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APPLICATION OF THERMOCHROMIC LIQUID CRYSTAL TO ROTATING SURFACES

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ABSTRACT

Encapsulated thermochromic liquid crystal (TLC) can be used to measure the surface temperature of stationary or rotating bodies. However, some research workers have reported a "rotational shift": when the temperature of a rotating body is measured by thermocouples and TLC, there is a difference between the two sets of temperatures, and this difference increases with increasing rotational speed.

Two research groups (Camci and Glezer in the USA, and Owen, Pilbrow and Syson in the UK) have independently examined the effect of speed on TLC applied to the surfaces of rotating disks. The USA group used narrow-band TLC on a disk of 305-mm diameter rotating up to 7500 rev/min, measuring the surface temperature using an infra-red (IR) sensor. The UK group used wide-band TLC on a disk of 580-mm diameter rotating up to 7000 rev/min, measuring the temperature with an IR thermal imager. Both groups used the so-called hue technique to evaluate the temperature of the TLC and concluded that, even for centripetal accelerations in excess of 10^4g, there is no significant effect of rotational speed on either narrow-band or wide-band TLC. It is suggested that the "rotational shift" observed by some researchers was probably caused by thermal-disturbance errors, which affected the thermocouples, rather than by changes in the TLC.

1 INTRODUCTION

Encapsulated thermochromic liquid crystal (TLC) is used extensively for surface-temperature measurements in heat transfer experiments. Originally, most research workers used narrow-band TLC, where the colors change from red to blue over a small change in temperature, typically 1°C. Using a single color (say yellow), the surface temperature can be determined with an uncertainty of around 0.1°C. More recently, wide-band TLC (with a bandwidth around 10°C), and the so-called hue technique has been used to determine the temperature. The hue technique uses hue, saturation and intensity (HSI) instead of the more conventional red, green and blue (RGB) system of color processing, and this can result in an order-of-magnitude improvement in accuracy. Details are given by Kim (1991), Camci *et al* (1992, 1993), Wilson *et al* (1993), Farina *et al* (1993), and Rizzo and Camci (1994).

Most of the applications of TLC have been on stationary objects but the technique has also been applied to rotating bodies. Metzger *et al* (1991) used narrow-band TLC applied to an acrylic rotating disk to determine the local heat transfer coefficients. Blair *et al* (1991) made measurements using thermocouples and narrow-band TLC on a large-scale low-speed turbine rig. These authors observed a "rotational shift" in which the TLC output at 400 rev/min changed by 2°C, compared with the thermocouple measurements. They also made measurements in a rotating cooling passage and reported a 3° to 4°C "rotational shift" at 525 rev/min, corresponding to a centripetal acceleration of around 280g.

Camci and Glezer in the USA and Owen, Pilbrow and Syson in the UK carried out independent research work on rotating-disk systems in which the disk temperatures were measured by TLC, thermocouples and infra-red (IR) thermography. Both groups found that, when thermocouples were used, there was evidence of the "rotational shift"; but, as described below, when IR measurements were used a different picture emerged. When Camci and Glezer presented their preliminary findings at the 1995 ASME Gas Turbine and Aeroengine Congress in Houston (Camci and Glezer 1995a), it became apparent that both groups were proceeding along parallel lines. They agreed to collaborate: each group would submit its detailed findings to an engineering journal for publication (Camci and Glezer 1995b, Syson, Pilbrow and Owen 1995), and a joint account of their work would be submitted to the 1996 ASME Gas Turbine Congress.

This paper contains the joint account of that research. The apparatus used by each group is described in Section 2, the experimental results in Section 3, and the conclusions in Section 4.

2 EXPERIMENTAL APPARATUS

2.1 Tests with narrow-band TLC

The rotating disk used by Camci and Glezer was 0.305 m in diameter and was made from aluminum. It could be rotated up to 7500 rev/min by means of an ac electric motor, and its speed was measured with an uncertainty of ±5 rev/min.

One surface of the disk was first painted black and then coated with narrow-band TLC. Separate tests were conducted with two narrow-band crystals: R30C1W and R45C1W (manufactured by Hallcrest Inc.) which were activated at 30°C and 45°C respectively. A color video recording of the TLC was made for each test, and the hue was determined using an image-processing system incorporating a 24-bit image processor, a video decoder/encoder and an array processor; further details of the hue technique are given by Camci et al (1992).

The surface temperature of the disk was measured using an infra-red (IR) point sensor (manufactured by Raytek Thermalert). The sensor head was located normal to the disk, an axial distance of 76 mm from it, and the effective circular target area had a diameter of 2.5 mm. The spectral response of the detector was between 8 and 14 μm, which made it insensitive to the lighting used to illuminate the TLC. For this illumination, a 250W incandescent light source was located at an angle of 45° to the target area and 1.5m from it. Although the emissivity of the surface of the TLC was not required for these tests, it was estimated to be $\varepsilon = 0.96$.

A stationary calibration plate, made from aluminum and coated with black paint and TLC, was used for the calibration. A thin-foil (10 μm thickness) K-type thermocouple was attached to the black surface, which was then coated with TLC. The plate was heated to 60°C by a hot-air gun and allowed to cool slowly (around 0.1°C/minute). The IR sensor was focused on the thermocouple, and a video recording was made during the thermal transient.

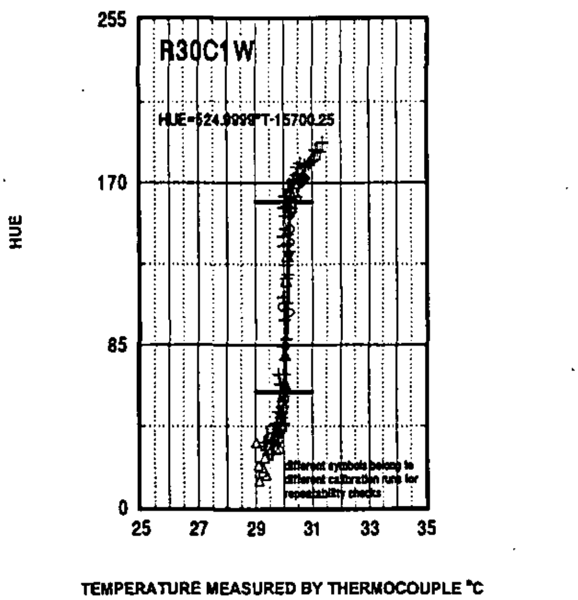

FIG 1 VARIATION OF HUE FOR NARROW-BAND TLC WITH TEMPERATURE MEASURED BY THERMOCOUPLE IN STATIONARY PLATE

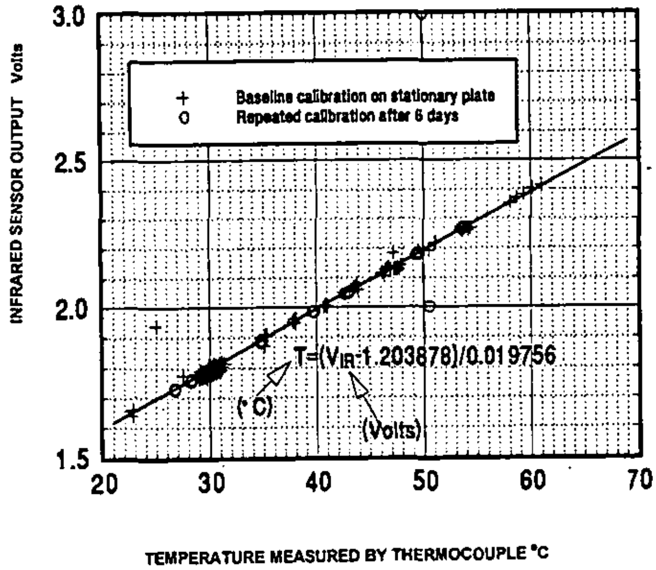

FIG 2 VARIATION OF VOLTAGE OUTPUT OF INFRA-RED SENSOR WITH TEMPERATURE MEASURED BY THERMOCOUPLE IN STATIONARY PLATE

Figs 1 and 2 show the respective variations of hue, from the 30°C (R30C1W) crystal, and voltage, from the IR sensor, with the temperature of the aluminum plate measured by the thermocouple; the different symbols refer to different tests used to determine repeatability. Using a cross-plot of these results, it was possible to obtain the variation of hue with IR voltage shown in Fig 3. The hue-temperature calibration tests were also successfully repeated on the surface of the aluminum disk when it was stationary. This calibration was used for subsequent tests on the rotating disk, thus avoiding the need to use thermocouples and sliprings with their associated errors.

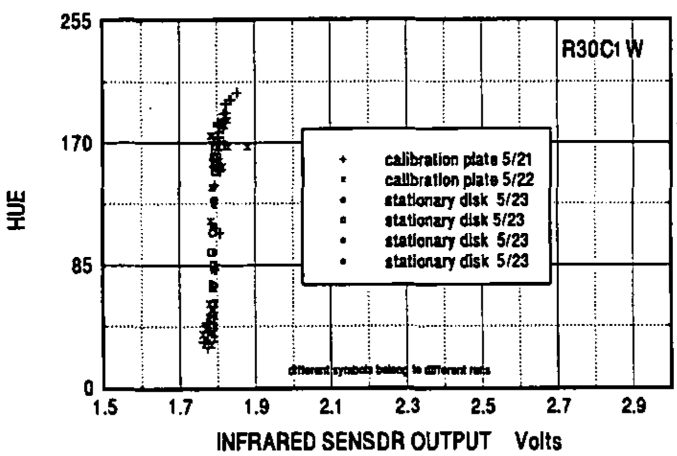

FIG 3 VARIATION OF HUE FOR NARROW-BAND TLC WITH VOLTAGE OUTPUT OF INFRA-RED SENSOR (STATIONARY MEASUREMENT)

2.2. Tests with wide-band TLC

The rotating disk used by Syson *et al* was 0.580 m in diameter and was made from steel. It could be rotated up to 7000 rev/min by a dc electric motor, and its speed was measured with an uncertainty of ± 1 rev/min. The disk could be heated up to 150°C by thyristor-controlled stationary radiant heaters.

One surface of the disk was sprayed with black paint, and an annular area (220 < r < 290 mm) was then coated with wide-band TLC (Hallcrest, R45C 10W) with an effective range of 45 to 55°C. A video recording was made of the heated surface, and an image-processing system, similar to that described by Wilson al (1992), was used to determine the hue of the TLC.

The surface temperature was measured using an Agema IR thermal imager, featuring a thermal scanner and associated hardware and software to convert the electrical signal to a temperature output. The scanner, which is sensitive to radiation with wavelengths between 2 and 5 μm, uses oscillating and rotating mirrors to scan a 70-line field at 25 fields/second, and the software generates a 140 x 140 pixel image of the viewed surface. The manufacturer's specified accuracy is 2% or ± 2°C, whichever is the larger, and the resolution at 60°C (which is at the top end of the TLC range) is 0.07°C. Improved accuracy was obtained by averaging 20 consecutive frames.

For the tests, the back face of the disk was radiantly heated and the front face, coated with TLC, was viewed using the IR imager and a video camera. The scanner was positioned to be normal to the disk at a distance of 0.5m from it, and the video camera and tungsten-filament lamp, used to illuminate the TLC, were located a distance of 0.4 m from the disk at respective angles to the axial direction of 30° and 60°.

Before conducting the rotating-disk tests, the IR imager and TLC were calibrated using a copper-block rig. A copper block (67 x 67 x 5mm) was embedded in insulating material, with one surface of the block exposed. A calibrated T-type thermocouple, embedded in the block, was used to measure its temperature, and the exposed surface was coated with black paint and TLC. Ten values of the measured temperatures were compared over the range 47.5 to 58.3°C. Using an emissivity setting of $\varepsilon = 0.96$, the IR and thermocouple readings agreed within 0.1°C for eight of these readings; the differences between the other two readings were 0.2 and 0.3°C.

3 EXPERIMENTAL RESULTS

3.1 Narrow-band tests

Using the apparatus described in Section 2.1, tests were conducted on the rotating aluminum disk. Fig 3 shows the variation of hue, from the 30°C (R30C1W) crystal, with "IR voltage" (that is, the voltage from the IR sensor) for the stationary disk. The results, which were obtained from four individual cooling tests, give confidence in the accuracy and repeatability of the experimental technique.

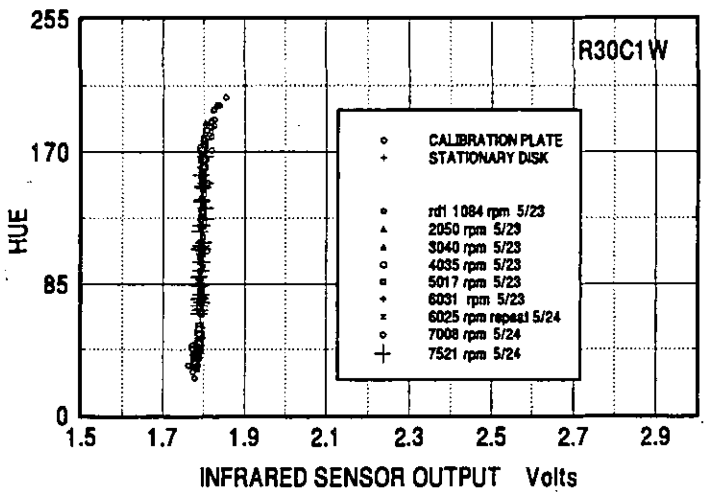

FIG 4 EFFECT OF ROTATION ON VARIATION OF HUE FOR NARROW-BAND TLC WITH VOLTAGE OUTPUT OF INFRA-RED SENSOR

Tests were carried out on the disk at a radius of r = 0.135m for rotational speeds up to 7500 rev/min, corresponding to centripetal accelerations up to 8500 g. Fig 4 shows the variation of hue, from the 30°C crystal, with "IR voltage" for various speeds. Several hundred data points on the figure confirm that there is no significant effect of rotational speed on the output of the TLC. Similar results were obtained from the 45°C crystal.

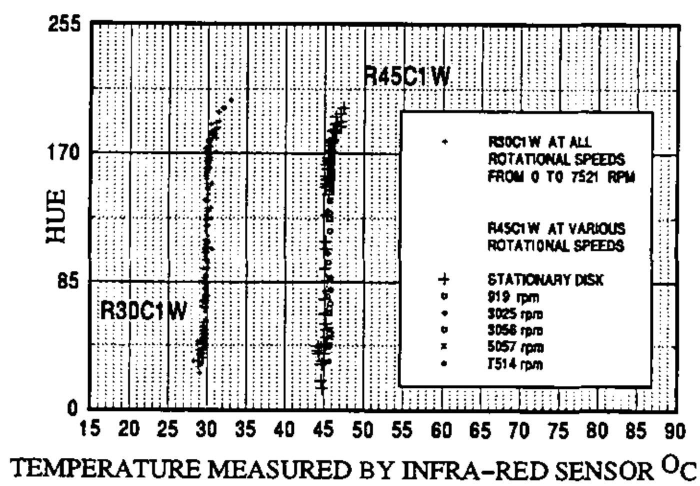

FIG 5 EFFECT OF ROTATION ON VARIATION OF HUE FOR NARROW-BAND TLC WITH TEMPERATURE MEASURED BY INFRA-RED SENSOR

Fig 5 shows the variation of hue, from both crystals, with the temperature measured by the IR sensor. Again, it can be concluded that, for speeds up to 7500 rev/min, there is no significant effect of rotational speed on the TLC.

3.2 Wide-band tests

Tests were conducted on the rotating steel disk, using the apparatus described in Section 2.2, for rotational speeds between 1000 and 7000 rev/min. For the coated ring on the disk, which extended radially from 225 to 285 mm, these speeds corresponded to centripetal accelerations between 250g and 15,600 g.

Fig 6 shows the variation of hue (obtained from the video-recording of the TLC) with the temperature of the disk 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 rev/min 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 rev/min 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.

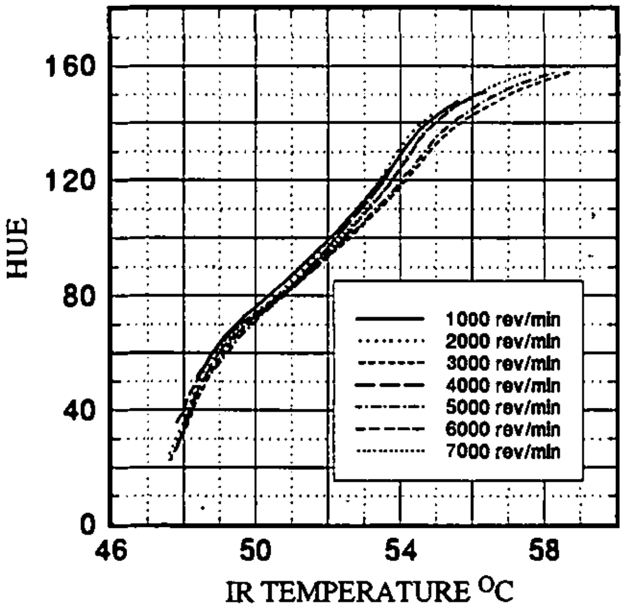

FIG 6 EFFECT OF ROTATION ON VARIATION OF HUE FOR WIDE-BAND TLC WITH TEMPERATURE MEASURED BY INFRA-RED IMAGER

Fig 7 shows the variation of the temperature measured by the TLC (obtained using the copper-block hue-temperature calibration) with the temperature of the disk measured by the IR imager. The calibration line, obtained from the copper block for a *stationary* frame of reference, is also shown on 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 disk. 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 disk when it was rotating at 1000 rev/min; owing to the way the disk was heated, tests on a stationary disk were impracticable. For the *in situ* calibration, the hue values for the TLC were calibrated using the IR measurements obtained from the surface of the heated disk; the emissivity setting of the IR imager was kept at $\varepsilon = 0.96$, the value used for the original copper-block calibration.

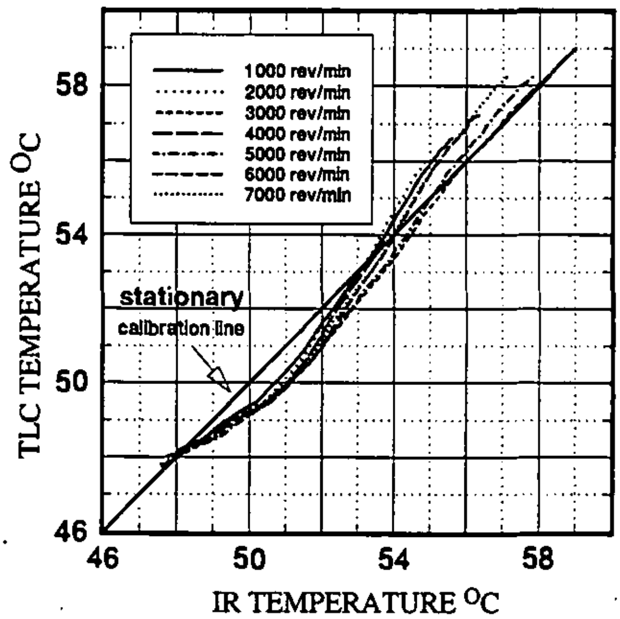

FIG 7 EFFECT OF ROTATION ON VARIATION OF TEMPERATURE MEASURED BY WIDE-BAND TLC (USING COPPER-BLOCK CALIBRATION) WITH TEMPERATURE MEASURED BY INFRA-RED IMAGER

Fig 8 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 rev/min from the calibration at 1000 rev/min is typically less than 0.3°C, although the departure of measurements at intermediate speeds (for example, 3000 rev/min) is up to 0.5°C. Whilst the departure from the calibration line is relatively small, and it does not increase monotonically with speed, the effect does appear to be speed related.

The bias referred to above appears to be caused by the colour-balance circuits in the video hardware. In the experiments, it was not possible to keep the radial temperature distribution on the disk the same for all tests, consequently there was a variation in the distribution of hue, from the TLC, from speed to speed. The apparent speed-related bias in the results was believed to be caused by the varying temperature distributions and not by any intrinsic effect of speed on the TLC.

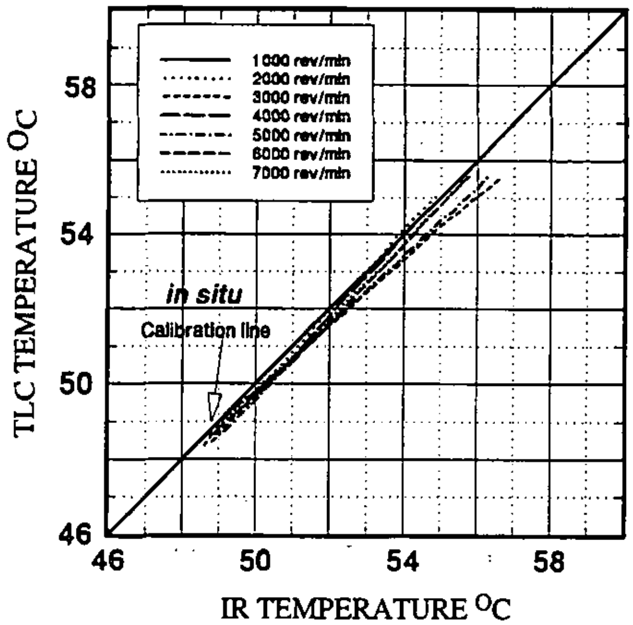

FIG 8 EFFECT OF ROTATION ON VARIATION OF TEMPERATURE MEASURED BY WIDE-BAND TLC (USING *IN SITU* CALIBRATION) WITH TEMPERATURE MEASURED BY INFRA-RED IMAGER

3.3. The "rotational shift"

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.

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.

4 CONCLUSIONS

Experiments have been conducted on narrow-band (1°C bandwidth) and wide-band (10°C bandwidth) TLC, by two groups of research workers in the USA and the UK, to determine if there is an effect of rotational speed on the output of TLC. The narrow-band tests were conducted on a disk of 0.305 m diameter rotating up to 7500 rev/min (corresponding to centripetal accelerations up to 8500 g). The wide-band tests were carried out on a disk of 0.580 m diameter rotating up to 7000 rev/min (15,600 g). In both cases, the so-called hue technique was used to determine the output of the TLC, and infra-red thermography was used to measure the surface temperature of the rotating disk: for the narrow-band tests, an IR point sensor was used; for the wide-band tests, an IR imager was employed.

Within the uncertainty of the experimental measurements, it was concluded that there is no significant effect of rotational speed on the output of TLC. The "rotational shift" observed by other research workers is believed to be caused by thermal-disturbance errors in their thermocouples and not by the TLC itself.

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