Effect of rotation on temperature response of thermochromic liquid crystal

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Encapsulated thermochromic liquid crystal (TLC) can be used to determine the surface temperature of stationary or rotating bodies. For narrow-band TLC, with a colour change from red to blue over a bandwidth of 1°C, temperatures on stationary surfaces can be measured with an uncertainty of around ±0.1°C. For gas turbine applications, where centripetal accelerations in excess of 10^4g are common, there is a belief held by many research workers that TLC is significantly affected by rotation: "rotational shifts" have been observed where temperature measurements made by thermocouples and TLC diverge with increasing rotational speed; shifts up to 7°C at around 10^4g have been observed. In this paper, the surface temperature of a rotating disc is measured simultaneously by an infrared (IR) thermal imager and wide-band TLC with an effective temperature range from 48 to 58°C. Within the uncertainty of the measurements, which was around 0.5°C, it was concluded that there was no significant rotational shift for accelerations up to $16{,}000g$.

Keywords: thermochromic liquid crystal; temperature measurement; rotation

1. Introduction

The use of encapsulated thermochromic liquid crystal (TLC) in heat transfer experiments is now a well-established practice. By spraying a thin film of microcapsules of TLC onto a solid material, the surface temperature can be measured accurately. Unlike thermocouples or other intrusive devices, TLC creates no local thermal disturbance errors and enables the temperature of the *entire* surface to be measured. Unlike infrared (IR) detectors, no special windows (such as germanium) are required for studying the heat transfer in internal flows: windows made from glass, acrylic, or polycarbonate provide adequate optical access.

Most research workers use narrow-band TLC that changes colour from red to blue during a small change in temperature (typically 1°C). Using a single colour (say yellow) in this range, the surface temperature can be measured with an uncertainty of around ±0.1°C. Narrow-band TLC has been used successfully (see, for example, Jones and Hippensteele 1988; Camci *et al.* 1992; Wang *et al.* 1995) to determine the heat transfer coefficients for an acrylic model suddenly exposed to a step-change in air temperature. If the initial temperature of the model at time $t=0$ is known, and the temperature at some later time is determined from the TLC then the so-called one-dimensional (1-D) semi-infinite slab solution can be used to determine the heat transfer coefficient.

Metzger *et al.* (1991) have shown that the TLC technique can also be applied to a rotating disc. In the experiments, an (initially cold) acrylic disc coated with TLC was suddenly exposed to an impinging jet of hot air. Using this technique, the authors were able to determine the axisymmetric heat transfer coefficients for the rotating disc, albeit at relatively low rotational speeds. For rotational speeds representative of those found in gas turbines, however, the centripetal accelerations can be of the order of 10^4g, where g is the gravitational acceleration, and there is a suspicion among many research workers that the characteristics of TLC change when it is exposed to these very high accelerations.

Recently, Camci and Glezer (1995), working in the United States, found evidence of a rotational shift between temperatures obtained using narrow-band TLC and thermocouples. The results, measured on a rotating disc, diverged as the speed increased, and at around $10{,}000g$ the rotational shift could be as high as 7°C. Subsequent results, presented by Camci and Glezer, were obtained using an infrared detector: the IR and TLC readings were in good agreement but both diverged from the thermocouple measurements. The rotational shift was attributed to a thermal disturbance error associated with the thermocouple. Their work, which has a clear relationship with the research presented here, will be published elsewhere.

While Camci and Glezer (1995) were investigating the rotational shift with narrow-band TLC in the United States, independent research on wide-band TLC was being carried out at the University of Bath in the UK. Thermocouples, TLC, and an infrared thermal imager were used to measure the surface temperature of a rotating disc subject to accelerations in excess of 10^4g. It is this work that is presented here.

The experimental apparatus is outlined in Section 2 and the thermochromic liquid crystals, image-processing, and calibration apparatus are described in Section 3. The calibration of the TLC and IR imager in a stationary frame, and the measurements on the rotating disc, are presented and discussed in Section 4. The principal conclusions are given in Section 5.

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2. Experimental apparatus

2.1. Rotating-disc rig

A sectional view of the rotating-disc rig is shown in Figure 1 and the rotor instrumentation in Figure 2. The whole assembly can be rotated up to 7000 rpm by a variable speed electric motor, and the speed can be measured with an uncertainty of ± 1 rpm by an electromagnetic transducer and timer–counter. The steel disc can be heated up to 150°C by thyristor-controlled radiant heaters, and the surface temperature measured by copper–constantan thermocouples embedded in the disc. (The rig is usually used for preswirl rotor–stator tests, see Wilson *et al.* (1995), and the fluxmeters and blade-cooling holes shown in Figure 2 were not used in the tests described below.)

The rotor is of composite construction comprising a steel front disc and an aluminum back disc separated by a layer of Rohacell lightweight foam insulation. The front face of the steel disc, which is 580-mm diameter, is covered with a 1-mm-thick layer of glass-fibre epoxy-resin ($k \simeq 0.3$ W/mK). This "glass-fibre mat" is slotted to enable the thermocouples and fluxmeters to be embedded in its surface without creating stress concentrations and thermal disturbances in the steel disc. The wires from the thermocouples and fluxmeters are brought out in slots in the mat to the connector pins at the centre of the disc, as shown in Figure 1. The pins act as an effective cold junction, and the electrical signals are brought out through copper wires connected to a 24-way slip ring assembly. The voltages are measured, with a resolution of ± 1 μV, by a computer-controlled datalogger.

The glass-fibre mat was sprayed with black paint with an emissivity of $\varepsilon = 0.96$ (estimated using the infrared thermal imager described below). An annular area, extending from $220 < r < 290$ mm, was coated with thermochromic liquid crystal, details of which are given in Section 3.

2.2. Infrared thermal imager

A cutaway view of the Agema 870C infrared scanner used in the tests is shown in Figure 3. Essentially, the scanner converts the electromagnetic radiation from an object into electronic video signals, and the scanner and its associated hardware and software are referred to as the infrared thermal imager. The basic principle of operation is described below.

The radiation from an object is focused by an infrared lens onto an oscillating mirror. The scanner may be used with a variety of interchangeable lenses, but for the tests described below, a 20° (38-mm) lens was fitted. This lens has germanium broadband optics coated for enhanced response in the 2.0–4.0 μm region of the infrared spectrum. The reflected radiation from the oscillating mirror is focused by three fixed mirrors onto a horizontal polygon mirror which rotates at 15,000 rpm. Both the oscillating and rotating mirrors are microprocessor-controlled and synchronised so that the whole of the object in view is effectively scanned as a 70-line field at a rate of 25 fields/s. These fields are phased so that four fields produce one fully interlaced 280-line frame. The reflected beam from the horizontal mirror is passed through a set of relay optics (containing a selectable aperture and filter unit) and focused onto a point detector by a concave mirror, as shown in Figure 3. For all tests reported here, the scanner's aperture was left fully open, and no filter was inserted.

The scanner uses a SPRITE single-point infrared detector consisting of a strip of mercury cadmium telluride, which is sensitive to radiation between 2 and 5 μm, mounted on a sapphire substrate. The detector is cooled by a three-stage thermoelectric Peltier element to a temperature of −70°C. The output signal from the detector is sent to an external amplification and control unit, and the video output signal from this unit is processed on a PC by the Agema CATSE software. This

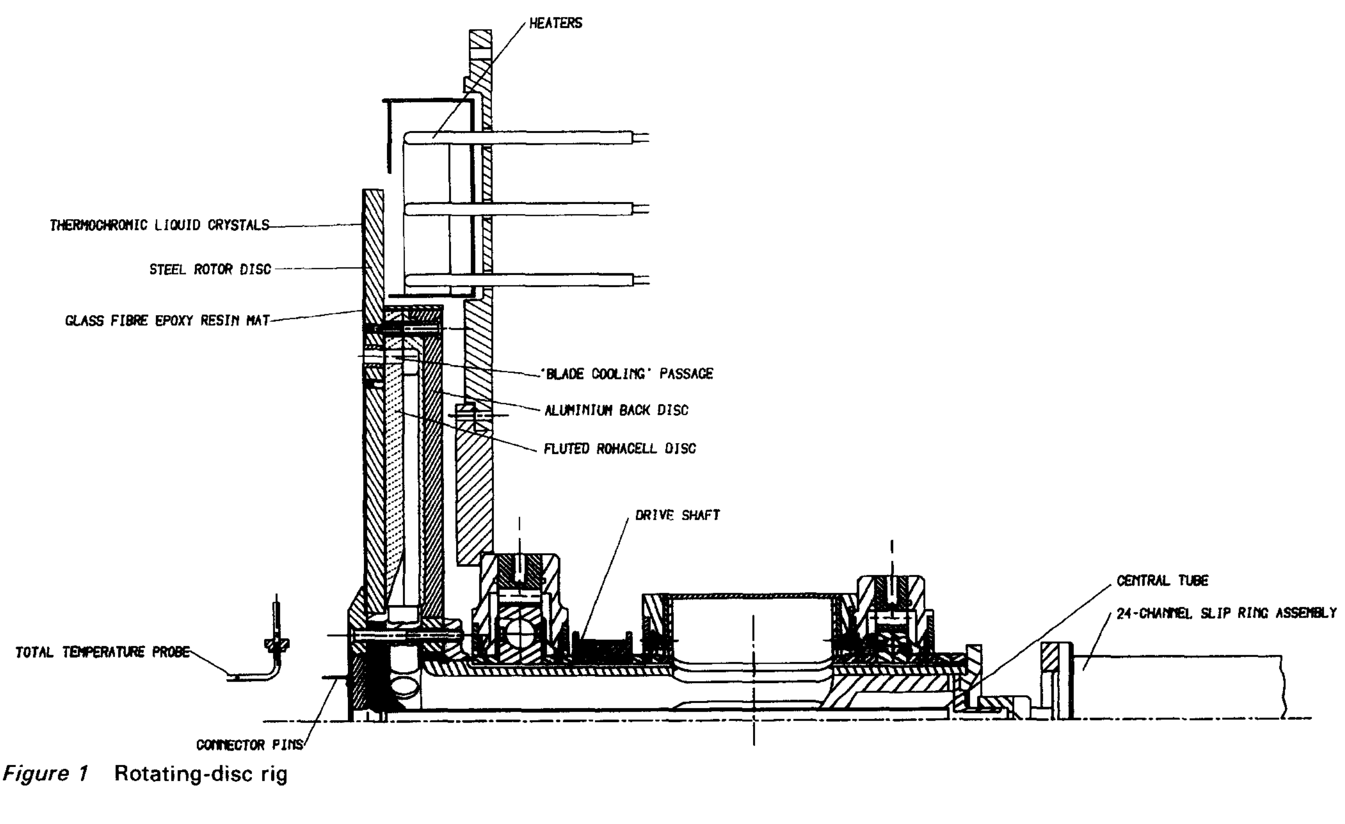


Figure 1 Rotating-disc rig

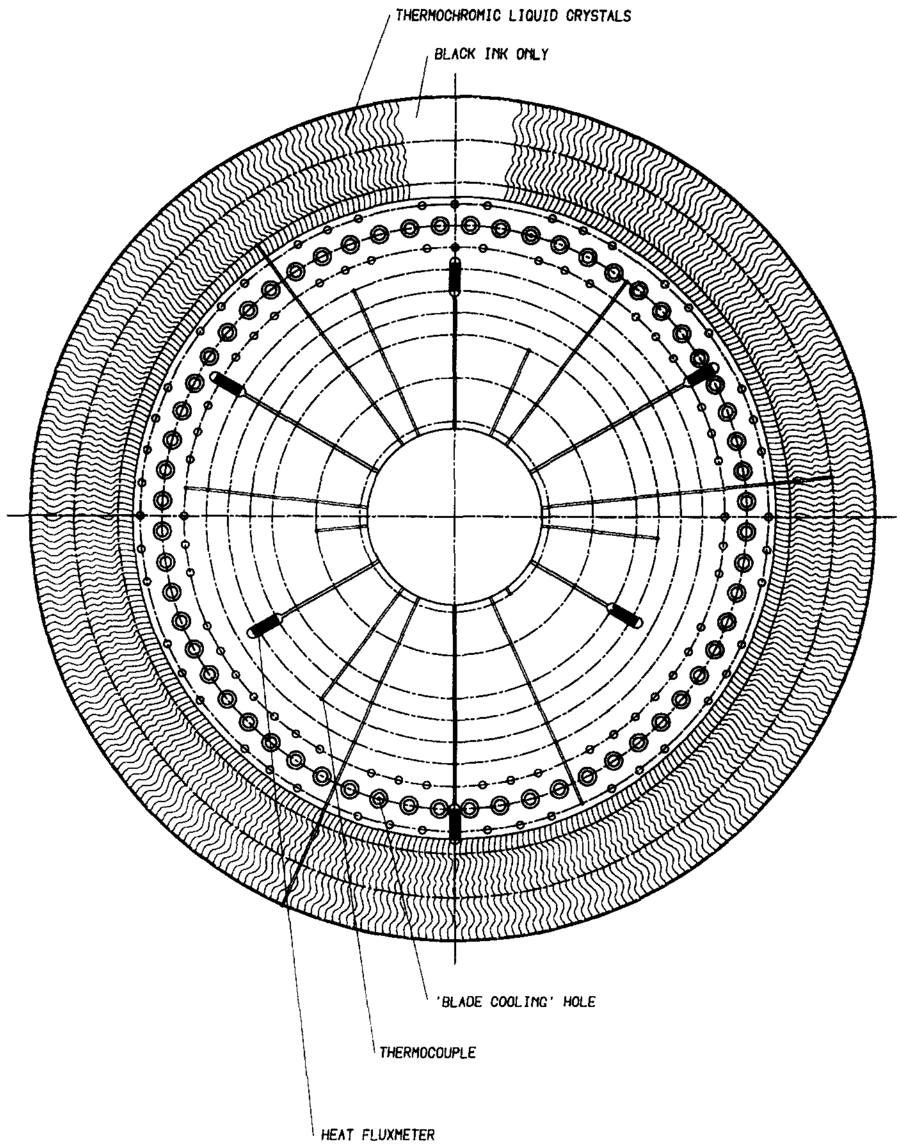


Figure 2 Instrumented rotating disc

software generates a 140 × 140 pixel orthogonal image of the object in view, and an image datafile is generated to transmit the data from the PC to a Silicon Graphics workstation for postprocessing.

The scanner is also capable of a line-scanning mode in which the oscillating mirror is locked in one position, and horizontal lines are scanned by the rotating mirror. The scanner can be positioned relative to the rotating disc so that radial lines will be scanned as the disc rotates, and the angular location of the lines can be determined by the software, using a trigger on the drive shaft of the rig. This mode enables the circumferential temperature distribution of the disc to be determined. Although the line-scanning mode has been used, no significant angular variations in temperature or thermal disturbances were found. For the tests described below, the standard orthogonal scanning mode was used; this produces a circumferentially averaged value of temperature.

The manufacturer's specified absolute accuracy for the scanner is ±2% or ±2°C, whichever is the larger, and the stated resolution at 60°C (which corresponds to the top of the range covered by the wide-band TLC) is 0.07°C. To improve the accuracy, an average of 20 consecutive frames was taken for each test, and the scanner was calibrated using the copper-block apparatus described in Section 3.

3. Thermochromic liquid crystals, image processing, and calibration apparatus

3.1. Thermochromic liquid crystal

Thermochromic coatings used for surface thermography usually exploit the properties of chiral nematic liquid crystal. This phase is characterised by a helical molecular structure, the periodicity of which governs the way in which it reflects light. When illuminated with white light, the liquid crystal selectively reflects monochromatic light whose wavelength is equal to the pitch of its helical structure. The liquid crystal will exhibit thermochromic properties if its pitch (and, hence, the wavelength of light it reflects) is a function of temperature. Usually the wavelength of light reflected decreases with increasing temperature: the colour changes from red, through the visible spectrum, to blue/violet.

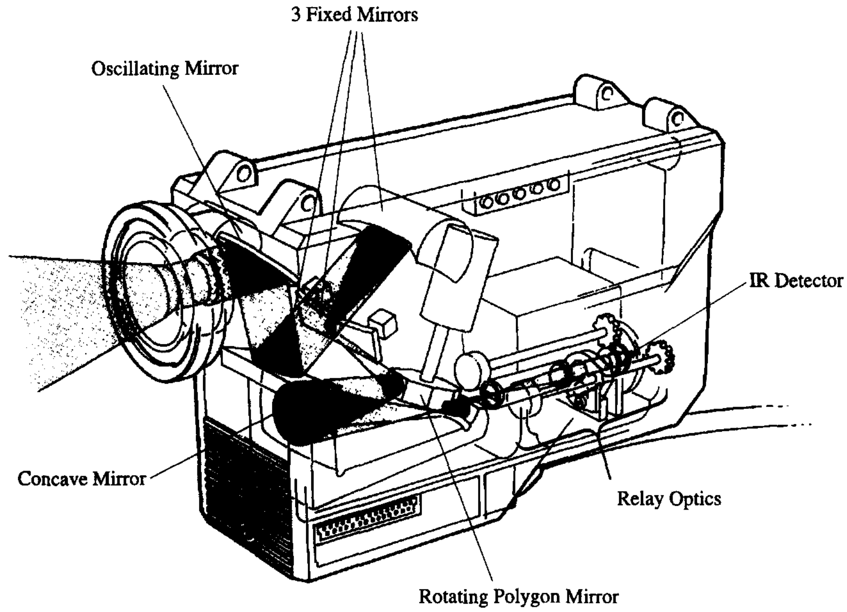
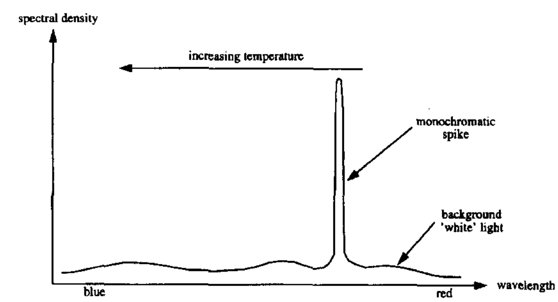


Figure 3 Cutaway view of Agema thermal scanner (reproduced by permission of Agema UK)

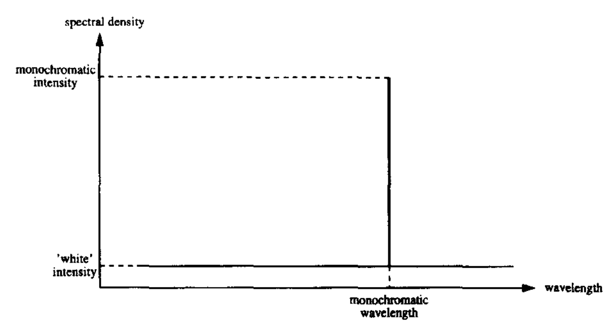
The liquid crystal is supplied in microcapsules: tiny droplets of liquid crystal are encased in polymer shells. In this form, the liquid crystal is easy to use and is isolated from the deleterious effects of solvents and impurities, and to ensure good adhesion, the microcapsules are mixed with a binder prior to application. Saturated colours are achieved by initially spraying the surface black so that most of the light which passes through the coating is not reflected back. Despite this precaution, the light reflected will not be purely monochromatic: some light will be reflected by the black paint and non-liquid-crystal constituents of the coating. The typical spectral content of the reflected light is shown in Figure 4a.

While the instrumentation must resolve the light reflected by the TLC coating, it must also provide sufficient spatial and temporal resolution. Although a spectrometer would be ideal for analysing the reflected light, colour CCD (charge coupled device) imagers are used, because they satisfy the stringent spatial and temporal requirements of most heat transfer work. A CCD, however, is essentially a monochrome device: it is sensitive to a range of wavelengths of light, but embodies no mechanism for discriminating between wavelengths within that range. The spectral resolution required for colour imaging is provided by the use of coloured filters. A typical colour CCD consists of a matrix of pixels sensitive to visible light, overlaid with a mosaic of red, green, and blue filters. Each pixel is then sensitive to a particular part of the visible spectrum, as dictated by the filter's response and sensitivity. While the signals from three adjacent pixels (one red, one green, and one blue) are sufficient to determine the colour (that is, the effect on the human eye) of incident light, detailed spectral information about the light is lost.

Fortunately, in the case of light reflected by a TLC coating, the general form of the spectral content can be approximated by a monochromatic spike plus background white light, as shown in Figure 4b. This approximation reduces the number of degrees-of-freedom to three: namely, hue (a measure of the wavelength of the monochromatic spike), saturation (the relative amounts of monochromatic and white light), and intensity (the total amount of light). Because colour can be described using three independent variables (usually the components red, green, and blue), the spectral content of the reflected light, and in particular its hue, can be estimated. Hue analysis of frames captured by colour



(a) Typical spectrum.



(b) Approximate spectrum.

Figure 4 Spectral content of light reflected by TLC coating

CCD imagers is best performed by computer, and because the HSI (hue, saturation, and intensity) colour model is often used as an alternative to the RGB (red, green, and blue) model, hardware and software for RGB to HSI conversion are readily available.

The same equipment was used to determine the reflective properties of the TLC coating for the stationary calibration and for all rotational tests. The TLC (Hallcrest R45C10W) changed from red at 45°C to dark blue at 55°C. The coating was illuminated by a tungsten-filament lamp and the reflected light monitored by a Panasonic WV-CL700 colour CCD video camera fitted with an 18–108 mm f2.5 zoom lens, and the illumination and viewing angles are shown in Figure 5. The ensuing YC video signal was recorded on SVHS videotape by a Panasonic AG-7355 video cassette recorder, and the video frames were analyzed by a Silicon Graphics Indigo R3000 workstation fitted with a video board. RGB to HSI conversion was performed using software from the ImageVision image-processing library, and additional image manipulation and data-processing routines were written in-house.

3.2. Image processing

Despite the fundamental difference between infrared and liquid–crystal temperature measurement, both techniques used were imaging systems and as such required similar processing. Being PC-based, images from the IR thermal imaging system were easily transferred to the Silicon Graphics workstation so that the same software could be used to process both the IR and TLC images. Details of this processing, which is an extension of that described by Wilson *et al.* (1993), are outlined below.

In the TLC calibration and the rotational tests, no data were taken until a steady state had been reached. Because the temperature distributions were not changing with time, simple frame averaging could be used to reduce the effect of noise in the time domain. An image suitable for further processing was created by taking the average of 10 TLC frames or 20 IR frames.

Spatial averaging was used to increase confidence in the measured values. This involves choosing an area of the image and calculating the average value of its constituent pixels, but the area chosen has to represent an isotherm. Choosing the isothermal area for the calibration apparatus was simple, because a copper block was used, see Figure 6a. The temperature distribution on the rotating disc was axisymmetric, but because there were radial variations, it was necessary to average the temperatures as described below.

The TLC coating was applied to the disc's surface between the radii $r = 220$ mm and $r = 290$ mm. The axisymmetric nature of the experiment allowed the colour CCD camera and infrared thermal imager to view just one part of this liquid–crystal ring, as shown in Figure 6b. Because the centre of the disc lay outside this field-of-view, two reference lines at $r = 225$ mm and $r = 285$ mm were marked on the disc. These enabled the position of the disc's centre (and hence the disc radius corresponding to each pixel in an image) to be calculated. Eight pixels of known disc radius (four on each reference line) were chosen from an image, and the disc's centre was found by minimising the sum of the square of the errors on these eight known radii. This regression was performed by software written in-house based on the nonlinear Newton–Raphson method.

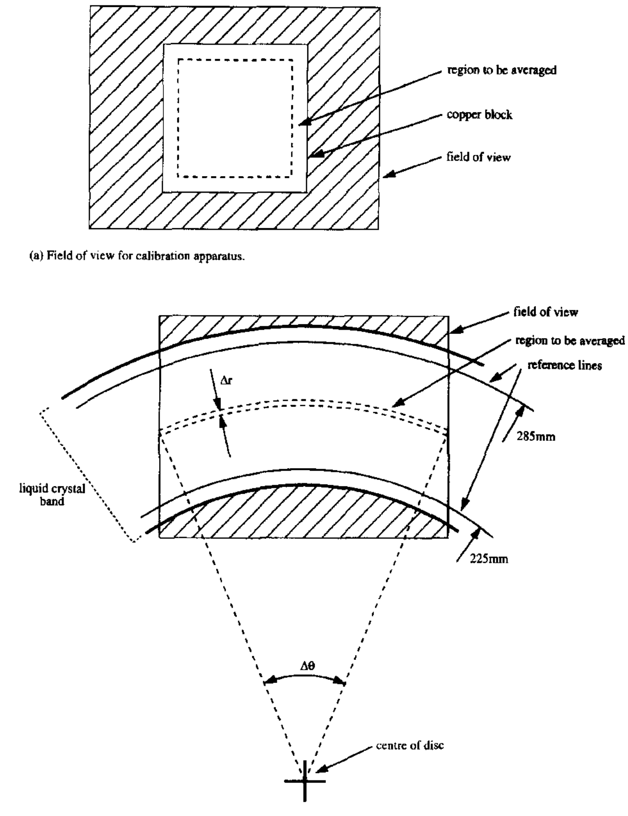


Figure 6 Field-of-view for thermal signal

The "local" temperature was calculated from a spatial average over a small segment of the disc. Because the temperature varied with radius, the radial height Δr of the segment was set to one millimeter. For the liquid–crystal analysis, the approximate angular width $\Delta\theta$ of the segment was 0.25 radians, and the resulting number of pixels in the average was 5000; for the infrared, the equivalent values were 0.6 radians and 100 pixels.

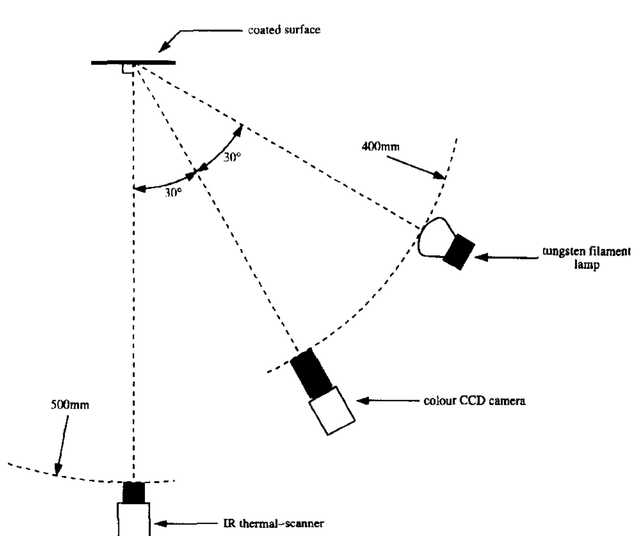


Figure 5 General arrangement of remote sensing equipment

3.3. Calibration apparatus

Stationary calibration of the liquid crystal was performed using the copper-block apparatus shown in Figure 7. It consists of a copper block (67 mm × 67 mm × 5 mm) mounted in polymethacrylimide insulation foam ($k \simeq 0.04$ W/mK). The block was heated electrically by a thin-film heater attached to the back face, and its temperature measured using a T-type thermocouple. The diameter of the thermocouple wires was 0.13 mm, and the bead was located in the centre of the block. The front face of the block was sprayed black prior to application of the TLC coating under test.

The thickness of the coating (black paint and liquid crystal) was measured and found to be approximately 25 μm. When the copper block was heated to 60°C (the upper limit of the R45C10W liquid crystal's temperature range), then, assuming a typical thermal conductivity of 0.2 W/mK, the temperature drop across

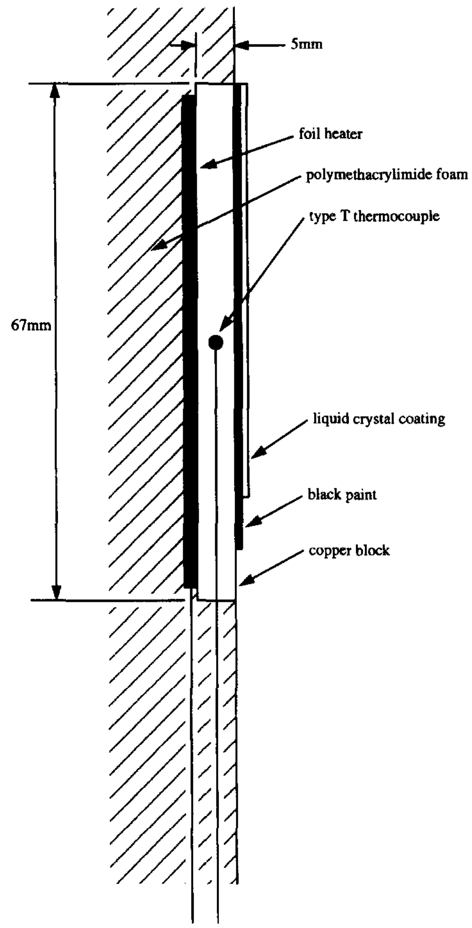


Figure 7 Schematic diagram of copper-block calibration apparatus

the coating due to radiative and free convective heat transfer to the ambient was estimated to be approximately 0.1°C. The temperature drop across the copper block itself was an order of magnitude smaller.

4. Experimental measurements

4.1. Calibration using copper-block apparatus

The copper-block apparatus described in the Calibration apparatus section was used to calibrate both the TLC coating and the IR thermal imager, employing the thermocouple as a secondary standard. The T-type thermocouple used in the copper block was one of a batch of three calibrated over the range 20 to 120°C in a Haake oil bath. The temperature of the silicone oil was measured using NPL mercury-filled thermometers with a manufacturer's specified accuracy of 0.025°C. The thermocouple cold junction, which was in an isothermal box at around 20°C, was measured with a platinum resistance thermometer (PRT) with a specified accuracy of ± 0.1°C at 0°C and ± 0.2°C at 100°C. The voltages from the PRT and thermocouples were measured using a Solatron 3535D datalogger incorporating a digital voltmeter with an uncertainty of ± 1 μV. Typically, 100 voltage readings were taken at each temperature over increments of 5°C. The average thermocouple voltages were fitted to the measured temperatures using a least-squares cubic polynomial, and the maximum difference between the fitted and measured temperature was 0.1°C in the range 20 to 70°C. The maximum difference between the calibration curve and the British Standard 4937 (part 5) for T-type thermocouples was also 0.1°C in this range.

The copper block was heated to the required temperature, measured by the thermocouple, and the power was adjusted to maintain the equilibrium. With the illumination, video camera, and IR scanner arranged as shown in Figure 5, the IR readings and the video recordings were made simultaneously. Tests were repeated at approximately 1°C intervals from 45 to 58°C, and the results from the IR and TLC calibrations are presented in Table 1.

An emissivity setting of $\varepsilon = 0.96$ on the IR imager was found to give good agreement with the thermocouple measurements, as shown in Table 1. The difference was within 0.1°C except for two values where the error was 0.2°C and 0.3°C. (Surprisingly, the emissivity of the TLC did not appear to change even when the surface colours changed; the reason for this is not understood.)

For the TLC calibration, Table 1 shows the number of pixels used to evaluate the hue, the average value of the hue, and the standard deviation for each of the measured temperatures. Figure 8 shows the variation of the (average) hue with temperature, measured by the thermocouple, together with the "uncertainty" in the hue based on two standard deviations (2σ). It should be pointed out that, owing to the large number of data ($> 10^4$) used in determining the average hue value at any temperature, the 95% confidence interval for this average is equivalent to less than ± 0.005°C. The "2σ uncertainty" is only meaningful when a single hue value is used to determine the temperature, in which case the uncertainty would be around ± 0.4°C; in all practical cases, averaging over a large number of data reduces this uncertainty to a negligible quantity.

It should be remembered that the copper block provides an isothermal surface which, in principle, is monochromatic. How-

Table 1 Calibration of IR thermal imager ($\varepsilon = 0.96$) and TLC using copper-block apparatus

Thermocouple temperature, °C	IR temperature, °C	TLC calibration: Number of pixels	Average value of hue	Standard deviation σ
47.5	47.4	42389	9.6	2.4
48.5	48.5	49263	59.3	3.6
49.5	49.6	36566	78.3	2.5
50.6	50.6	33538	90.7	2.2
51.5	51.5	39370	98.3	2.2
52.4	52.4	46706	107.2	2.2
53.5	53.8	51938	119.2	2.2
55.0	55.0	50897	135.3	1.8
56.7	56.7	36018	148.0	1.1
58.3	58.5	19604	156.1	0.8

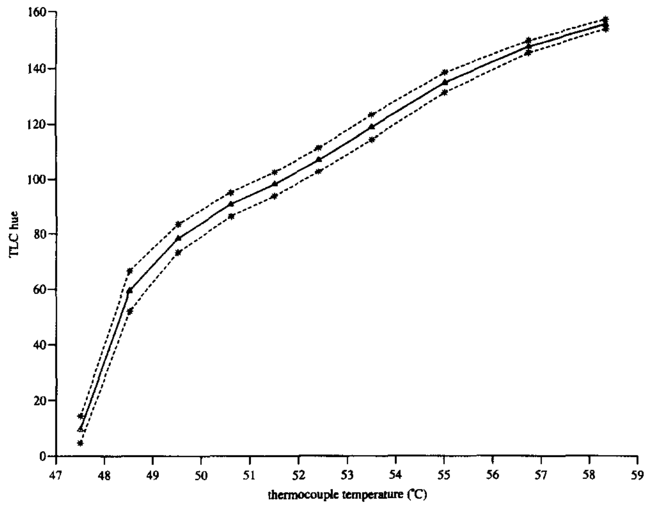


Figure 8 Variation of TLC hue with temperature (measured by thermocouple) of copper block

ever, the temperature of the rotating disc varies with radius, and so the complete spectrum of colours may appear in the field-of-view. As discussed in Section 4.2, the colour balance circuits in the video hardware can create a bias in the recorded colour adding to the uncertainty in the measurement of temperature using TLC.

4.2. Temperature measurement on rotating disc

The video camera, IR scanner, and lighting were set up as shown in Figure 5, and measurements were made for rotational speeds between 1000 and 7000 rpm in increments of 1000 rpm. For the coated ring on the disc, which extended for $225 \leq r \leq 285$ mm, these speeds gave rise to centripetal accelerations between 250 and 15,600g, where g is the acceleration due to gravity. In case there were any time-dependent systematic errors, which could be confused with the effects of rotational speed, high-speed and low-speed tests were carried out alternately rather than in a rising or falling sequence of speeds.

Figure 9 shows the variation of hue (obtained from the video-recording of the TLC as described above) with the temperature of the disc measured by the IR imager. Despite the scatter in the experimental results, there appear to be no *obvious* effects of rotational speed. For speeds between 1000 and 7000 rpm and for a fixed value of hue in the range 80 to 120, the temperature variation with speed may be around 0.5°C, but the temperature variations for the results at the extremes of 1000 and 7000 rpm are smaller than this. If there is an effect of rotational speed then it is not progressive: the effect does not increase monotonically as the speed increases.

Figure 10 shows the variation of the temperature measured by the TLC (obtained using the copper-block hue-temperature calibration shown in Figure 8) with the temperature of the disc measured by the IR imager. The calibration line, obtained from the copper block for a *stationary* frame of reference, is also shown in the figure. The measurements show both scatter and an "oscillatory bias" around the calibration line: there appears to be some effect of rotational speed, but the scatter is relatively small, and the bias is not a monotonic function of speed.

The "oscillatory bias" was *originally* thought to be caused not by moving from a stationary to a rotating frame *per se*, but by moving from the *surface* of the copper block to that of the disc. The two surfaces could have different emissivities and reflectivities, and this would affect the optical and IR signals in different ways. To test this hypothesis, an *in situ* calibration was performed on the disc when it was rotating at 1000 rpm. (Ideally the calibration should have been performed on a *stationary* disc, but this was impracticable owing to the nonaxisymmetric temperature variations that are created on a heated vertical surface in a (single g) gravitational field.) For the *in situ* calibration, the hue values for the TLC were calibrated using the IR measurements obtained from the surface of the heated disc; the emissivity setting of the IR imager was kept at $\varepsilon = 0.96$, the value used for the original copper-block calibration.

Figure 11 shows the variation of the temperature measured by the TLC (using the *in situ* calibration) with the temperature measured by the IR imager. There is still scatter in the measurements, but the oscillatory bias has been reduced significantly. The departure of the measurements made at 7000 rpm from the calibration at 1000 rpm is typically less than 0.3°C, although the departure of measurements at intermediate speeds (for example, 3000 rpm) is up to 0.5°C. While the departure from the calibra-

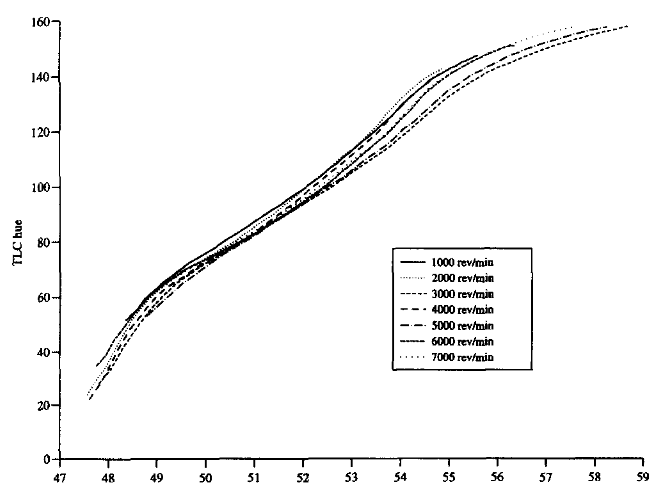


Figure 9 Variation of TLC hue with disc temperature (measured by IR imager)

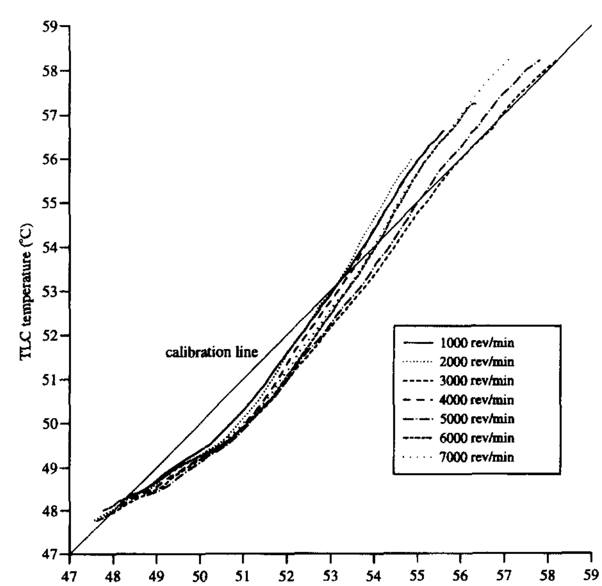


Figure 10 Variation of disc temperature measured by TLC (using copper-block calibration) with temperature measured by IR imager

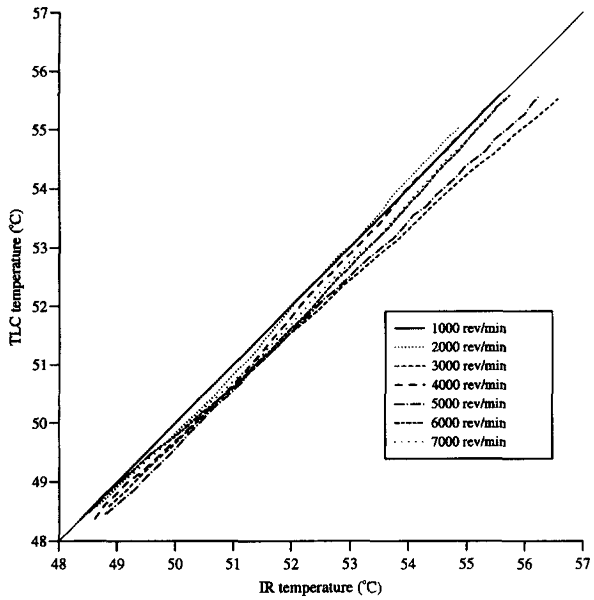


Figure 11 Variation of disc temperature measured by TLC (using in situ calibration) with temperature measured by IR imager

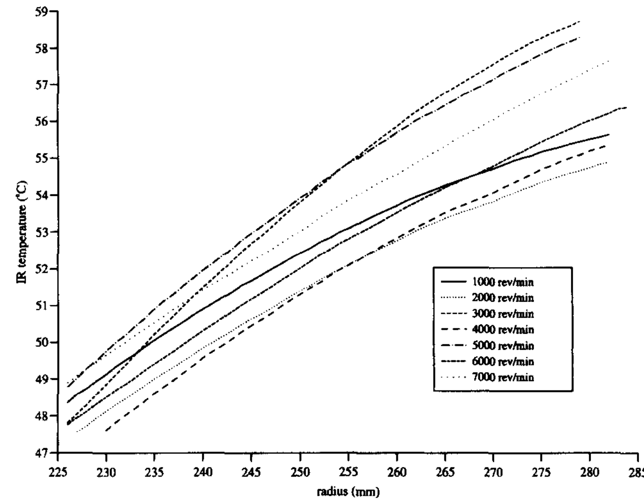


Figure 12 Radial distribution of disc temperature measured by IR imager

tion line is relatively small, and it does not increase monotonically with speed, the effect does appear to be speed related.

The reason for this bias is believed to lie with the colour-balance circuits in the video hardware (CCD camera, recorder, and frame grabber) used for recording the TLC signal. As stated above, in the copper-block calibration, the surface is isothermal, and only one colour is visible at any instant: the variation in the hue from pixel to pixel will, therefore, be relatively small. In the disc experiments, the surface is nonisothermal, and the variations in hue will be large. In principle, the radial distribution of temperature over the disc should have been the same for all tests, making any bias invariant with speed. In practice, however, the temperature distribution varied from test to test, and, consequently, any systematic error in the video hardware would produce what appears to be a "speed-related bias" in the TLC temperature measurements.

Figure 12 shows the radial distribution of the disc temperature (measured by the IR imager) for the seven speeds. Although the distributions are similar, their magnitudes are different. The relationship between the maximum temperature and speed shown in Figure 12 is similar to that between the hue and speed shown in Figure 11. It would appear, therefore, that the "speed-related bias" in hue is caused, indirectly, by the temperature distribution on the disc and not by the speed *per se*.

The precise mechanism by which the hue values become dependent on the distribution of temperature is not fully understood by the authors, but investigations have begun to ascertain if the problem can be solved using a digital video system rather than the current analog one. However, despite this relatively minor problem, it can be reasonably concluded that, for accelerations up to 16,000*g*, rotational speed has no significant effect on the temperature response of wide-band thermochromic liquid crystal.

4.3. A comment on the "rotational shift"

As stated in the introduction, the principal reason for studying this phenomenon was to prove or disprove the "rotational shift" observed by other experimenters. There has been speculation that the TLC could be sheared by surface strain on a rotating body or could be centrifuged by the "*g* forces". Because we have established beyond reasonable doubt that there is no "rotational shift," then we might be permitted to speculate on why so many experimenters were wrong.

Since submitting this paper for publication in October 1995, we have joined forces with Cengiz Camci and Boris Glezer in the United States, and the two groups have produced a short paper on the separate experiments: theirs with narrow-band TLC and ours with wide-band. In that paper (Camci *et al.* 1996), we suggest a reason for the "rotational shift." For completeness (and in deference to one of the reviewers of *this* paper), we repeat that suggestion here.

> A thermocouple, which will be a different material from that of the body in which it is embedded, will cause a local disturbance of the temperature distribution in the body. This creates a thermal-disturbance error in which there is a difference between the true (undisturbed) temperature and the measured temperature. The magnitude of the error depends, amongst other things, on the size of the thermocouple, on the thermal properties of the materials, and on the local heat flux.
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> For a rotating body at a constant temperature, the heat transfer coefficient, and hence the surface heat flux, increases as the rotational speed increases. Consequently, the thermal-disturbance error created by an embedded thermocouple will increase with rotational speed. If thermocouples and TLC are used to measure the temperature of a rotating body then the difference between the two measurements will also increase with speed.
>
> This phenomenon has been observed independently in experiments carried out by the two groups of authors. It is believed to be the reason why other research workers have observed what they (wrongly) believed to be the "rotational shift" in TLC output referred to in Section 1.

5. Conclusions

Wide-band TLC and an IR thermal imager have been used to measure the surface temperature of a rotating disc. The hue technique was employed to determine the temperature of the TLC, which had an effective range of 48 to 58°C, with a resolution of around 0.1°C. The IR imager, which also had a resolution of approximately 0.1°C, was used as a datum to determine the effect of rotational speed on the temperature response of the TLC.

Tests were conducted at rotational speeds between 1000 and 7000 rpm, corresponding to centripetal accelerations from 250 to 16,000 *g*. Although there was a scatter of around 0.5°C in the measurements, the typical difference between the temperatures measured by the TLC and the IR imager at the extremes of the speed range (1000 and 7000 rpm) was less than 0.3°C.

What appeared to be a small speed-related bias in the measured temperatures was attributed to the characteristics of the video hardware used to measure and record the images from the TLC. The value of the hue obtained from the video recordings was found to be weakly dependent on the *distribution* of temperature on the rotating disc. Despite this equipment-related bias, it is concluded that, for accelerations up to 16000 *g* and within the uncertainty of the measurements, there is no significant effect of rotational speed on the temperature response of wide-band TLC.

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