation with Δp result in an equation correlating ΔI with ΔI as [14]

$$\Delta I = B_1 \sin^2 (B_2 \Delta p), \tag{1}$$

where B_1 and B_2 are constants. The data in figure 7 have been fitted with equation (1). The solid line in figure 7 represents the ΔI versus Δp relation from equation (1) for $B_1 = 0{\cdot}22$ and $B_2 = 15{\cdot}4$. The experimental results are in excellent agreement with equation (1). Thus the present system provides a novel sensor for air or gas flow in aerodynamics testing and experimentation.

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