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Quantitative measurements in thermo-fluid dynamics based on colour processing

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ABSTRACT

Colour can be expressed as a weighted combination of three attributes: hue, intensity, and saturation. Non-coherent light reflected by thermo-sensitive liquid crystals holds a variable hue, moving in a generally narrow temperature interval and also depending on its inclination with respect to the plane of the crystals and on the characteristics of the impinging light. In experimental practice it is not feasible to ensure uniform lighting over an extensive area and its entire view under the same angle. Thus, the acquired hue field is non-uniform even if the liquid crystal sheet is isothermal. However, by means of proper filtering and calibration of the colour attribute, this optical technique, besides being non-intrusive and inexpensive, is capable of mapping the temperature with an accuracy better than 5% of its measuring-range amplitude. A similar method can be applied for measuring the thickness of a thin liquid film. In this case, the colour attribute to be processed is its intensity. In fact, the light transmitted through a dyed liquid decreases with an increasing thickness of the layer. Again, a perfectly uniform light source is unattainable and the recorded intensity field is non-homogeneous even if the liquid free surface is flat. Nevertheless, the film thickness can be determined by this colour-processing procedure with an accuracy better than 8% of the measuring-range amplitude, which is dictated by the utilised dyestuff concentration. Further thermo-fluid dynamic measurements performed over extensive areas could be handled with analogous methodologies. Surface temperature by emitted infrared waves and void fraction in ducts by light absorption are particular examples.

1. Introduction

In experiments involving complex geometry or fluid dynamics, where high gradients of the physical variables to be measured are present, techniques capable of mapping the entire measurement surface are needed. Traditional sensors, besides monitoring only a discrete number of sites, generally disturb the physical phenomenon, due to the presence of the instrument probes. It is then convenient to develop non-intrusive measurement techniques such as optical methods. Other favourable characteristics to be sought for in a technique are simplicity, reliability, and low cost.

Two very useful fields to be quantitatively determined in experiments in thermo-fluid dynamics are the local temperature of a heat transfer surface and the local thickness of a thin liquid film. Both measurements can be performed by similar optical techniques, based on colour processing. In particular, temperature can be mapped over an extensive area by means of thermochromic liquid crystals (TLCs), whereas film thickness can be evaluated by measuring the attenuation of the intensity of light passing through the layer of dyed liquid.

Every colour is a weighted combination of the three primary colours: red, green, and blue (*RGB*). However, it is convenient to express it by means of another set of three attributes, namely: hue (also called chromaticity or tonality), saturation, and intensity (*HSI*). Most colour sensors, including colour photo and video cameras, employ the *RGB* format. Nonetheless, the *HSI* model is more appropriate for electronic image processing and analysis [1–3]. The following relationships show how to perform the conversion from the *RGB* to the *HSI* colour space [4]:

$$\begin{cases} H = \dfrac{1}{2\pi}\cos^{-1}\left[\dfrac{R-(G/2)-(B/2)}{\sqrt{(R-G)^2+(R-B)(G-B)}}\right] \\ S = 1-\dfrac{3\min(R,G,B)}{R+G+B} \\ I = \dfrac{R+G+B}{3} \end{cases} \quad H,S,I,R,G,B \in [0,1] \tag{1}$$

where min( ) is the minimum function and the inverse cosine has to be interpreted as between 0 and π radians if $B<G$ and between

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Nomenclature

B	normalised blue intensity (between 0 and 1)
C	dyestuff-to-water concentration in mass
D	distance in pixels
G	normalised green intensity (between 0 and 1)
H	normalised hue (between 0 and 1)
I	normalised intensity (between 0 and 1)
L	channel width (m)
M	calibration-grid element side in pixels
N	filtering-square side (or kernel size) in pixels
Q	falling-film mass flow rate (kg s^{-1})
R	normalised red intensity (between 0 and 1)
Re	falling-film Reynolds number, defined in Eq. (3)
s	liquid film thickness (m)
$\langle s \rangle$	mean s on the channel width (m)
S	normalised saturation (between 0 and 1)
T	temperature (K)
$\langle w \rangle$	mean falling-film velocity on a channel cross-section (m s^{-1})
μ	liquid dynamic viscosity (Pa s)
ρ	liquid density (kg m^{-3})

π and 2π radians if $B > G$. All the colour attributes are normalised between 0 and 1, independently of their resolution or number of bits of the digital image.

Among several colour models, the *HSI* space is the one that best resembles the colour-sensing properties of human vision. Intensity is related to the luminous flux (measurable in lumens) perceived by the human eye observing light from a particular direction. Hue and saturation are also related to the way in which human beings perceive colour. Specifically, saturation indicates the colour purity, or the degree by which the colour is undiluted by grey, and hue is a function of the spectral composition of the luminous radiation [5].

Among the new attributes, the hue field displayed by TLCs can be re-expressed as a local temperature field and the intensity field of the light transmitted through a liquid film can be correlated with its local thickness; these are shown in Sections 2 and 3, respectively.

2. Liquid crystal thermography

2.1. Properties of thermo-sensitive liquid crystals

Thermochromic liquid crystals have the valuable property of exhibiting a selective reflectance of non-coherent light as a function of their temperature. The internal structure of the crystals changes with temperature over a known reproducible range [6]. Consequently, the wavelength of the reflected light is varied and the liquid crystals assume the corresponding colour pattern. The reflected light belongs to the visible spectrum in the temperature range named colour-play interval, whose centre is called the nominal event temperature. This interval is generally narrow, with colours shifting from the red to the blue tonality in a range of only a few centigrade degrees. However, the width of the colour-play interval, as well as the nominal event temperature, can be adjusted by altering the liquid crystal composition.

The liquid crystal compounds are generally encapsulated in thin adhesive sheets, directly attachable to the surface under test. In this way, they are protected from chemical contamination, ultraviolet light, and mechanical stresses, which could harm them [7].

The reflected image displaying the colour pattern can be acquired by a digital camera and then be processed by a computer. The accuracy of the correlation between the hue and the temperature fields depends particularly on the calibration procedure performed. Since angle of view and lighting conditions, including possible shadows and reflections, can have a significant influence on the recorded chromaticity at a given temperature [6], care must be taken in running the experiments in the very same conditions that were fixed during calibration.

2.2. Image-processing procedure

Frequently, in experiments, a visibility access from the side opposite to the monitored heat transfer surface is impracticable. Then, the liquid crystals have to be viewed non-orthogonally and the image acquired by a camera is trapezoidal, owing to the distortion of perspective. For instance, Fig. 1 is a photograph of an isothermal liquid crystal sheet ($113 \times 109\,mm^2$) taken by a Nikon E995 digital photo camera positioned at a distance of about 52 mm from the centre of the sheet and at 40° inclination. Hence, the first step of the image-processing procedure is the anti-projection of the trapezoid into a rectangle, as illustrated in Fig. 2.

Fig. 1. Typical image under perspective (40° inclination).

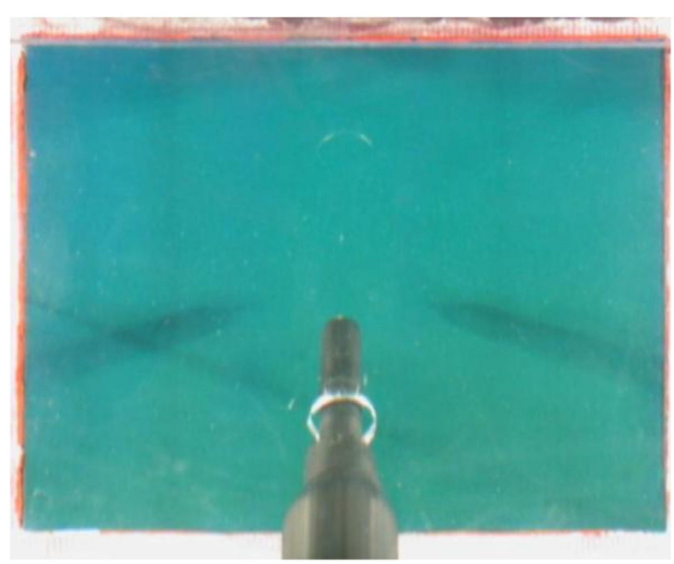

Fig. 2. Anti-projection of the image in Fig. 1.