VISUALISATION OF TRANSITION ON AN AXISYMMETRIC BODY USING SHEAR SENSITIVE LIQUID CRYSTALS

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Abstract

The present work is concerned with the development and application of techniques for quantitative calibration and use of liquid crystals for measuring surface skin friction under laminar, transitional and turbulent flow conditions.

The scope of the research has been two-fold. Firstly, laboratory calibrations of different liquid crystal mixtures have been undertaken at Surrey University using a mechanical rotational shear rig in conjunction with both a spectrophotometer (for point measurement and assessment of the full spectrum of both the incident and reflected light) and a 3-CCD video camera with a digital image processing system (for full-field determination of the reflected colours in terms of HSI co-ordinates). Secondly, aerodynamic tests, under subsonic and transonic conditions, have been carried out using an axisymmetric body with an ogive nose in the slotted wall transonic wind tunnel at City University.

The laboratory calibrations have indicated the manner in which the observed reflected light from the crystal layer varies with the location and angle to the surface of both the incident illumination and the receiving optics. The wind tunnel tests showed that the crystal type BCN/165 (a mixture of cholesteric and chiral-nematic crystals) gave the best overall performance in terms of both colour play and durability. In addition, the experiments demonstrated the feasibility of the present approach for the quantitative assessment of skin friction in laminar and turbulent flows, coupled with the detection of the transition region.

1 Introduction

The use of both temperature sensitive and shear stress sensitive liquid crystal formulations have increased greatly over the past few years, with the main emphasis being the qualitative visualisation of surface flow phenomena in high-speed aerodynamic testing. The colour of the crystals changes with external stimulus, typically going from red at the lower shear stresses or temperatures through to blue at the higher shear stresses or temperatures. However, in some applications using thermochromic crystals the colour play with changes in temperature may be reversed. This is because there are two mechanisms operating within the crystal layer, one being an expansion of the helical molecular structure along its axis with an increase in temperature (leading to a greater pitch length between crystals and, hence, a higher wavelength of the reflected light) and the other being a twisting or tightening of the helix about its axis with an increase in temperature (resulting in a smaller pitch length and a lower wavelength of reflected light). Thus, different formulations can be produced in which one or other of these processes dominates. By balancing these two actions the temperature-insensitive but shear stress sensitive liquid crystal mixes are achieved. The actual bandwidth of the reflected colours depends upon the particular formulation of the crystal mixture.

Early research using liquid crystals generally focused upon qualitative assessment of parameters such as heat transfer [1,2], boundary layer transition [3-6] and skin friction [5]. Nevertheless, a number of researchers have developed systems for quantitative measurement of the colours, with varying degrees of success. Such techniques have used colour digitisation of

CCD camera video images or photospectroscopy techniques. This research has included the analysis of both temperature sensitive crystals, for example [7-10], as well as shear stress sensitive crystals [5,6,12-19].

Unlike temperature sensitive mixtures, the shear sensitive crystals are unencapsulated and, therefore, the physical processes that occur within the crystal layers as the material is sheared are not well understood. Furthermore, because the observed colour reflected from the surface varies with the location and angle relative to the surface of both the incident light and receiving optics, conducting calibrations under well-controlled conditions is very difficult. Early research [12] utilised a rotational shear rig in which the change in reflected wavelength, detected by a photomultiplier, was related to the shear applied to the crystal layer. Although this relationship was found to be approximately linear for shear stresses up to about $300N/m^2$, beyond this range the shear stress values tended to become indeterminate. The same workers also attempted to produce a shear stress calibration by carrying out turbulent pipe flow experiments [20], but no calibration was achieved because the maximum shear stress was rather low, at about $54N/m^2$ and so the observed colour changes were very slight. Other research subsequently utilised a rotational shear rig [13] in order to study the spectral characteristics of the light reflected from a crystal in its unsheared and sheared states. The increasing application of shear produced a shift in the wavelength position of the peak response towards the blue end of the spectrum. Associated with this shift was a general attenuation and broadening of the peak, probably associated with the breakdown of the crystal structure, such that at the higher shear stress levels it was not possible to observe a distinct dominant wavelength. They developed another method for low shear stress measurements, at air velocities as low as 20m/s, in which the applied shear was related to the time taken for the crystal to change from its colourless (focal conic) state to the colourful (grandjean) texture [14]. More recently, a shear stress vector measurement technique has been developed, using liquid crystals together with spectrophotometric analysis of the reflected light [16-19], which has potential for a better understanding of the optical characteristics of the crystal layers. The calibrations were achieved by examining colour changes beneath a wall jet for which the relative, but not absolute, shear stress distributions could be calculated.

The main drawback of spectrophotometry is that only a small area of the surface can be viewed and analysed at any one time since fibre optic sensors are normally used for both the surface illumination and for observing the light reflected from the crystal layer. In order to carry out real-time, full-field, surface shear stress measurements it is necessary to utilise video digitisation techniques in which a relatively large area may be viewed with sufficient resolution by employing a high-quality 3-CCD camera, ideally incorporating at least a 512 x 512 pixel sensor array. This approach was adopted for some initial wind tunnel calibrations carried out involving the present authors [15] in which crystals were applied to a 150mm diameter circular force balance mounted in the tunnel roof. From experiments over a range of Reynolds numbers and Mach numbers a limited calibration was achieved over the low shear stress red/orange region of the colour play.

The present authors have extended the range of flows examined using shear sensitive liquid crystals in order to assess the performance of different mixtures in terms of both colour play and durability. This work has included surface mounted half-bodies at M=2 [19], turbulent boundary layer flow at M=3 [20], flow on a flat plate and around a fin model at M=6.85 [21] and flows in yawed rectangular cavities at M=2 [22]. In all cases the flows were illuminated using tungsten halogen lighting, with the reflected colours observed by a CCD camera and the video recordings analysed by a digital image processing system. One aim of the present paper is to investigate the behaviour of the liquid crystals at subsonic and transonic speeds and to assess their capability for assessment of transition and skin friction measurement on an axisymmetric body. The authors have developed the image processing approach further by using a mechanical rotational shear rig in conjunction with a spectrophotometer for point measurements of the full spectrum, as well as the PC-based video digitisation system for full-field analysis. A second aim of this paper is to illustrate how liquid crystal calibrations, for a wide range of different crystal types, may be achieved in the laboratory by using such a device.

2 Experimental Details

2.1 Liquid crystals and image processing systems

A number of different liquid crystal mixtures have been investigated during the course of the research programme. Details of these are outlined in Table 1.

Crystal Mixture	Type	Nominal viscosity (cps)
TI 511	chiral-nematic	250
BNR/50C	chiral-nematic	250
BCN/165	mixed	1000
CN/R2	cholesteric	4500
CN/R30	cholesteric	7000
CN/R7	cholesteric	13000
CN/R8	cholesteric	40000

Table 1: Types of liquid crystal mixtures and their viscosity

The cholesteric crystals are naturally occurring sterols, whereas the chiral-nematic mixtures are derived from non-sterol synthetic cholesterics. Type BCN/165 crystals are a mixture of these two types, whilst TI511 and BNR/50C have the same composition but are manufactured by different companies. The viscosities given in the table are those quoted by the manufacturers and can be considered as nominal or approximate values, to within ±20%, allowing differentiation between the very fluid mixtures such as TI511 and the extremely stiff mixtures, which cannot be readily brushed onto a surface, such as CN/R8.

The crystals may be applied to the test surface by using one of two methods, namely spraying after diluting the crystals in a solvent such as isopropyl alcohol (typically 1:5 ratio solution) or using a fine brush with gentle strokes in order to minimise brushmarks in the crystal layer. In the present work all of the crystals were applied by brush. The surface onto which the crystals are applied must be matt black, in order to minimise background reflection of light, and, in order of preference, this may be achieved by either black anodising, stove enamelling or spray painting. In the present work the test surfaces were black anodised.

Two different image processing systems have been utilised in the present work. In the first instance a 3-CCD true colour RGB (red, green blue output) video camera has been used for full-field analysis of the liquid crystal colours, as described in detail in [15]. The images are normally recorded on video tape for subsequent analysis, although on-line colour assessment of the live camera output is also possible. The image processing system has a PAL decoder to transform the composite or Y/C images to RGB format and these signals are then analysed on a frame-by-frame basis by a colour video frame grabber installed in a PC.

The necessary software for acquisition and analysis was developed as part of the research programme and this permits transformation of the image data into the HSI (Hue, Saturation, Intensity) colour space. It is the hue of the colour which is calibrated against the shear stress and it has been found that the present system has an accuracy of ±6% in terms of the hue measurement over a range of test conditions. In the experiments illumination is provided from tungsten-halogen sources. It has been found that, contrary to earlier work in this field, a single source illuminating the surface in a single direction gives a much greater colour play from the crystals than several light sources acting in many directions.

In order to provide more information about the crystal colours, rather than relying solely upon the value of hue, a spectrophotometer was utilised, in conjunction with the mechanical rotational rig described in the next section, to yield the complete visible spectrum of the reflected light with a wavelength resolution of 0.5nm. The layout of this apparatus is given diagrammatically in figure 1 along with the conventions used for the viewing (subscript V) and lighting (subscript L) angles in both the horizontal (α) and vertical (β) planes. The variable intensity tungsten halogen illumination is taken to the test surface via a fibre optic link and a focused beam probe. A second beam probe and fibre optic link is used to gather the light for the spectrophotometer. The acquisition and analysis of the data, including the conversion to the HSI colour space when required, is carried out under the control of a PC.

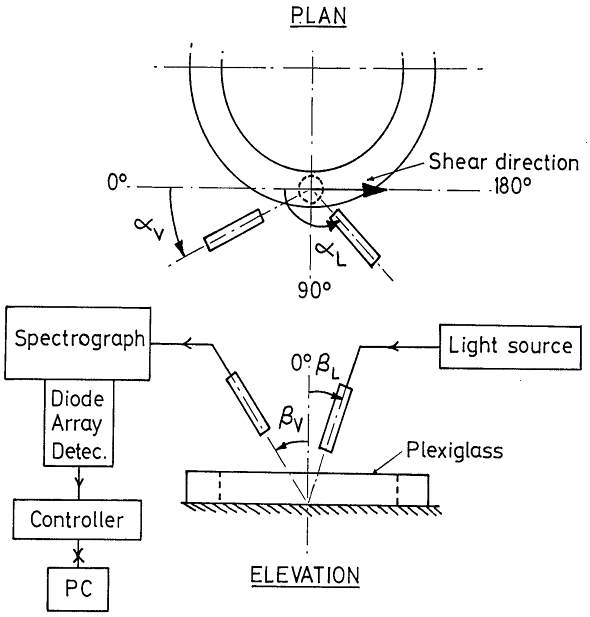


Figure 1: Layout of spectrophotometric apparatus and lighting/viewing angle conventions

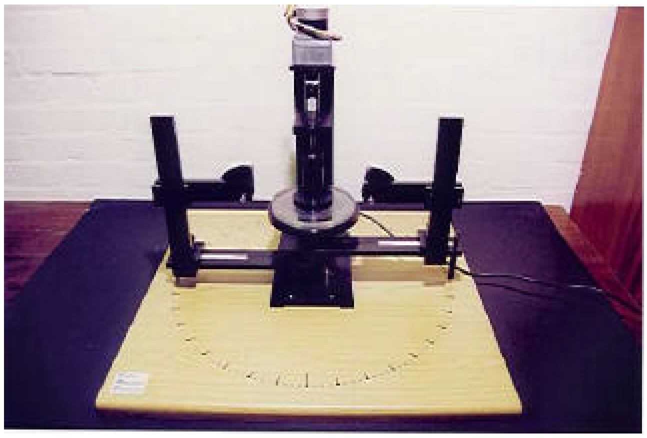


Figure 2: General overview of the complete rotational shear rig and probe holders

2.2 Apparatus for laboratory calibration of liquid crystals

In a previous paper [15] the present authors described a rotational shear rig which was utilised in some preliminary calibrations of liquid crystals. However, it was found that the rig was cumbersome to operate and it was difficult to precisely set the spatial and angular positions of the illumination and viewing sources around the rig. Hence, a new rig has been developed to permit assessment of the variation of measured hue with applied shear stress, taking into account the illumination and viewing locations, an overview of which is illustrated in figure 2. The equipment features a ground board with locating holes to allow precise horizontal alignment, in 2.5^o increments, of the two fibre optic beam probes (light source and sensor) associated with the spectrophotometer described earlier. The new apparatus has been directly based upon the experiences gained in using the initial rig and its operation is based upon the same principles as outlined in [15]. The device has an annular bearing surface of the same width (20 mm along the radius) as before but at a greater radius (outer radius of 80mm as compared to 50mm). Beneath the upper 10mm thick plexiglass disk and the lower, black anodised, aluminium bearing surface is the 2kg load cell which is utilised for the shear stress measurements to within $\pm 0.8 N/m^2$. Precise setting of the crystal layer thickness is achieved by a micrometer gauge.

The major feature of the new rig is the apparatus which permits very accurate setting, relative to the crystal surface, of the spatial positions and angles of the two beam probes. The control electronics and software for the rig allow the shear stress data to be obtained using conditional sampling, triggered by an optoswitch, so that measurements are always taken over the same 5^o sector of rotation, thereby minimising any effects due to minor misalignment of the two bearing surfaces. The rotation of the rig is generated by a stepper motor, via a gear box, so that the rotational speed can be precisely determined using clock pulses generated by the same computer which samples the load cell data.

2.3 Transonic wind tunnel and test model

The wind tunnel experiments were carried out in the 0.20m x 0.25m slotted-wall transonic wind tunnel at City University [23]. The model was a cylinder of 25mm diameter (D) with an ogive nose section, illustrated in figures 3 and 4, attached to the tunnel sting. It was decided to opt for this type of model for these transition and liquid crystal calibration tests, in preference to a flat plate surface, since it was known that a well-defined transition region occurs on the cylinder downstream of the shoulder of the nose section. Hence, it was anticipated that a wide range of shear stresses and, hence, crystal colours would be present on the model. In addition, despite the curvature of the cylinder surface, it was considered that centre portion of the projected model surface along its main axis would present approximately normal viewing and lighting conditions.

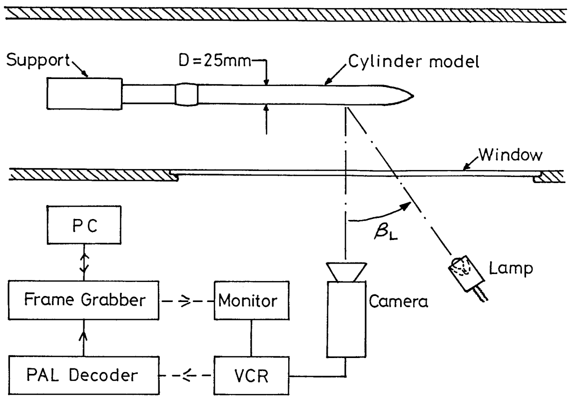


Figure 3: Diagrammatic layout of apparatus for wind tunnel tests

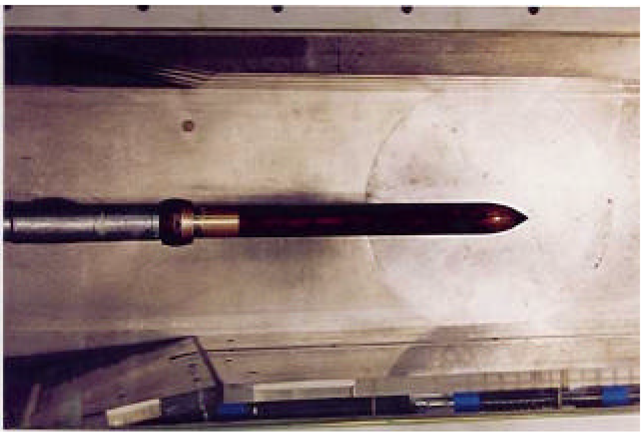


Figure 4: Model in wind tunnel

Experiments were carried out over a Mach number range from 0.19 to 1.0 in which four different types of crystals were examined. In the first series of tests the video camera viewed normal to the cylinder surface, with the illumination from the 12W tungsten-halogen spotlamp in the direction of shear and at an angle of 45^o to the model surface, as shown diagrammatically in figure 3 and by the photographs in figures 4 and 5. In subsequent experiments the effects of lighting angle relative to the model, for normal viewing by the video camera, were investigated, as were the effects of model incidence angle to the flow.

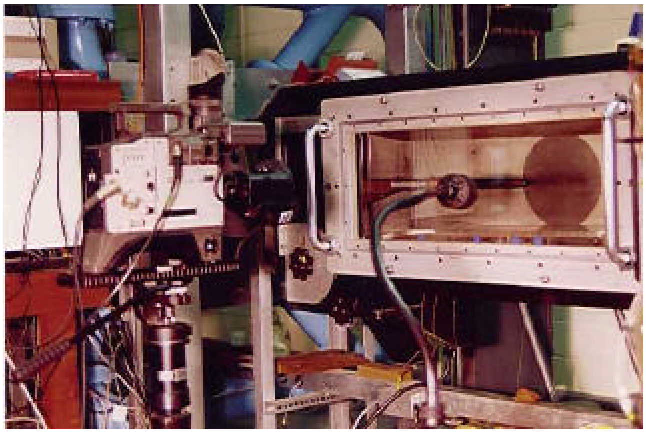


Figure 5: Typical arrangement of tungsten halogen spotlamp and colour video camera

3 Results And Discussion

3.1 Rotational shear rig experiments

The discussion will first examine the response of the crystal mixture BCN/165 whilst being sheared in the rotational rig under different lighting and viewing conditions. Figure 6 shows the change in reflectance over the visible wavelength range as the shear is increased for a fixed crystal layer thickness of 40μm with lighting angles of α_L=0^o and β_L=20^o and viewing angles of α_V=180^o and β_V=5^o. Thus, the lighting and viewing angles are

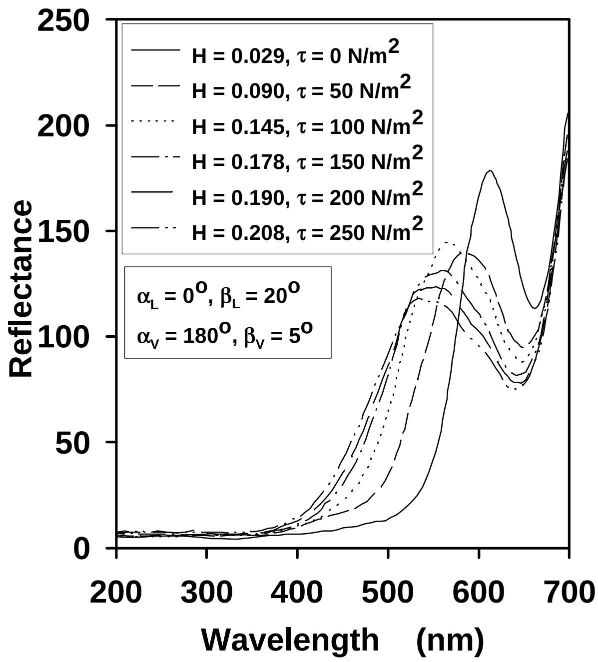


Figure 6: Variation of spectrum with increase in shear for fixed optical conditions

in the same vertical plane but with the illumination in the direction of the shear and the viewing in a direction slightly opposite to that of the shear. The plots clearly demonstrate the manner in which the spectral peak shifts towards the lower wavelengths as the shear is increased, thereby producing an increase in the hue of the colour. At the same time as the hue increases the spectral peak attenuates and broadens. Indeed, at the highest shear stresses it is often difficult to determine the peak value, since the spectrum becomes very broad band, and this is associated with the decreased sensitivity in the hue versus shear stress calibration observed in previous work [15,21].

Figure 7 shows the effect of varying the viewing angle in the horizontal plane for fixed illumination and shear stress level. The

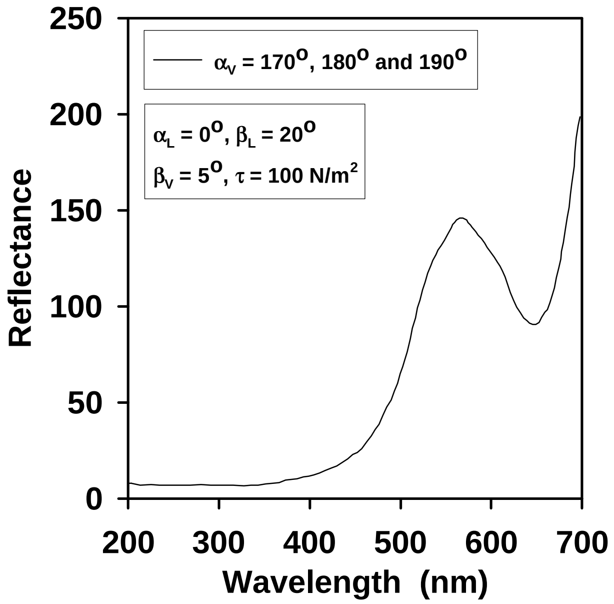


Figure 7: Variation of spectrum with change in horizontal viewing angle for constant shear

illumination angles and the vertical viewing angle are the same as for figure 6 but the horizontal viewing angle is varied by $\pm 10^{o}$ from that in the previous figure. It may be seen that there is little effect on the measured spectrum as the angle is changed and this has been found to prevail at all the shear stress levels examined in the present work.

However, it is the changes in the measured reflected hue with changes in viewing or illumination angles in the vertical direction which are the most important and which need to be taken into account if the crystals are to be calibrated and used for aerodynamic shear stress measurements. Figure 8 shows how the hue versus shear stress response is modified by changes in the vertical illumination angle, β_L, which is varied from 2^{o} (close to the normal) to 40^{o} in the direction of shear, whilst the viewing direction is kept normal to the surface. The crystal layer thickness for these tests is 120μm.

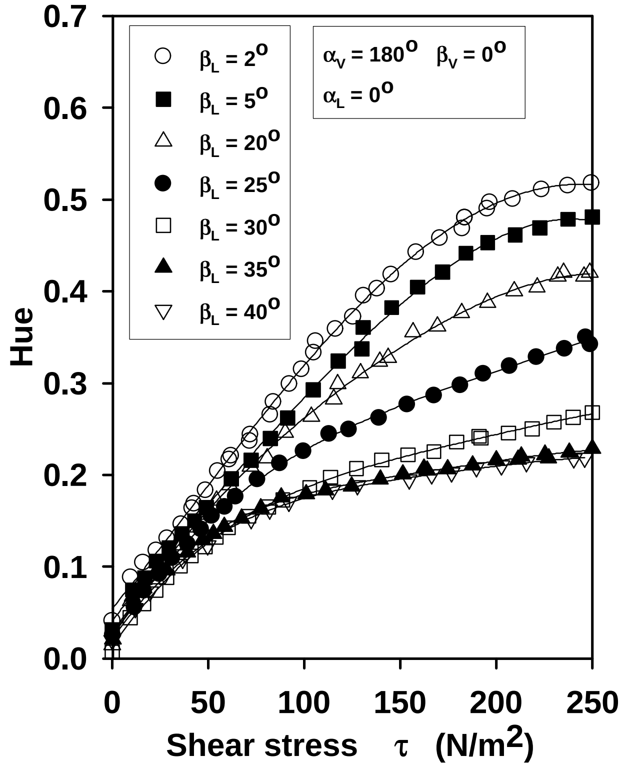


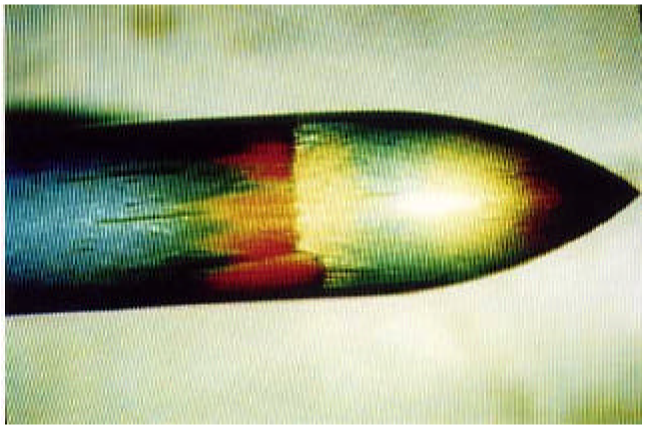
Figure 8: Variation of hue-shear calibration with changes in vertical illumination angle

It may be seen that a family of curves is produced, each of which displays encouragingly little scatter. At any given shear stress level the value of hue obtained increases as the lighting location is moved away from the normal and more towards the direction of shear. This is not simply an offset shift since the whole colour play range is increased by this change.

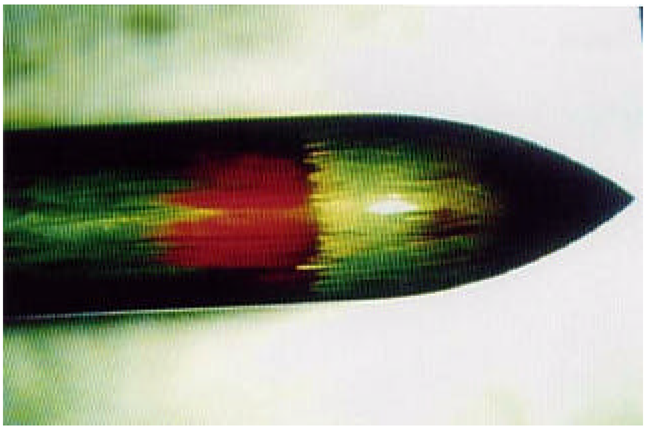
Other plots, together with the results from the wind tunnel tests, show that when the lighting is in a direction opposite to that of the shear the extent of the colour play is further reduced until, eventually, no colour change is observed and a nearly constant red is measured at all shear stress levels. This is illustrated in the discussion of the wind tunnels test results in the next section.

3.2 Wind tunnel experiments

The initial wind tunnel experiments, with the illumination set at an angle to the model of 45° in the direction of shear, were carried out at Mach numbers of 0.37, 0.58, 0.82, 0.96 and 1.00 using BCN/165 crystals.



(a) Illumination: $\alpha_L = 0^o$, $\beta_L = 45^o$



(b) Illumination: $\alpha_L = 0^o$, $\beta_L = 12^o$

Figure 9: Response of BCN/165 liquid crystals on model with M = 1 at 0° flow incidence

The results obtained for the M=1.00 case are illustrated by the images in figure 9. The start of the transition region is indicated by the pronounced change in brightness immediately beyond the shoulder of the nose section, being a low shear stress (red) region in the colour image. Downstream, turbulent wedges occur where the shear stress increases (green) and, beyond this, the highest (blue region) shear stresses are encountered in figure 9(a) where the illumination angle is 45° to the normal. The range of colours is significantly reduced when the illumination angle is closer to the normal, as in figure 9(b), such that blue does not appear in the turbulent region. From examination of the video recordings it is evident that the length of the transition region tends to decrease in size with increase in subsonic Mach number. However, it then changes in size, location and character with the influence of shock structures present along the model at M=0.96.

Comparison of the performance of the different types of crystals showed that the BCN/165 crystals were the best for the test model and shear levels encountered. The viscosity of type TI511 was too low and the crystals were swept along the model, even at low Mach numbers, thereby obscuring any dominant colour patterns. The colour play of the CN/R2 and CN/R7 type crystals, at a given Mach number, was significantly reduced when compared to BCN/165. Even for very low Mach numbers these two crystals gave a nearly uniform blue colour over all of the region viewed by the camera. From the present work it is clear that there is no direct relationship between the viscosity of a crystal mixture and the hue of the colour at a given shear stress level. Such information can only be obtained through calibration of each crystal type.

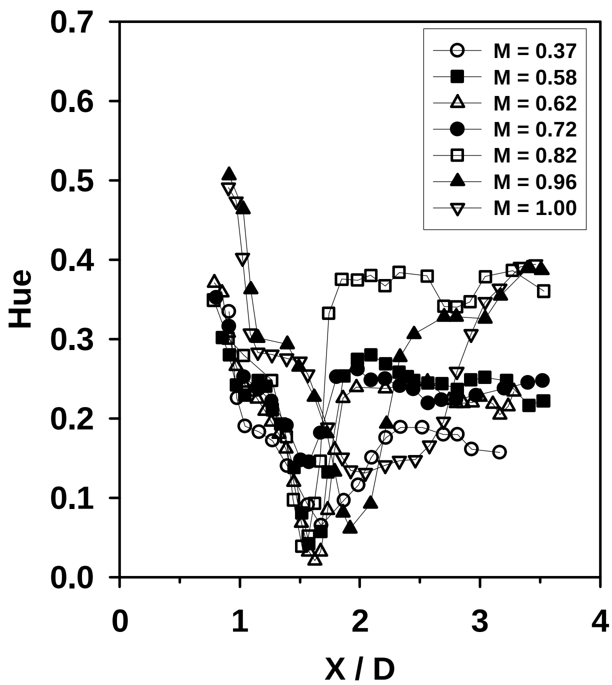


Figure 10: Variation of hue with distance along model axis at different Mach numbers

Figure 10 shows the variation in hue along the model axis for different Mach numbers with the lighting at 45° to the normal from the cylinder surface and in the direction of shear (α_L=0° and β_L=45°). The data from the nose to X/D=1 cannot be readily assessed because of glare from the curved nose section. Investigation of this region would require the lighting to be set at a different angle to the surface. For all Mach numbers, beyond X/D=1 the hue data show a decrease with increasing distance along the surface, which is associated with the laminar flow region. This is followed by a relatively rapid increase in hue (and shear stress) through the transition region and then a region of fairly constant or decreasing hue, associated with turbulent flow. A simple boundary layer calculation method was employed to estimate the shear stresses present on the model in both the laminar and turbulent regions for all the Mach numbers tested. The hue distribution data was then utilised to produce the streamwise extent of the transition regions for each case and the corresponding shear stress versus Reynolds number plots are shown in figure 11. The rapid change in the size and location of the transition region as M=1 is approached is very evident.

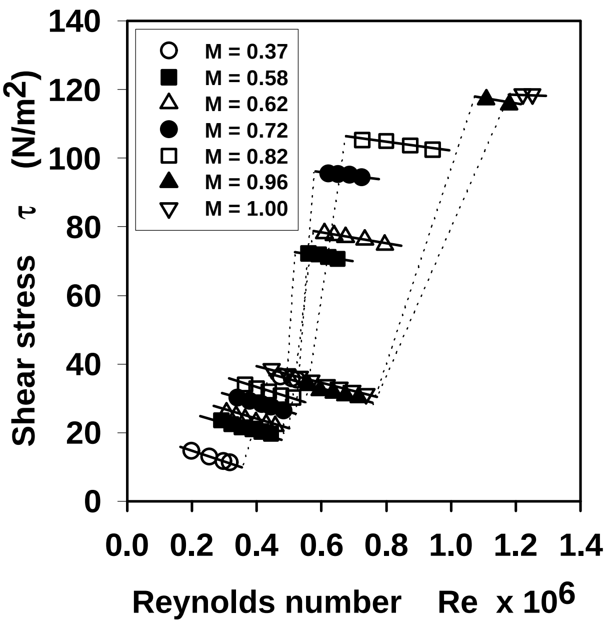


Figure 11: Variation of shear stress with Re for the different Mach numbers

The variation of hue with shear stress is illustrated in figure 12 which shows curves from two positions on the model, namely at X/D=1.2 in the laminar region and X/D=3.5 in the turbulent region. The relatively low data scatter in each plot is very encouraging. The differences between the

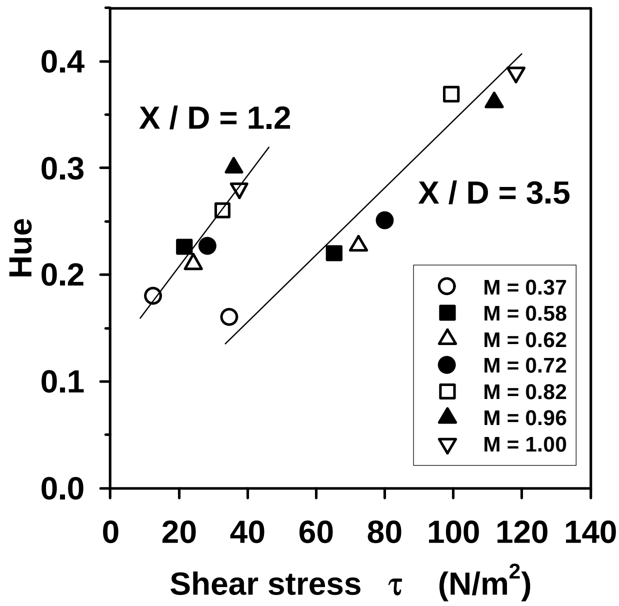


Figure 12: Variation of hue with shear stress for two locations on the model

two plots may be partly due to a fundamental dissimilarity in the behaviour of the laminar and turbulent calibrations (as with many other measurement techniques) but is primarily due to small variations in the incident lighting angles at the different points along the model. This aspect has been investigated using the rotational rig and spectrophotometer by calibrating a 120μm thick layer of BCN/165 crystals for the range of incident lighting and viewing angles experienced by the wind tunnel model. This crystal thickness

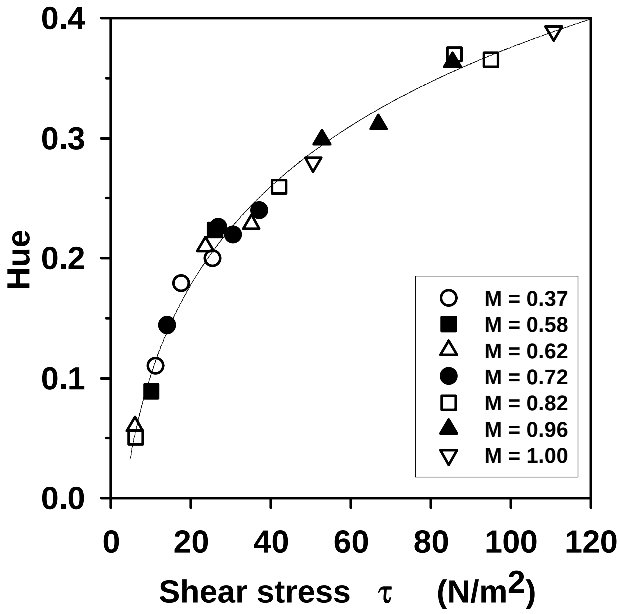


Figure 13: Variation of hue with shear stress taking into account illumination angle

was chosen as an estimate of that present on the model. It may be seen from figure 13 that when the calibration data is applied to the hue values measured at different locations on the model, taking into account the change in incident lighting angle, the data from the different runs tend to collapse upon a single calibration curve.

Experiments were then carried out using the same crystal mixture and with a fixed Mach number of 1.00. The camera viewing was fixed in the normal direction ($\alpha_V=180^o$ and $\beta_V=0^o$) whilst the illumination angle was varied from $\alpha_L=0^o$ and $\beta_L=45^o$ from the normal, in the direction of shear (as before), to $\alpha_L=0^o$ and $\beta_L=12^o$ from the normal in the direction of shear and then $\alpha_L=180^o$ and $\beta_L=22^o$ from the normal in the direction opposite to the shear vector. The shift towards the red end of the spectrum with change in lighting angle away from the direction of shear, at any given point on the model, and the associated decrease in observed sensitivity of the crystal colour response to shear was evident in all the images obtained. This decrease in hue is illustrated in figure 14 which shows the variation of hue along the axis of the model for the different illumination conditions.

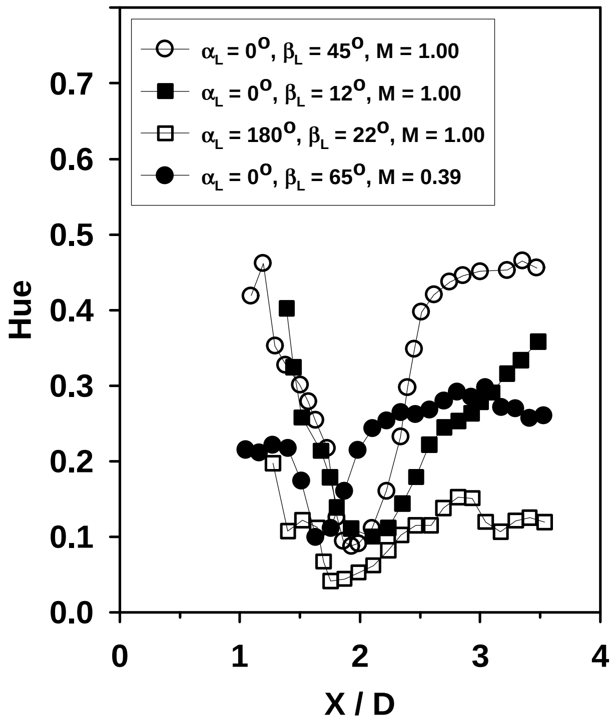


Figure 14: Effect of illumination on hue along model axis at M = 0.39 and 1.00

The influence on this colour sensitivity of illumination position was indicated further from some tests carried out at significantly lower Mach number but with a much more extreme illumination angle of $\alpha_L=0^o$ and $\beta_L=65^o$ from the normal in the direction of shear. At M=0.39 it was found that a significantly larger colour range could be observed (covering the red to green range of the spectrum) when compared to the earlier M=0.37 case where the lighting was at an angle of $\alpha_L=0^o$ and $\beta_L=45^o$ in the direction of shear. Indeed, as shown in figure 14, the colour play at M=0.39 was greater than that found for the two M=1 cases with the illumination at $\beta_L=12^o$ and 22^o. Furthermore, in these experiments a change of hue with shear stress along the model was even discernable at the extremely low speed of M=0.19. This suggests that the angle of illumination, and perhaps that of viewing, can be used to select the desired colour play.

4 Concluding Remarks

The present work has illustrated how two complementary techniques may be utilised together in order to analyse the colours reflected from shear stress sensitive liquid crystals, namely spectroscopy for detailed spectral measurement of the local colour response and true colour CCD video analysis for full-field measurement. It should be noted that in both cases care must be taken in order to calibrate the colour response of the complete systems before they are used for liquid crystal calibration or measurement. The wind tunnel results have been encouraging, particularly the manner in which they confirm the effects on the hue-shear stress response of changes in the vertical illumination angle found in the rotational rig tests. However, further wind tunnel experiments are required in order to produce precise calibration of the liquid crystals under aerodynamic conditions.

5 Acknowledgements

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