Paper 20

Session 7 - Heat Transfer Measurements

LIQUID CRYSTAL MEASUREMENT TECHNIQUES FOR HEAT TRANSFER AND SURFACE FLOW

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Introduction

Liquid crystals have been used for many years in order to monitor the temperature of a model surface or of a fluid. In addition the flow field over the surface has also been indicated using liquid crystals. A brief survey of such methods used in steady state and transient heat transfer measurements has been given by Baughn et al [1]. A more recent account is contained in the paper by Moffat [2]. In the main the particular liquid crystals used are those which have a cholesteric phase and hence selectively reflect a certain wavelength when illuminated with white light. The structure of this phase is sensitive to many external influences such as temperature, shear and chemical contamination. When used for measuring temperature therefore the material is often mechanically isolated from the environment by containing this within thin plastic sheets or within minute gelatin spheres of order 10μm diameter. The materials when in the cholesteric phase appear to be of a greasy nature with a wide range of consistency.

Liquid Crystal States

A brief description of liquid crystals and their chemistry has been given by McDonnell and Sage [3] and some of their properties relevant to the present paper are given below. The liquid crystalline state is one taken up by some materials constituted from rod-like molecules which are in the process of melting. This process can be a prolonged phenonema in which the material takes up certain ordered states or phases. Two well known phases are the nematic phase and the cholesteric phase which is a modification of the former. In the nematic phase the molecules arrange themselves in layers with the molecular axes pointing in the same direction as shown in Fig. 1. In the case of the cholesteric phase, due to the asymmetry of the molecules, the molecular axis in consecutive planes rotates (Fig. 2). This helical structure of the molecular axis, or director, is the cause of the colourful display of these liquid crystals.

When light interacts with the liquid crystals various phenonema occur. In the case of the cholesteric phase the wavelength of visible light can be of the same order as the helical length or pitch and this results in an interference effect similar to Bragg reflection as sketched in Fig. 3. The selectively reflected light is circularly polarised in the same direction as the liquid crystal helix. The pitch of the helix is temperature dependent and hence so is the colour of selectively reflected light (Fig. 4).

Nematic liquid crystals as might be expected are bi-refringent (i.e., their refractive index differs in the direction along the director to that at right angles). This bi-refringence is also temperature dependent, Fig. 5, and hence is a property that can be used to measure temperature [4]. Another property that may be exploited is the wave-guiding that nematics can produce; if a twist is mechanically introduced into the nematic structure then the plane of polarisation of light will rotate with this twist. The rotation can be detected with crossed polarisers. In this case the pitch of the helix is far greater than the wavelength of light. Such a method is commonly used in liquid crystal display systems.

Heat Transfer Measurements

Steady state heat transfer measurements may be effected by placing an electrical heater strip on the model surface and monitoring the surface temperature with liquid crystals. The method is described in [1]. A typical result for the end wall (platform) of a cascade is shown in Fig. 6. A range of heater strips are available and are usually evaporated or attached with adhesive to plastic sheets. Of course, the restriction of this method is that the surface must only have curvature in one direction. The liquid crystal may be in a plastic sheet attached to the surface or may be encapsulated and sprayed onto the surface in a binder. By altering the heater current the liquid crystal display can be made to move over the surface and access a wide range of heat transfer coefficient.

A transient method may also be employed by using a sudden onset of hot or cold flow to cause a change in the surface temperature which is monitored with the liquid crystal. If the model surface is an insulator and the testing time is short then the conduction into the model may be considered to be one dimensional. This allows the local heat transfer coefficient to be found from the surface temperature rise [6]. A typical result for a cascade endwall is shown in Fig. 7 from [8] using transient methods. Developments of this method have enabled detailed heat transfer coefficients over rough surfaces to be measured for the first time [7]. In this case the encapsulated liquid crystal is sprayed onto the model surface underneath the roughness elements and viewed from within the perspex model. A typical result for a cascade endwall is shown in Fig. 7 from [8] using transient methods.

The steady state and transient methods using liquid crystals have been compared in [1] and [9]. The agreement is good as shown in Fig. 8 and the absolute accuracy may be seen as 4% and 7% for the steady and unsteady techniques respectively.

Both photography and video recording are used for data acquisition and the major challenge is in analysing this image. Various schemes are possible for automating the proceedure and analysis the colour image [2,7]. The response time of the measurement using the cholesteric colour change can be of order several milliseconds [10] however, colour display deteriorates at higher frequencies and bi-refringence methods can be employed [4]. The steady state heat transfer method also provides an excellent means of determining the state of the boundary layer and transition [11].

Shear Stress

As mentioned previously mechanical effects cause changes in the liquid crystal and this may be used to infer information about the shear stress on a model surface. Quantitative measurements were first made at Oxford [12] using the change in texture of a liquid crystal when in the cholesteric phase. It is necessary to explain the properties of the textures in order for the process to be clear. In the cholesteric phase the helical structure exists, however, this structure may be fragmented forming a "focal conic" texture as opposed to the ordered helical structure previously described which is called the "grandjean" texture. The material will pass from the focal conic to the grandjean texture if sheared so as to flow align to the helices. The focal conic texture is not colourful and the liquid crystal may be set into this texture by heating until it is in the liquid state and then cooling back to the cholesteric state. When the material is then sheared to give a shear of approximately 4 it aligns to a colourful grandjean texture. Thus, the time to become colourful depends on the material viscosity and the surface shear stress. Suitable calibration of a certain material gives a means of measuring local shear stress. A typical calibration is given in Fig. 9 and an example of the measurement of shear stress on a flat plate from [11] is shown in Fig, 10.

Once the material is in the grandjean texture further colour change does take place as a result of shearing the material. This process has been used by NASA to observe changes and transition in flght tests [13]. The distortion of the helical structure which takes place is very complex and is rather difficult to calibrate [12] however, it can be a useful visualisation method.

New shear stress systems have been developed at Oxford using nematic materials which flow align from some preferred direction which is dictated by model surface preparation [14]. The time for flow alignment is again measured and this is observed using the wave guiding effect of the nematic liquid crystal and cross polarisers.

Conclusion

The status of liquid crystal techniques for flow and heat transfer measurements has been discussed and the potential of the systems demonstrated. The behaviour of the material has been briefly explained from a molecular viewpoint. Further developments depend on an understanding of the physics and chemistry of the present materials and of new materials based on liquid crystals which are becoming available.

REFERENCES

[1] **Baugh, J.W., Ireland, P.T., Jones, T.V. and Sanii., N.**
A comparison of the transient and heated-coating method for the measurement of local heat transfer coefficients on a pin fin. ASME, J. of Heat Transfer, Vol. 111, p877, Nov. 1989.

[2] **Moffat, R.J.**
Experimental heat transfer. Proc. 9th Int Heat Transfer Conf., Vol. 1, Paper KN11, p187, 1990.

[3] **McDonnell, D.G. and Sage, I.**
New thermochromic liquid crystals. Recent Advances in Medical Thermology, Eds., E.F.T. Ring and B. Phillips, Plenum Press, p305, 1982.

[4] **Bonnett, P.**
Applications of liquid crystals in aerodynamic testing. Oxford University, D.Phil Thesis, 1989.

[5] **Hippensteele S.A. and Russell, L.M.**
High-resolution liquid crystal heat transfer measurements on the end wall of a turbine passage with variations in Reynolds number. ASME, 25th National Heat Trans. Conf., Houston, July 1988, also NASA TM100827.

[6] **Ireland P.T. and Jones T.V.**
Detailed measurements of heat transfer on and around a pedestal in fully developed flow. Proc. 8th Int. Heat Trans. Conf. Vol 3, p975, 1986.

[7] **Wang, Z, Ireland, P.T. and Jones, T.V.**
A technique for measuring heat transfer at rough surfaces. ASME, Gas Turbine Conference paper 90-GT-300, Brussels, 1990.

[8] **Harvey, N.W. Wang, Z. Ireland, P.T. and Jones T.V.**
Detailed heat transfer measurements in nozzle guide vane passages in linear and annular cascades in the presence of secondary flows. AGARD, CP469, Paper 24, 1989.

[9] **Hippensteele S.A. and Jones, T.V.**
High resolution heat transfer coefficient maps applicable to compound curve surfaces using liquid crystals in a transient wind tunnel, NASA TM89855, 1988.

[10] **Ireland, P.T. and Jones, T.V.**
The response time of a surface thermometer employing encapsulated thermochromic liquid crystals. J. Phys. E, Sci. Instrum, Vol 20, p1195, 1987.

[11] **Mee, D.J. Walton, T.W. Harrison, S.B. and Jones T.V.**
A comparison of liquid crystal techniques for transition detection, AIAA paper No. 910062, Reno, Nevada, Jan. 1991 (to be presented).

[12] **Bonnett, P., Jones, T.V. and McDonnell D.G.**
Shear stress measurement in aerodynamic testing using cholesteric liquid crystals, Liquid Crystals, Vol. 6., No. 3, p271, 1989.

[13] **Holmes, B.J., Gull, P.D., Croom, C.C., Manuel, G.S. and Kellihen, W.C.**
NASA, TM 8766, 1989.

[14] **Walton, T.W.**
Shear stress measurments using nematic liquid crystals. 1991 (To be published)

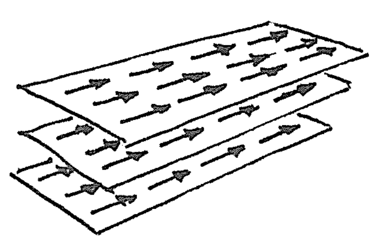


Fig. 1 The nematic structure.

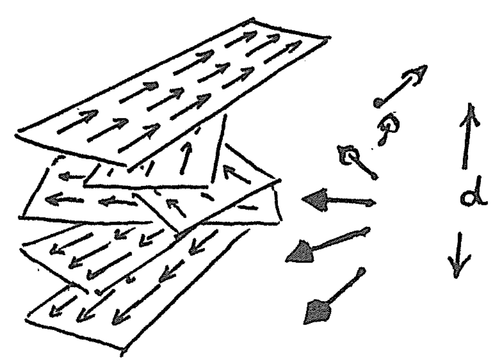


Fig. 2 The cholesteric structure.

Fig. 3 Bragg-like reflection from the cholesteric layers.

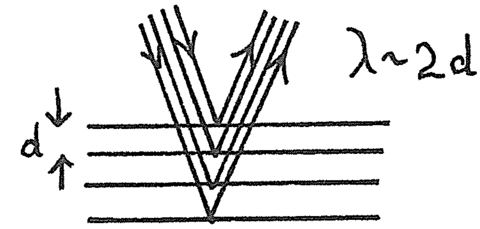
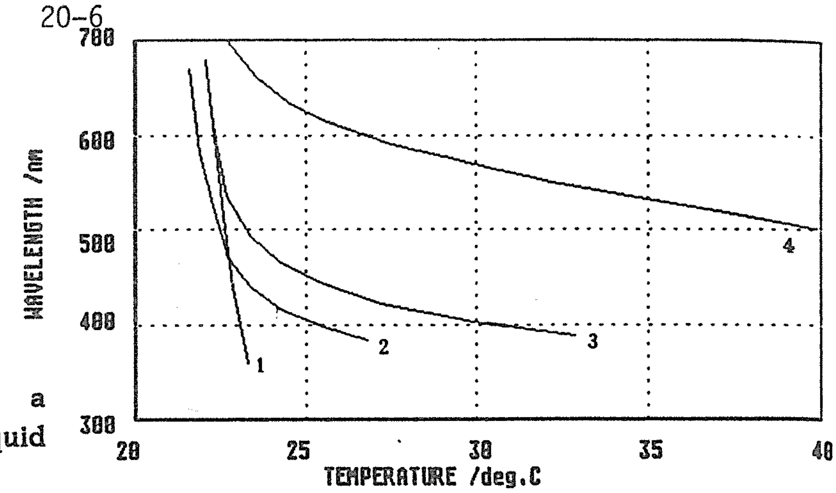
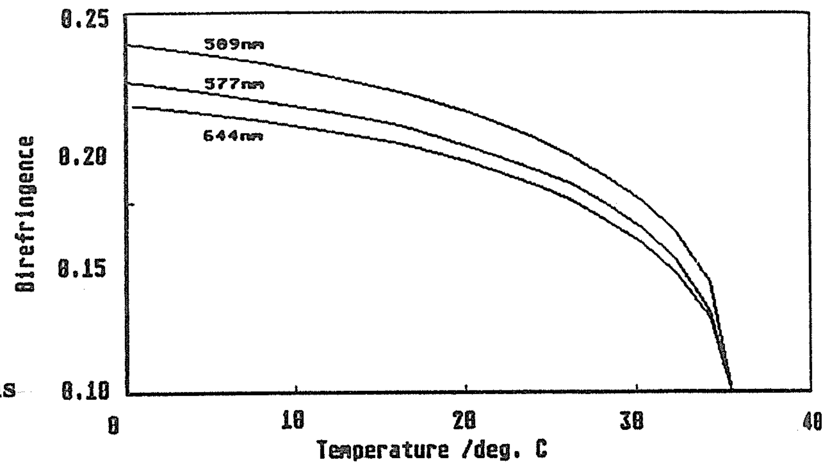


Fig. 4

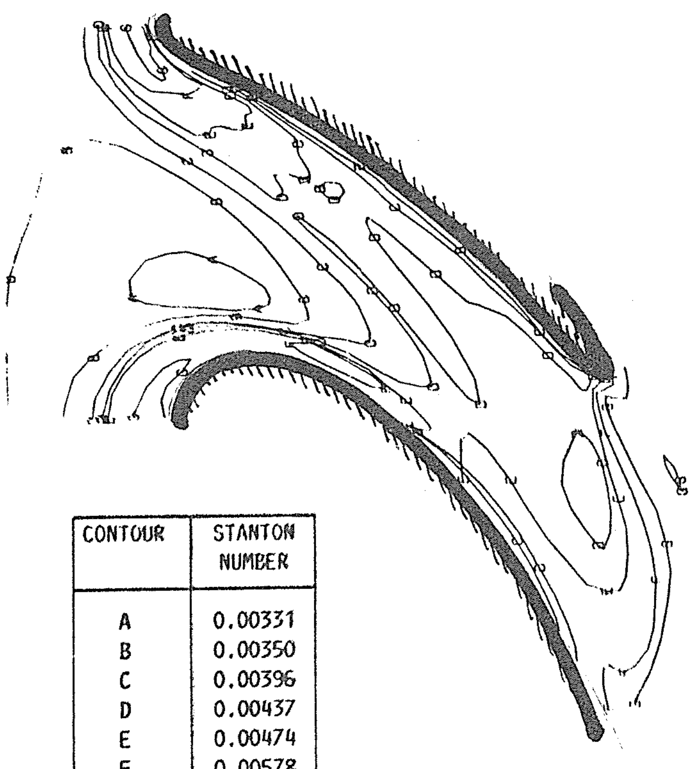


Selectively reflected wavelength as a function of temperature for several liquid crystals in the cholesteric phase.

Fig. 5



Bi-refringence of a nematic liquid crystal as a function of temperature.



CONTOUR	STANTON NUMBER
A	0.00331
B	0.00350
C	0.00396
D	0.00437
E	0.00474
F	0.00578
G	0.00714

Fig, 6 End wall heat transfer contours in a nozzle guide vane passage from [5] obtained using the steady state method.

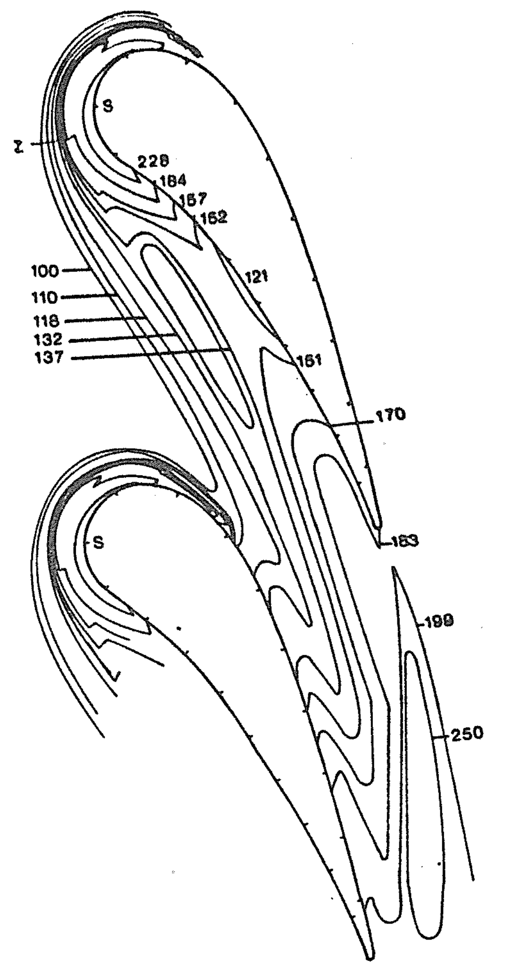
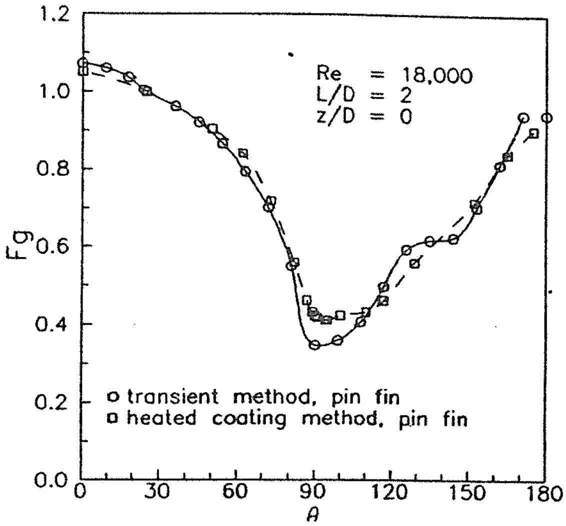


Fig. 7. End wall heat transfer contours in $^{W}/m^{2}K$ in a nozzle guide vane passage from [8] obtained using a transient method.

Fig. 8 A comparison of heat transfer around a cylinder in fully developed channel flow as measured by the steady state (heated coating) and transient method from [1]. Fg = Froesling number = $\frac{\text{Nusselt number}}{(\text{Reynolds Number})^{1/2}}$

Differences at large angles are due to differing thermal boundary conditions.



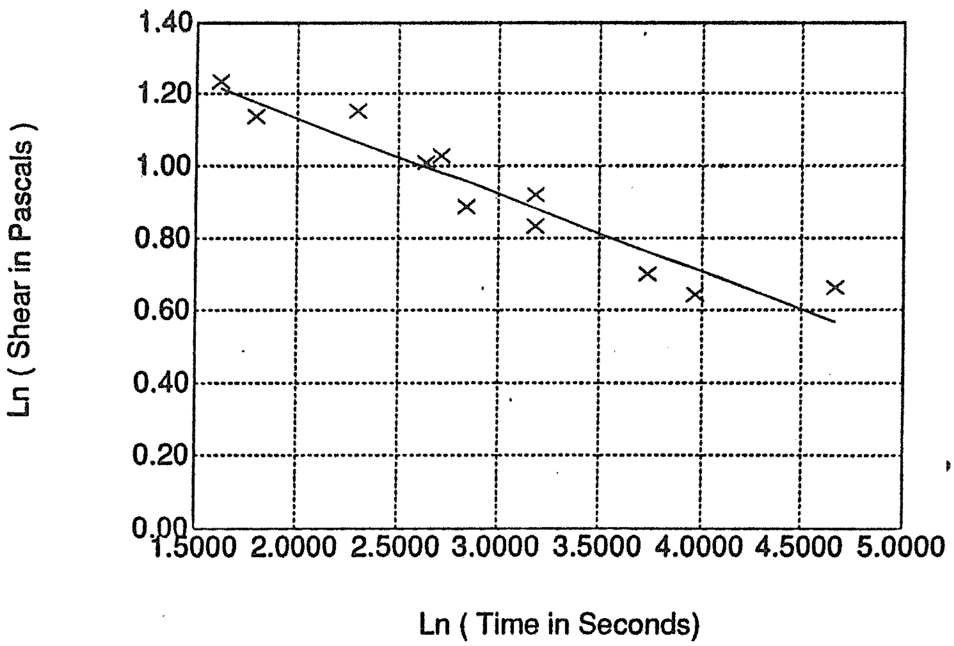
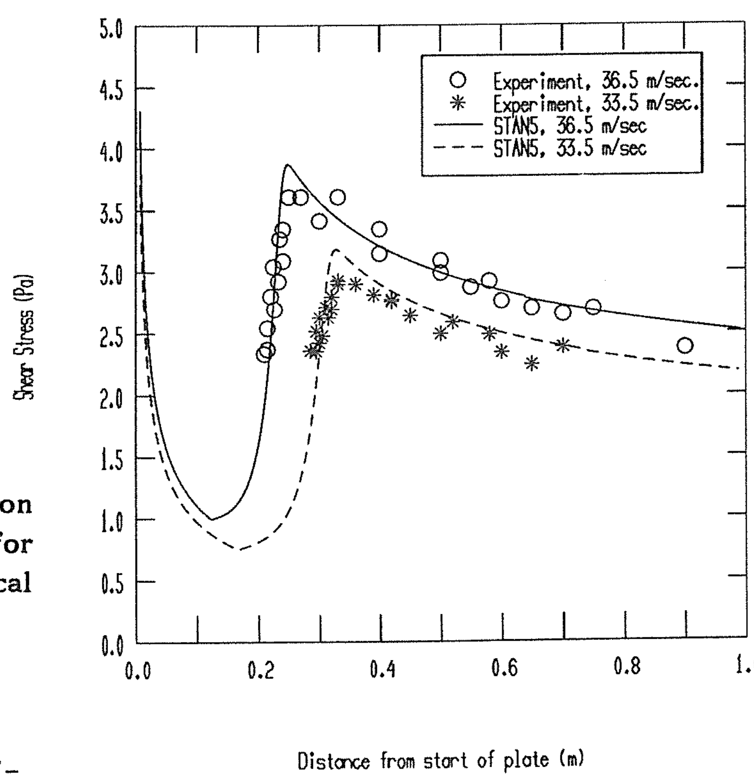


Fig. 9 A calibration curve of shear stress versus time for the focal conic to grandjean texture change.

Fig. 10



Shear stress measured through transition using liquid crystals on a flat plate for two freestream velocities. Theoretical lines are also given.