Shear-stress measurement in aerodynamic testing using cholesteric liquid crystals

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Shear-stress measurement in aerodynamic testing using cholesteric liquid crystals

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The change in the selective reflection spectra of cholesteric liquid crystals with shear is described, and the results indicate that, although it appears to be a promising technique for flow visualization in aerodynamic testing, the method is only suitable for approximate measurement of shear. An improved method for visualising flow is proposed that utilizes a shear-induced texture change from the uncoloured focal-conic state to the selectively reflecting Grandjean state. The sensitivity of the transition to shear is investigated and the effects of adding silica particles to modify the viscosity is examined.

1. Introduction

The measurement of surface shear in aerodynamic testing provides important information to aid the design of low-drag vehicles. In particular, it is desirable to visualize the laminar-to-turbulent boundary-layer transitions over the surface of the vehicle. Conventional methods [1] of studying boundary-layer behaviour such as hot films or Preston tubes are either difficult to interpret or only provide local measurements of shear stress. More recently a new technique for visualizing flow using cholesteric liquid crystals has been reported [2, 3]. In this method neat liquid crystal was applied to the test surface and an air flow over the surface produced a shear stress that induced a colour change between high-shear turbulent-flow and low-shear laminar-flow regions. In these tests the shear was applied perpendicular to the helical axis, producing a velocity gradient parallel to it, which is similar in effect to previous studies using either rotating parallel discs [4–6] or linearly sheared plates [7, 8]. These concluded that increasing shear caused a shift in the wavelength of the cholesteric selective reflection to the blue end of the spectrum, with an associated decrease in reflected intensity. Critical shear rates have also been observed in the experiments employing shearing between plates where structural instabilities and texture changes occured.

We report an extension of this work by examining in detail the selective reflection from chiral nematic liquid crystals [9] as a function of illumination and viewing angles under precise shearing conditions in a wind tunnel as well as between rotating parallel disks. The results are discussed in relation to their application for flow visualization and shear measurement in aerodynamic testing. In addition, we present an improved method for detecting laminar-to-turbulent boundary-layer transitions that utilizes a flow-induced texture change from focal-conic to Grandjean.

2. Experimental

The chiral nematic liquid crystal materials were formulated from components supplied by BDH Ltd (Broom Road, Poole, Dorset, U.K.). The compositions and transition temperatures for the mixtures studied are given in the table. E7, E9, E44 and S2 are eutectic mixtures based on 4-*n*-alkyl- and 4-*n*-alkyloxy-4'-cyanobiphenyls; (+) CB15 is an acronymn for (*S*)-(+)-4-(2″-methylbutyl)-4'-cyanobiphenyl. For purposes of comparison a cholesteryl ester material (C-N/G114F, $T_{Chl} = 45°C$) supplied by Hallcrest Ltd (1820 Pickwick Lane, Glenview, Illinois, U.S.A.) was also studied. Two techniques were employed to apply a shear stress to the liquid crystal. The first of these comprised of two 5 mm transparent polycarbonate discs of diameter 100 mm separated by a gap of 50 μm (see figure 1). The lower plate was fixed and the upper plate was rotated by a D.C. electric motor with a variable-speed control enabling angular velocities up to 7 rad s^{-1}, determined from the measured rotation rate.

Compositions and transition temperatures of chiral nematic mixtures.

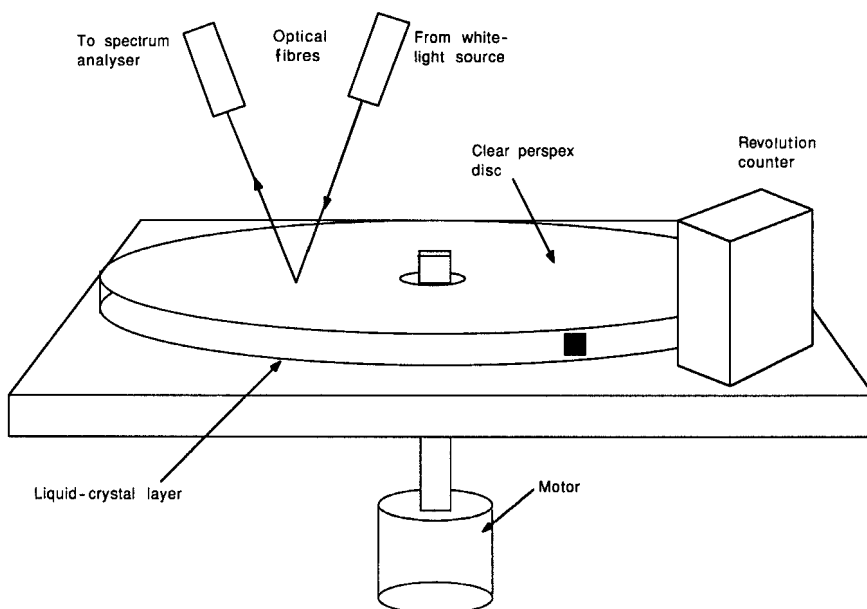|		Percentage by weight	$T_{Chl}/°C$
1	S2	67	22·9
	(+) CB15	33	
2	E7	65	28·8
	(+) CB15	35	
3	E44	60	48·0
	(+) CB15	40	
4	E9	65	43·8
	(+) CB15	35	

Figure 1.   Schematic diagram of the rotating disc apparatus. The disc is of diameter 100 mm and can rotate up to 7 rad s^{-1}. The effect of shear on the selective reflection was examined with a spectrum analyser.

In the second method a thin layer (20–50 μm) of liquid crystal was applied to a temperature-controlled surface located within a duct, which was connected to a suction pump and thus operated as a blow-down wind tunnel (see figure 6). A convergent channel was used to produce a shear-stress gradient, which was independently monitored at several positions along the surface by means of Preston tubes, using the razor-blade technique [10]. This technique enabled shear-stress levels in excess of $100 \, N \, m^{-2}$ to be obtained. In both experiments a matt-black backing layer was used to enhance the contrast of the selective reflection from the liquid-crystal layer. Spectral measurements were made using a Rofin–Sinar RSO 6000 spectrum analyser and RSO 0200 control unit interfaced to a BBC 32K microcomputer. Viscosity measurements were made on a Contraves Low Shear 30 concentric cylinder viscometer and obtained by determining the gradients from plots of shear stress against shear rate over a range of temperature.

3. Results and discussion

The four materials used in the tests (see the table) were selected for their relative colour-temperature insensitivity shown in figure 2. In general, the effect of shear from both the rotating-disc and wind-tunnel experiments on the selective reflection of the mixtures was similar, resulting in a blue shift and a reduction in the reflected light intensity. The typical change between the spectra of the sheared and static samples as seen in figure 3 for mixture 3 (E44/CB15) is representative. The magnitude of the decrease in the reflected intensity produced by shearing was found to be very dependent on whether the illumination was provided by a diffuse or point source. Diffuse illumination produced a smaller difference in the two intensities, which is consistent with a change from a specular to a more diffuse reflection from the unsheared to sheared sample. The increase in the bandwidth with shear is also a function of the flow-induced break up of the monodomain ordering. The extent of the blue shift in the peak reflected wavelength as a function of shear was found to be small for the mixtures, and a typical variation is shown in figure 4 for mixtures 1, 3 and the cholesteryl ester (C-N/G114F). As the shear stress was increased, the intensity and bandwidths $\Delta\lambda$ of the peak reflections gradually changed, until at high shear-stress
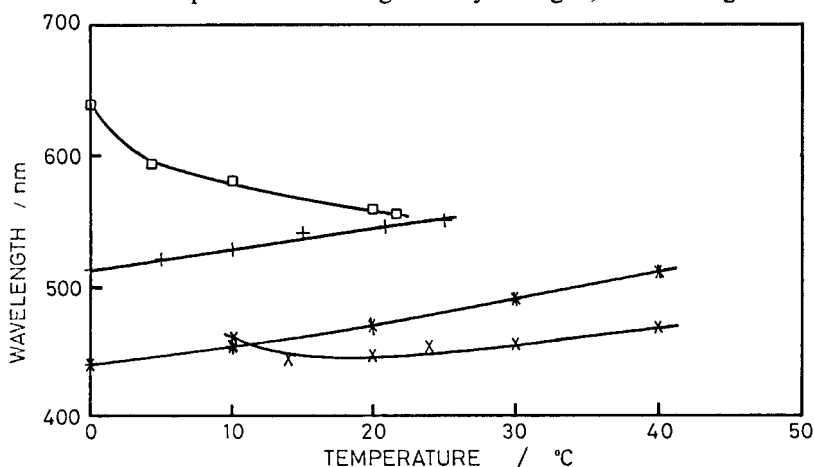

Figure 2. Peak reflected wavelength variation with temperature for the mixtures in the table +, E7 + 35 per cent CB15; □, S2 + 33 percent CB15; x, C-N/G114F; ∗, E44 + 40 per cent CB15.
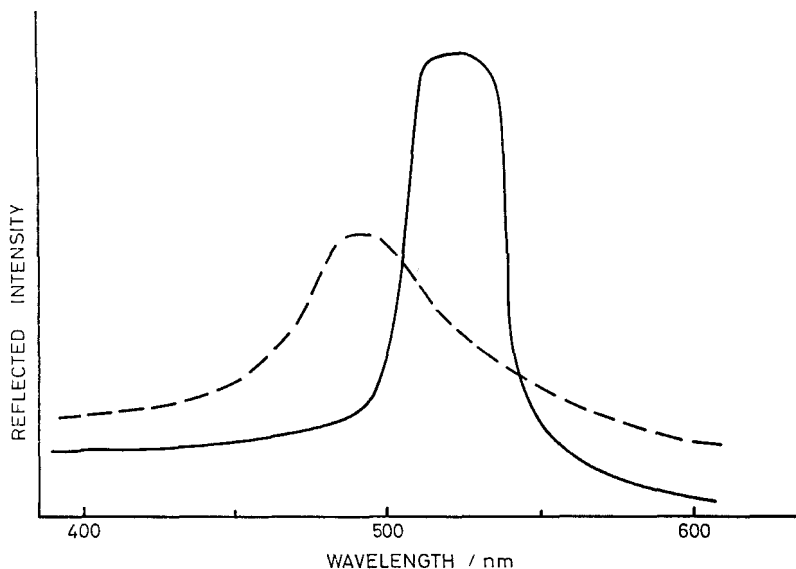
Figure 3. Typical effect of an applied shear stress on the normal reflection spectrum of mixture 3.
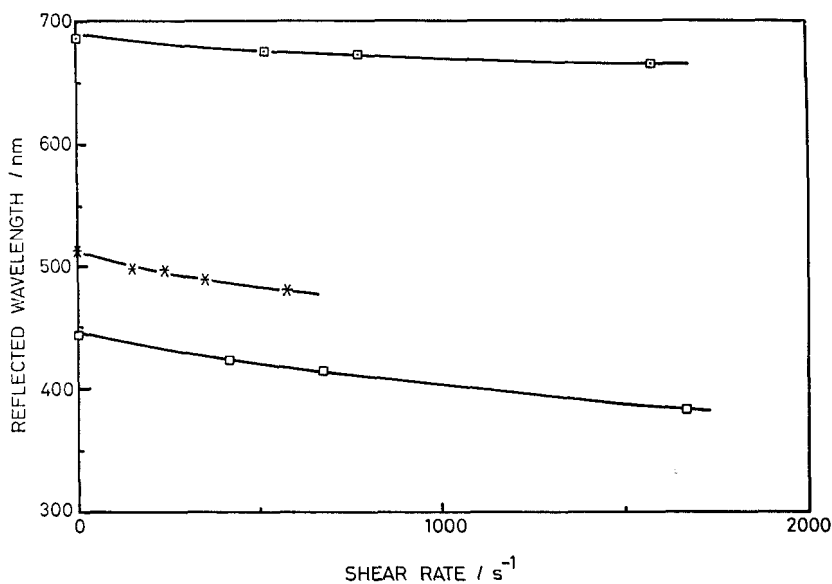

Figure 4. Effect of shear on the peak reflected wavelength for mixtures 1, 3 and the cholesteryl ester at a viewing angle of approx 15° off normal incidence. ☐, S2 + 33 per cent, CB15; *, E44 + 40 per cent CB15; ☐, C-N/G114F.

levels the selective reflection was undetectable. These observations are in agreement with those reported previously [4, 8] and support the conclusion that the helix undergoes a tilt distortion, which is seen in the asymmetric angle dependence of the selective reflection shown in figure 5.

Although gross changes in shear were observed as colour changes in the wind-tunnel experiment and therefore gave a rough indication of where the laminar/turbulent
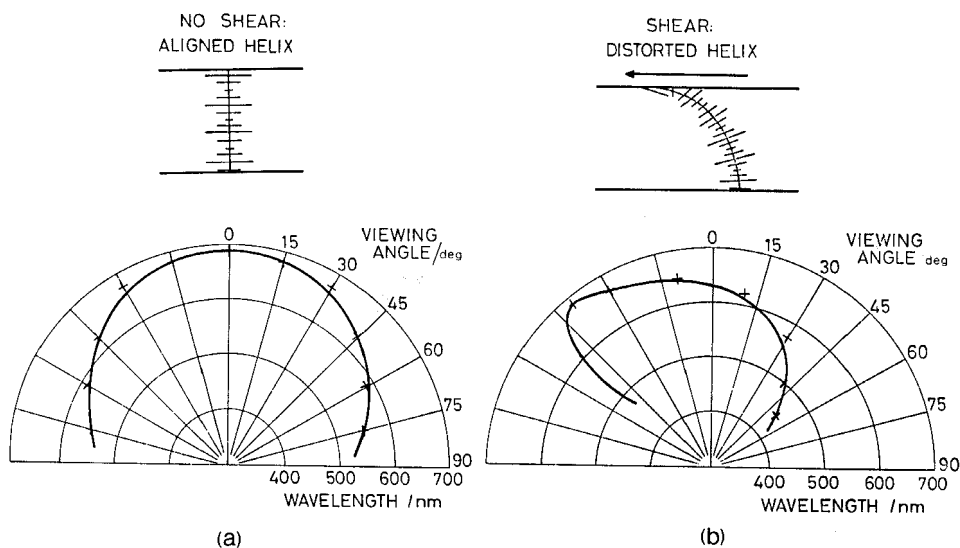
NO SHEAR:
ALIGNED HELIX

SHEAR:
DISTORTED HELIX

(a)

(b)

Figure 5. (*a*) Schematic diagrams of the cholesteric helices with and without distortion due to shearing. (*b*) Measured variations of the wavelength of peak reflected intensities as a function of viewing angle for E7 + 35 percent by weight of CB15. Results are presented without shear and with a shear rate of $1200\,s^{-1}$.
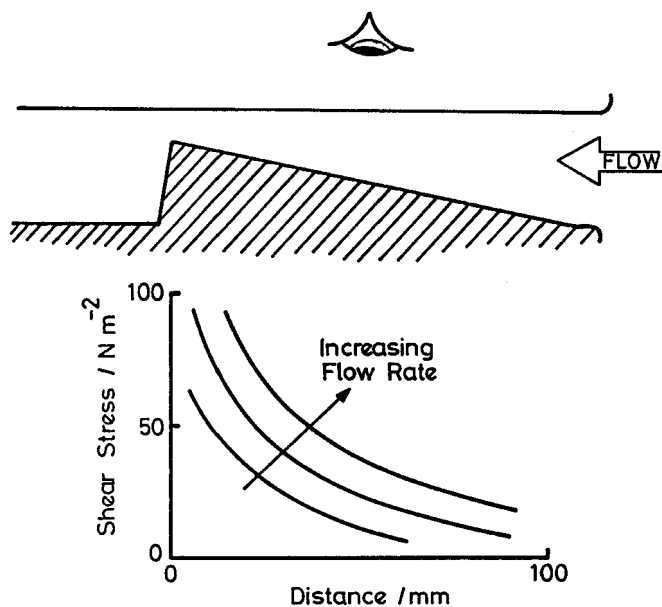
Figure 6. Schematic diagram of the converging duct and indication of shear-stress variation along the duct.

boundary layer was located, the results suggested that the method was unsuitable for quantifying surface shear stress levels. As a consequence, a novel approach [11] was investigated with the aim of exploiting the shear-induced texture change from the uncoloured focal conic to the coloured Grandjean state [12].
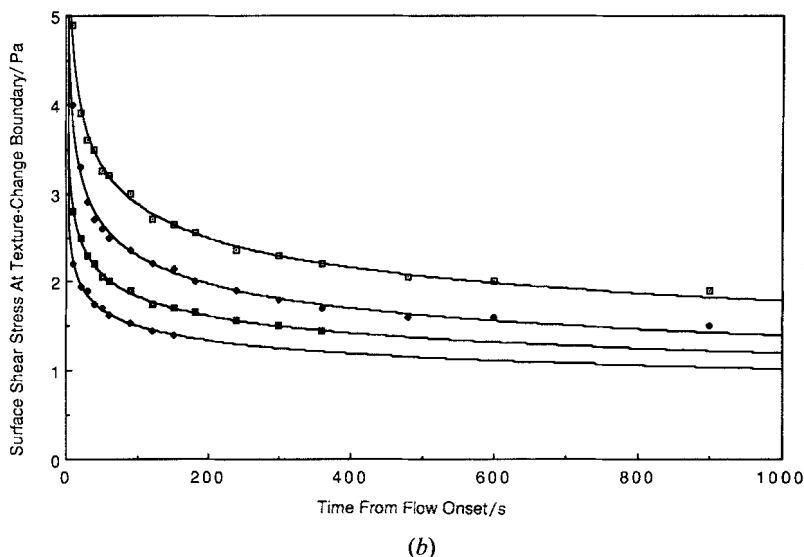
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(*a*)

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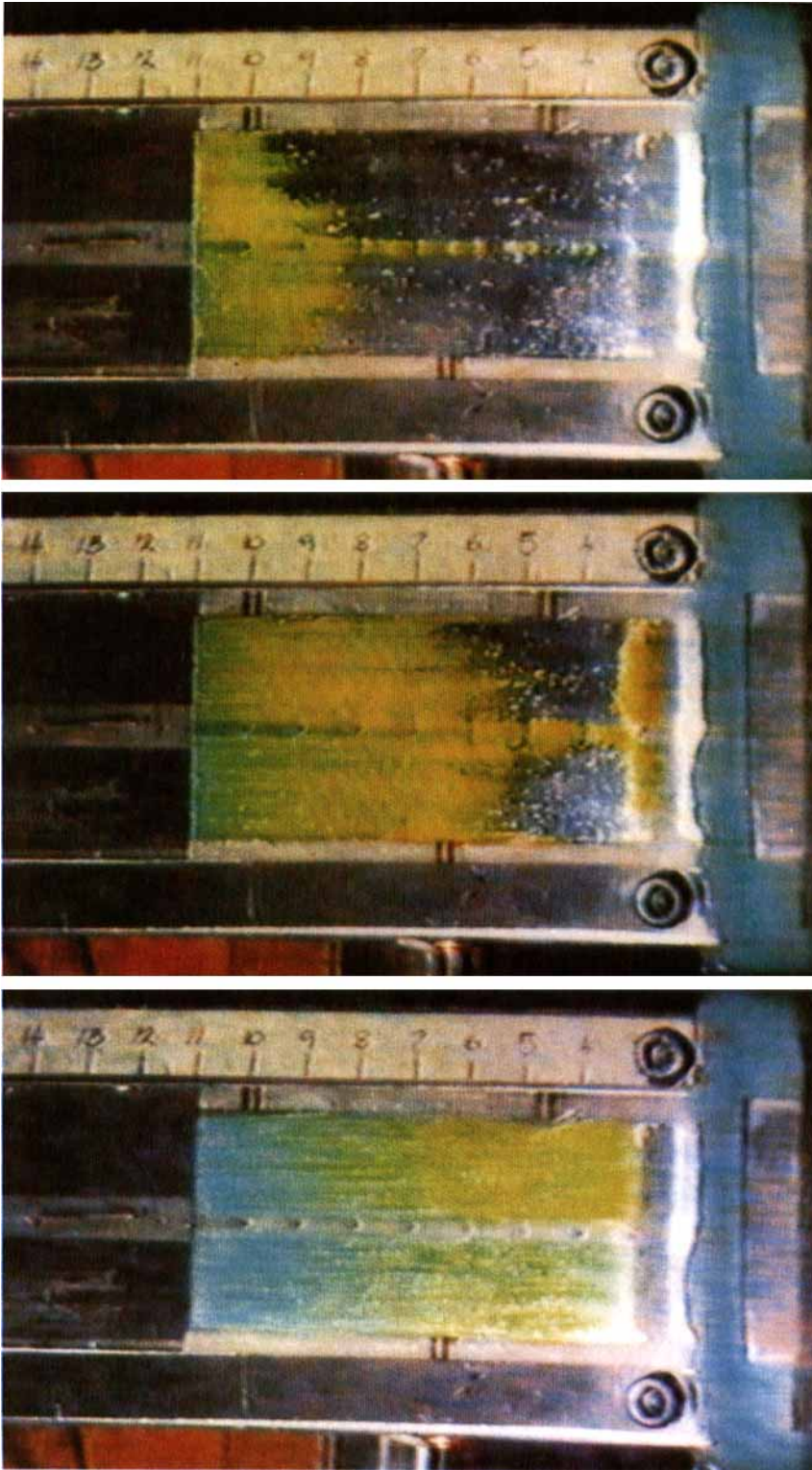
Figure 7. (a) Photographic sequence showing progression of texture change boundary within the duct of figure 6 for increasing flow rates. (b) Variation of the surface shear stress at the texture-change boundary as a function of time for fixed air flow. Results are shown for several surface temperatures for E7 + 35 per cent by weight of CB15; □, 5°C; ◆, 10°C; ■, 15°C; ◇, 20°C.

In order to coat the surface to be tested with cholestric material in the uniform off-state focal-conic texture, two techniques were examined.

(a) The liquid crystal was dissolved in a suitable solvent (e.g. trichlorotri-fluoro ethane) in the ratio 1 : 8 and sprayed onto the test surface, providing a fairly uniform coating (about 20 μm) of the cholesterogen, which, as the solvent evaporated, formed the required focal-conic texture. Care was taken to ensure that all of the solvent had been removed from the liquid-crystal layer.

(b) The neat crystal was applied directly onto the test surface by painting or silk-screen printing and then heated with a hot-air gun into the isotropic phase, which then cooled into the thermodynamically preferred focal-conic state.

Although the second method avoided possible contamination by the solvent, silk-screen printing was only suitable for flat surfaces.

Coated test surfaces from both application techniques were examined in the blow-down wind tunnel (see figure 6) described previously. At a particular shear-stress level a well-defined boundary appeared between the uncoloured focal conic texture and the brightly coloured flow-aligned Grandjean texture. This boundary was observed to shift towards lower shear levels with time, and eventually (after about 5 min) was independent of flow rate. If either the flow rate for a fixed time was increased or the time period increased for a fixed flow rate, the boundary moved as shown in figure 7(a) . The results imply that a minimum flow-driven displacement is required to align the material, and therefore that there is a threshold that may be determined by the material flow viscosity.

In order to investigate this move fully, the boundary shear stress level was examined as a function of temperature for mixtures 2 and 4 (figure 8). At a particular time (20 s) after the onset the shear-stress level at the boundary was proportional to the mixture viscosity. The boundary shear level of mixture 2 between 5°C and 20°C dropped by a factor of two, corresponding to a viscosity change from 200 cP to 75 cP. At a longer times the texture-change boundary moves to a position of lower surface shear stress, and therefore provides a convenient method of accessing a range of shear stresses using a single material at a fixed temperature. Thus using mixture 2 at 15°C enables measurements of shear-stress values between 1 Pa and 3 Pa over a 200 s time interval as shown in figure 7 (*b*). Moreover, higher shear-stress ranges may be accessed by using bias temperature control to increase the liquid-crystal viscosity.
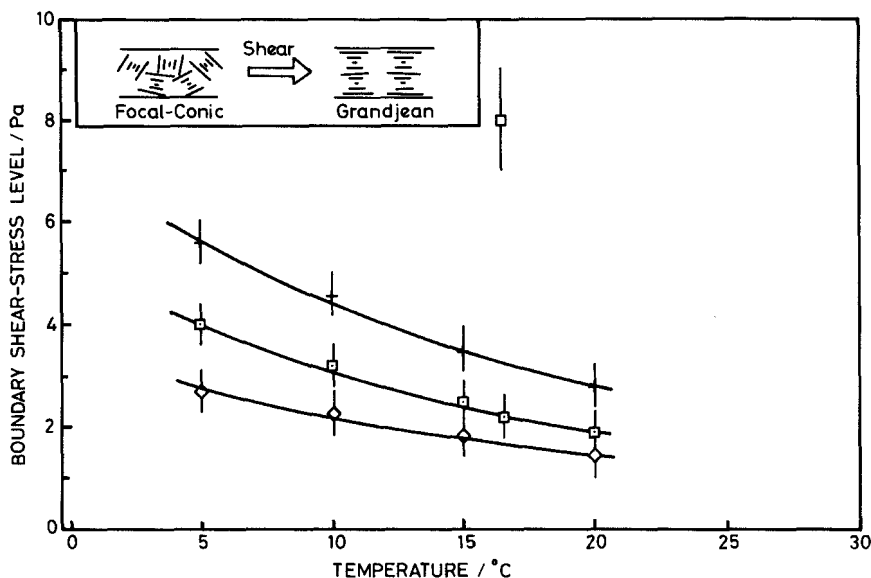

Figure 8. Surface shear-stress level at the location of the texture-change boundary as a function of temperature at a fixed time after flow onset for a range of mixtures: □, E7 + 35 per cent CB15 + Aerosil after 20 s; +, E9 + 35 percent CB15 after 20 s; ⊡, E7 + 35 per cent CB15 after 20 s; ◇, E7 + 35 percent CB15 after 2 min.

Another useful attribute of liquid crystals when used to measure shear stress is that they also provide a clear and convenient indication of the direction of the surface flow. This results because when the material flows, its viscosity is reduced considerably. Thus those regions where liquid-crystal flow starts will develop into a thin stream of coloured material that indicates the flow direction. An example of this flow visualization is given in figure 9. In this figure regions of low shear stress are uncoloured since their shear-stress threshold has not been reached. In other regions a very high shear stress has removed the material completely. Any ambiguity in these regions can be resolved by observing the development of the colour play with time after starting the air flow. In some cases where higher air-flow shear stress is present the viscosity of the material may be increased by the addition of a fine silica particulate (Aerosil [13]). An example of this using 2 per cent by weight of Aerosil 805 is shown in figure 8. It has been found that such mixtures act rheologically as pseudo-plastics [14]. Further studies on this subject are to be published [15].
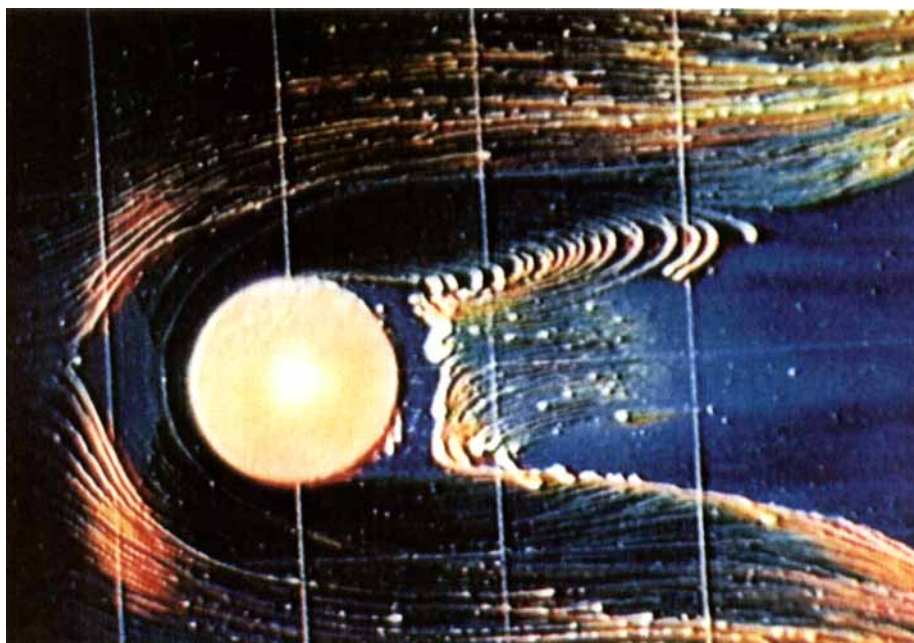
Figure 9.   Flow visualization and shear-stress indication of horse-shoe vortex using mixture 2 (flow velocity $40 \, \mathrm{m \, s^{-1}}$).

4.   Conclusions

Gross changes in shear stress have been shown to induce a change in the selective reflection wavelength of cholesteric liquid crystals, which has been used [2, 3] for coarse flow visualization in aerodynamic testing. An improved visualization technique has also been described that can enable low shear-stress levels to be quantified; this employs the flow-induced change from focal-conic to Grandjean texture. A convenient technique for modifying the rheological properties of the liquid crystals by adding a silica particulate has been outlined and shown to enable higher shear stress levels to be accessed. Flow visualization around a pedestal has been demonstrated, and, using the induced texture change in cholesteric liquid crystals, region of high and low stress associated with the horse-shoe vortex have been observed.

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