Image processing techniques applied to wide−band thermochromic liquid crystals

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Report No. 039/1993

Summary

The "hue" technique for image−processing, based on experiments using thermochromic liquid crystals, is being investigated as part of a three−year research project on the use of thermal imaging techniques applied to rotating−disc systems representing those found in gas−turbine engines. Although at an early stage, it is expected that heat transfer coefficients, calculated from thermal image data, will provide valuable information for the validation of computational fluid dynamics codes being developed for rotating−disc applications.

1.0 Introduction

This paper describes work carried out during the early stages of a three−year UK SERC−funded project to investigate thermal−imaging techniques applied to the measurement of heat transfer from rotating discs, using a number of purpose−built experimental rigs. The rigs model the air−cooled turbine discs found in gas turbine engines. The work will feature evaluation of both liquid crystal and infra−red thermal imaging (using an existing Agema system) methods. The results will be used in the continuing validation of computational fluid dynamics (CFD) codes for turbulent flow and heat transfer in rotating−disc systems. Remote sensing by LR or IR techniques have a number of advantages compared with conventional techniques that use thermocouples and fluxmeters: being able to dispense with slip−rings is perhaps the most important advantage. Metzger et al., (1989) have already demonstrated that TLCs can be used for this purpose.

Thermochromic liquid crystals (TLCs) reflect light at a wavelength that is a function of temperature. Most heat transfer research work has been undertaken using narrow−band TLCs with a bandwidth of around 1^{o}C: Jones and Hippensteele (1988) in common with many others use the yellow band, which occurs over a very narrow temperature range.

Greater accuracy can be obtained by applying image processing techniques to the TLC colour band width. Wang et al., (1993) process monochrome images of the TLC coated surface to identify the colour with maximum intensity. Camci et al., (1991) use the "hue" technique applied to a narrow band TLC, as described in section 4. The hue technique allows TLCs to be calibrated over their entire bandwidth, making use of information ’lost’ in the single colour approach. It also opens up the possibility of using wide−band TLCs to measure temperature over a much wider range.

The first stage of the present work comprises the calibration of both narrow−band and wide−band TLCs using simple experiments such as the cooling of a copper block. These studies serve to gain familiarity with experimental and analytical methods, and to prompt ideas for the future work. Section 2 of this paper describes the commercial software used for analysis of experimental results and some of the reasons for its choice, and the TLC hue calibration method is outlined in sections 3 and 4. Preliminary conclusions are presented in section 5 together with proposed directions of future research.

2.0 Choice of software

Commercial image−processing software development and availability continues to increase, with much expertise deriving from applications in a wide range of disciplines in which imaging plays a key part in data reduction and analysis. In engineering science there are two possible routes for incorporating image−processing into the analysis of experimental results. Personal−computer−based systems offer physically portable, rapid−throughput facilities which allow image−processing to be carried out in an analogous fashion to other data−acquisition systems. Real−time processing loses some of its attraction if the experiment is to be recorded onto video tape. Furthermore, image data storage and processing usually requires access to large amounts of computer memory and disk store, so that a multi−tasking networked Unix workstation environment has many advantages if image−processing is to be carried out from videotape records of experiments.

A Silicon Graphics Indigo R3000 workstation was identified as a suitable base for analysis work in the current investigations. The system (illustrated in Fig. 1) brings together video support, flexible image handling and processing software, and access to reasonably large amounts of computer memory and storage.

The proprietary video input/output board is interfaced to the (8−bit) graphics hardware for throughput of live video without affecting response of the usual multi−tasking operating system. A software frame−grabber can be used to capture still colour images from a video recording, under manual control of playback. Alternatively, frames can be collected automatically at a fixed rate of between 1 and 20 frames per second during playback of a section of the tape. The captured images (complete PAL−sized frames) are stored on disk in (typically) uncompressed Red−Green−Blue (RGB) graphics file format, requiring about 0.5MB per image. The stored frames are then used as input data to a sequence of colour image−processing routines as described below.

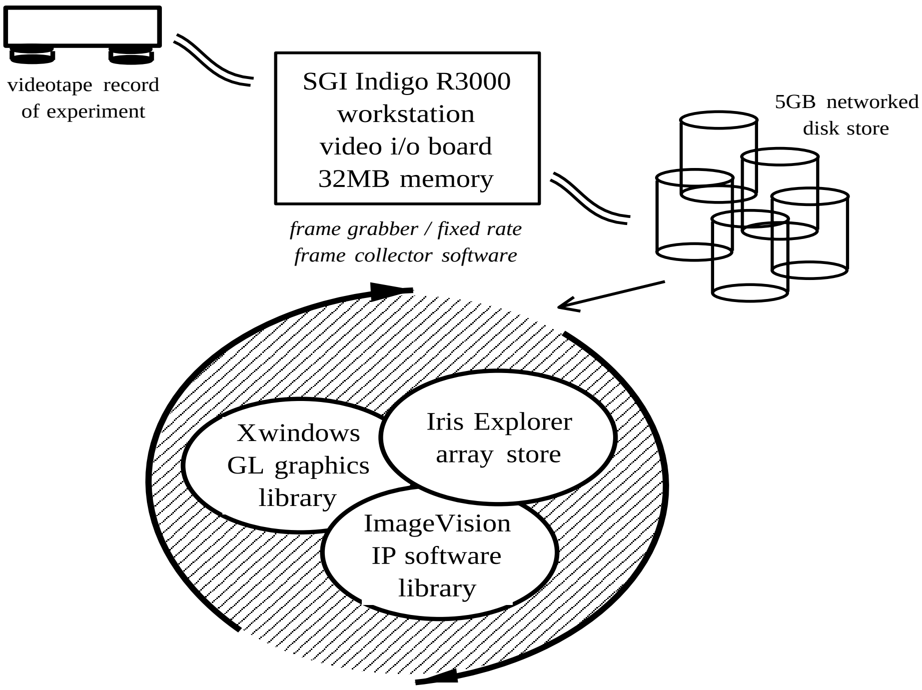


Fig. 1 Hardware and software environment for workstation−based image processing

The Silicon Graphics Iris Explorer data−visualisation software system was selected, on the basis of functionality and flexibility, as the basis for the imaging processing work to be undertaken in the present project. The software comprises a visual programming environment for linking manipulation and display operations (in the form of high−level executable code modules) acting on data stored in shared memory in strongly−typed array structures. This framework allows user code to concentrate largely on image−processing sequences themselves rather than on the associated data handling. The environment binds together 2D/3D graphics software libraries and a suite of image processing routines, and it allows the user to write new code for these applications in FORTRAN, C or C++ as convenient. Many examples of user code are now available in the public domain, held at access sites in the UK and USA, and a forthcoming version will offer integration with the proprietary video−board hardware and software for data input, as described above. This should allow, for example, cropping of images at video source, reducing the overheads of working from full−sized frames stored on disk.

A system devised for the calibration exercise described in section 4 is shown in Fig. 2. It incorporates graphical cropping of stored images, colour−space conversion, and analysis of the resulting hue histogram for the selected region. A loop function increments the numeric part in the construction of filenames, so that the next image in a previously stored sequence is processed on completion of the previous task. A concurrent display operation gives a graphical "polar histogram" for the cropped image which, in future applications, would be replaced by a module to compute heat transfer coefficients, as outlined in section 5.

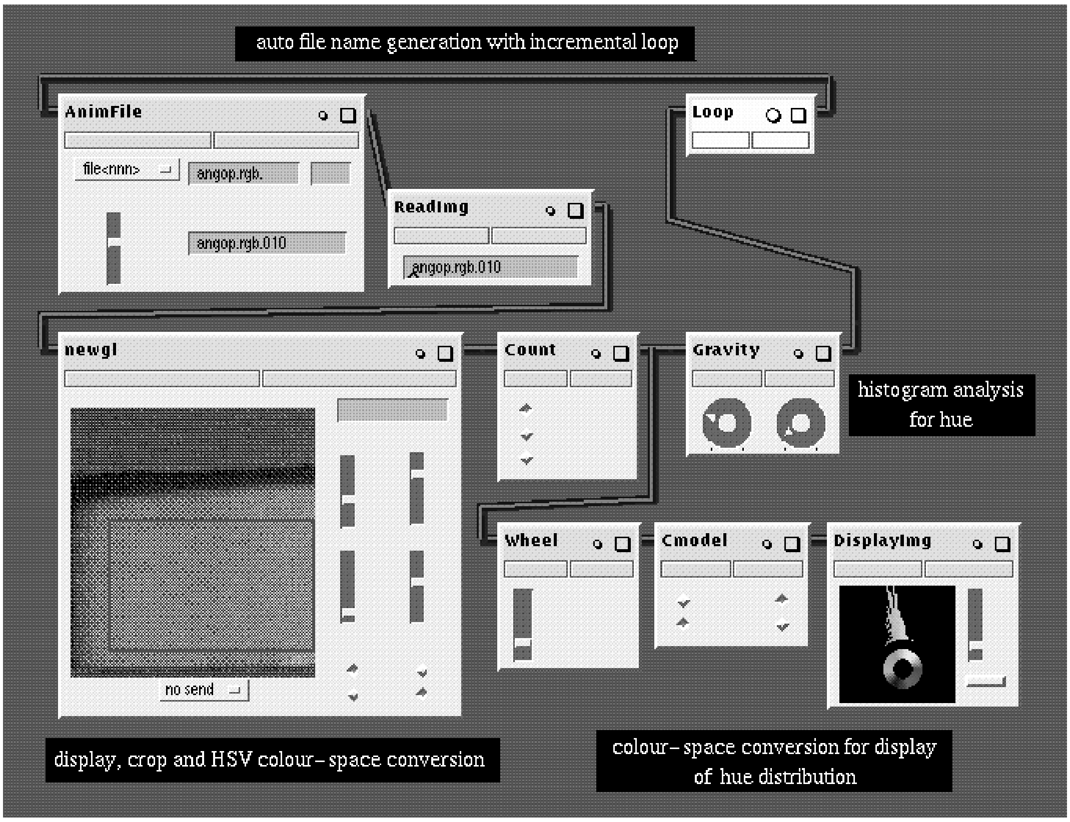


Fig. 2 The Iris Explorer visual programming environment (hue calibration example)

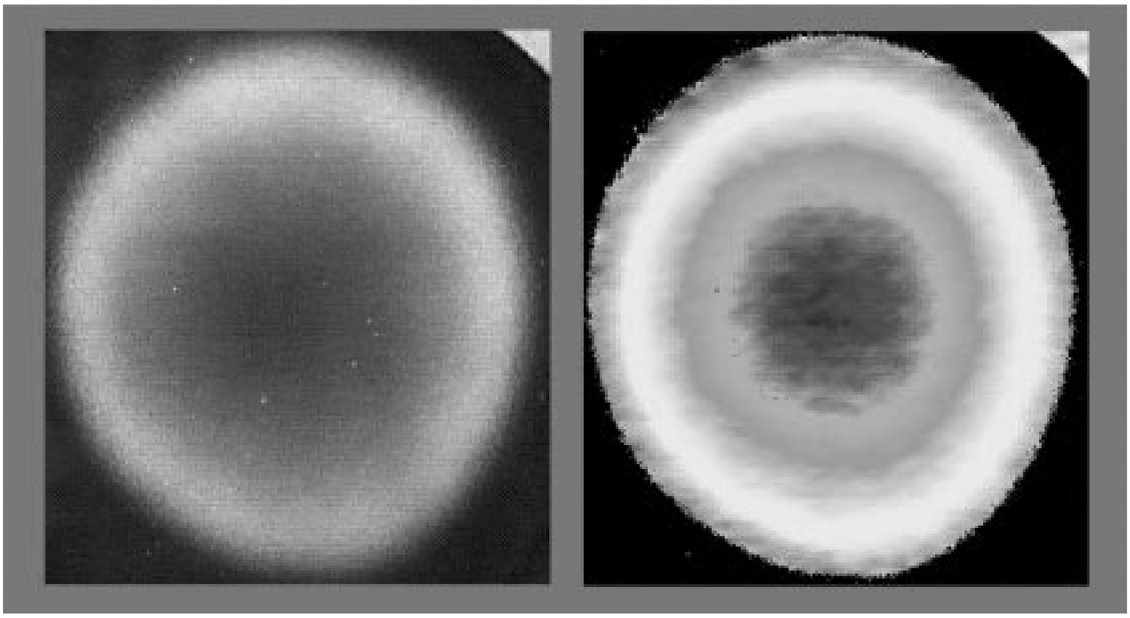
The modular working environment described will be very familiar to users of, for example, the commercial Application Visualisation System (AVS) package or the public domain Khoros 2D image processing suite. The Explorer system, delivered as part of the workstation operating system, was found to have a more immediate interface to user data than machine−independent public−domain software. Although large in scale and requiring a good deal of tailoring to particular applications through user coding, modular data visualisation packages offer a very attractive route for image analysis in a research project framework. For example, additional programs for the calculation of heat transfer coefficients from processed data can be included (and interchanged) in the analysis loop for rapid evaluation, while other features of the system may be used for visualisation and integration of other data, such as the results from 3D computational fluid dynamics (CFD) simulations.

The image processing system is being developed and tested by application to the calibration of narrow−band (1^{o}C) and wide−band (20^{o}C) TLCs, and some of the details are given below.

3.0 The hue technique.

The image of a TLC coated surface captured on video−tape is a red−green−blue (RGB) image, where the colour of each pixel is described by red, green, and blue intensity values. As described by Camci et al., (1991) the three independent coordinates of the RGB colour−model can be mathematically transformed into any other set. The most useful of these is the hue−saturation−intensity (HSI) colour−model, where intensity is a measure of the brightness, saturation is a measure of the depth of the colour, and hue is a measure of the dominant wavelength. As TLCs reflect light at a wavelength dependent on temperature, the hue of the reflected light is also a function of temperature. Therefore, if the RGB image of a TLC coated surface is converted to an HSI image, the hue value of each pixel indicates the temperature of the corresponding location on the surface.

Fig 3a shows the effect of a hot jet impinging on a TLC coated surface. Fig 3b shows the same image after the saturation and intensity have been set to their maximum values, the "real" colours being replaced by "pure" colours of the same wavelength. (The contrast of the two coloured images is of course more pronounced than in the grey−scale images shown here.)



a) RGB video image   b) processed image

Fig. 3 The hue technique applied to a hot impinging jet

4.0 Calibration procedure.

The TLCs (supplied by Merck) are calibrated by applying them on an isothermal surface as shown in Fig 4. The isothermal surface used in the TLC calibration is a copper block first sprayed black to highlight the colours. The Biot number of the block under free convection is very small so that temperature gradients can be considered negligible. Therefore the temperature of the block's surface can be assumed constant and equal to that measured by a thermocouple embedded in the block.

The surface is then gradually cooled or heated so that the TLCs pass through their temperature band. The temperature−time history of the TLCs is recorded by a data logger while the colour−time history is recorded on video tape by a camera viewing the surface. The two histories are synchronised by a light−emitting−diode (LED) in the video camera's view being turned on by the data logger at the start of the experiment.

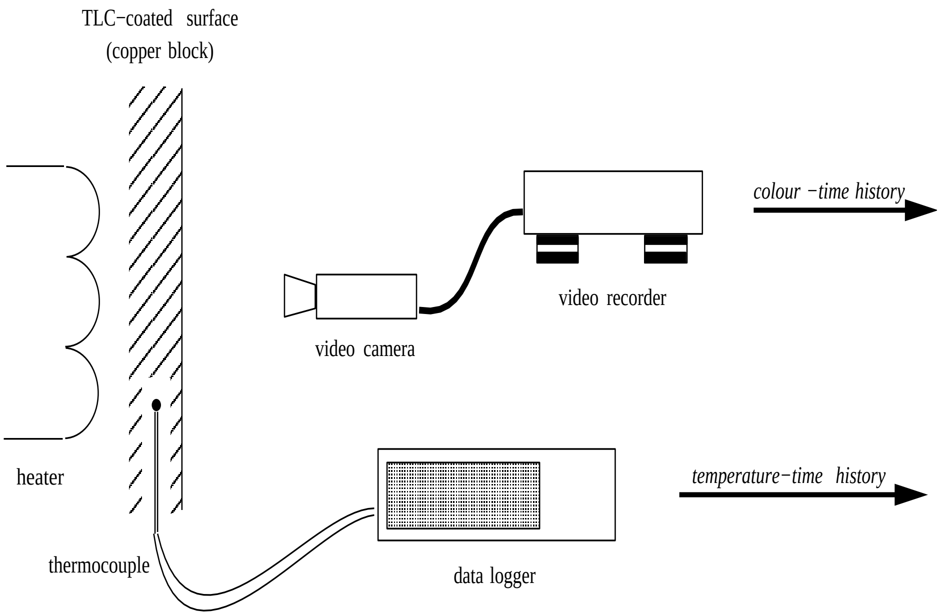


Fig. 4 Diagram of experimental apparatus

To find the hue of the TLC at a particular time, the appropriate image is 'grabbed' from the video tape and processed. Firstly its "colour−model" is changed from RGB to HSI. The mean hue value and its standard deviation is taken from the image's hue histogram, constructed on a pixel−by−pixel basis. Combining the hue−time and temperature−time histories gives the temperature−hue calibration.

Fig 5 shows the calibration of a 1^{o}C TLC. The TLCs can be used to measure temperatures accurate to at least 0.1^{o}C, the accuracy of the calibration being limited by the experimental apparatus rather than by the TLCs themselves. Calibration of 5^{o}C and 20^{o}C TLCs is progressing and preliminary results from the 5^{o}C crystal indicate that it can be used to measure temperature to an accuracy of 0.1−0.2 ^{o}C.

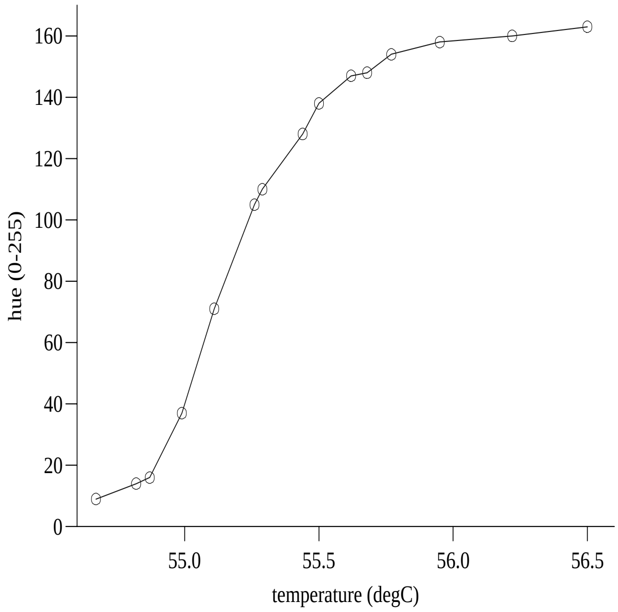


Fig. 5 Narrow band (1ºC) TLC calibration result

It should be noted that the calibrations described above are being used to determine the suitability of wide−band TLCs for accurate temperature measurement rather than as definitive calibrations of given TLCs. Camci et al., (1991) discuss the effect of viewing angle and illumination on TLC calibration, and TLCs used in a particular experiment should be calibrated in situ. The illumination, position and settings of the camera, video−recorder settings, and image−processing technique should not be changed between the calibration and actual experiments.

5.0 Conclusions and future work

Initial tests with the hue method and image−processing techniques have shown that there is considerable potential for the use of wide−band crystals for surface temperature measurments. The next step is to evaluate the uncertainty in the experimental and analytical techniques on a stationary rig, and then these techniques will be applied to rotating−disc rigs.

TLC techniques are often used in transient heat transfer experiments in which, for example, a model made from acrylic or polycarbonate is suddenly exposed to a hot gas. Under suitable conditions, it is possible to use analytical solutions of Fourier’s 1D conduction equation to evaluate the heat transfer coefficient, h. The so−called semi−infinite−solid model is often used to provide an analytical solution for the case of a step−change in fluid temperature; for "slow transients", in which a more gradual change of fluid temperature occurs, Duhamel’s theorem (see, for example, Schneider (1955)) can be used for Fourier's equation, or Fourier's equation can be solved numerically. For a step−change, it is necessary to know the final temperature of the fluid, the initial temperature of the solid, and the surface temperature at one subsequent time: a narrow−band TLC provides the single surface temperature. For "slow transients", it is necessary to know the variation of surface temperature with time for the duration of the experiment: a wide−band crystal provides this surface temperature but it is still necessary to measure the fluid temperature.

The semi−infinite−solid model is ideally suited to materials of low thermal conductivity or, more correctly, to heat transfer with large Biot numbers. By contrast, the so−called lumped−capacitance model, in which the solid is assumed to have a uniform temperature, is suited to materials of high conductivity or small Biot numbers. Consider, for example, a copper block suddenly exposed to a hot fluid. The temperature of the block approaches that of the fluid exponentially, the time constant being proportional to the thickness of the block and inversely proportional to h. In the limiting case where the thickness tends to zero, a thin copper foil will reach the fluid temperature very rapidly. It is, therefore, possible to design a simple device in which the surface temperature of a foil attached to an insulating substrate is used to measure the fluid temperature. By coating one surface of the foil with wide−band crystals, the variation of fluid temperature with time can be measured remotely. If, in addition, a second (thick) copper block is embedded in the substrate, it is possible to determine h.

The above techniques will be used for a rotating−disc rig made from transparent polycarbonate. Under conditions of practical importance, it is not feasible to create a step−change in the air temperature, and wide−band crystals will be used to determine the temperature of both the air and the disc surface. A video−recording, made using stroboscopic lighting, will then be analysed as outlined above.

Acknowledgements

The authors wish to thank SERC and MOD for providing the funds to support this research programme.

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