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Use of Liquid Crystals as Temperature Sensors in Food Processing Research

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ABSTRACT

Liquid crystal is a chemical compound which changes its color with temperature. It is useful in non-intrusively visualizing instantaneous surface temperature changes, where other conventional temperature sensors cannot be used. The thermal field visualization can either be (a) qualitative, by observing the pattern of color change, or (b) quantitative by calibrating it with a thermocouple at a known temperature range. The material is available in the temperature range of −30°C to 115°C. The minimum and average error values associated with the temperature measurement are 0·01°C and 0·5°C, respectively.

NOTATION

A	Surface area (m^2)
$f_n(\lambda)$	Transmittance function
h, h_{fp}	Surface heat transfer coefficient (W/m^2 °C)
H	Hue value of liquid crystal color measured using image analysis interface
I	Intensity of light (J/m^2)
Q	Convective heat gained (lost) by the test specimen (J)

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$S(\lambda:T)$ Spectral distribution function
T Temperature (°C)
T_s Surface temperature of the specimen (°C)
T_f Fluid temperature measured by a thermocouple (°C)

λ Wavelength (m)

INTRODUCTION

Recently there has been widespread food industry interest in technologies such as aseptic processing and ohmic heating. Before these technologies can be routinely approved by the Food and Drug Administration (FDA) for commercial processing of particulates, it is necessary (among other things) to understand the heat transfer mechanism between liquid and solid. It is not possible to determine the temperatures of flowing solid particles using conventional sensors such as thermocouples. One promising alternative is the use of thermochromic liquid crystals, which change color with temperature. The objectives of this paper are to review the application of liquid crystals in heat transfer studies and to discuss potential applications in food processing research.

Background

Liquid crystal is a chemical compound which changes its color in response to surface temperature changes as a consequence of a molecular structure rearrangement. It shows color by selectively reflecting incident white light. Upon heating, most liquid crystal materials turn from colorless to red at the low end of their temperature range, and pass through the other colors of the visible spectrum before turning colorless again at higher temperatures. Red, green and blue are some of the dominant colors observed during this process. These color changes are reversible upon cooling; hence the measurements do not represent thermal history, but rather, genuine instantaneous temperatures. By calibrating the color–temperature responses of the liquid crystal material against a standard temperature sensor, it is possible to determine the temperature of a liquid crystal coated surface. A typical form of the wavelength–temperature response of a liquid crystal is shown in Fig. 1.

The properties of liquid crystal materials were first studied by an Austrian botanist, Friedrich Reinitzer in 1888. However, only after the 1970s did researchers accept liquid crystal color change as a valid temperature measurement technique. Some of the main advantages of liquid crystal are (Moffat, 1990):

(1) Measurements are rapid and the pattern is reversible.
(2) It is a convenient technique to visualize the complex temperature distribution over surfaces where other surface temperature sensors such as thermocouples or infrared thermography cannot be used.
(3) The technique provides satisfactory accuracy and resolution, provided calibration is accurate.

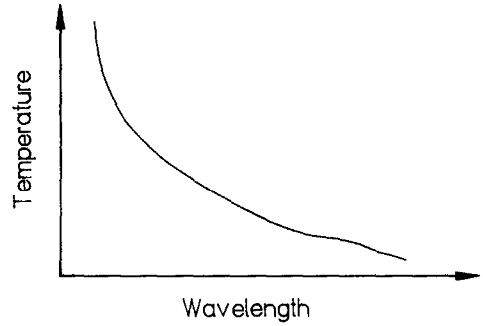

Fig. 1. Typical wavelength–temperature response of liquid crystal material.

(4) An entire temperature field may be mapped, instead of a single point measurement, as with thermocouples.

Some of the disadvantages are:

(1) Transparent test materials are necessary to see the color changes.
(2) Extracting quantitative information can be labor intensive, although this could be by-passed using more expensive equipment.
(3) The observed color varies with viewing and illumination angles; thus careful control is necessary.
(4) The heat generated by the light source may cause an increase in liquid crystal temperature; thus it is important to select light sources with minimal heating effects.

Availability

Depending on molecular structure arrangement, liquid crystal can be broadly classified into one of three categories: smectic, nematic or cholesteric. Both cholesteric and nematic materials are useful in thermal field visualization studies. Pure liquid crystal exhibits brilliant colors, but deteriorates rapidly with time, being susceptible to ultraviolet rays and atmospheric contaminants. The color change is also strongly influenced by viewing angle. Many of these problems have been eliminated or reduced by encapsulation of liquid crystal material in spherical capsule form.

Properties

The response of liquid crystal to temperature change is nearly instantaneous. The time constant was found to be in the range of 0·01–0·03 s (Parker, 1971). Certain restrictions apply to their use. For example, the heat capacity of the object of temperature measurement should be larger than that of the liquid crystal layer. The rate of temperature change of the test surface must be such that a significant temperature change does not occur within one time constant, so that the instantaneous color represents an accurate temperature. The temperature variation in the test specimen should lie within the temperature range of the liquid crystal (Meier *et al.*, 1975).

The liquid crystal display is influenced by the camera viewing angle and the angle of incidence of the light. Hence, it is advisable to keep the camera viewing angle normal to the test surface and the incident light within a 45° angle. If the lighting conditions change, the color spectrum may be shifted to an artificially high value. For example, instead of green, one may record a blue color and hence erroneously over-predict temperature. Proper care must be taken to maintain the same type of lighting conditions during both calibration and actual experimental runs.

Commercially available liquid crystal materials are generally custom formulated and their properties may vary. Accordingly, it is advisable to determine the relevant properties prior to use. For surface heat transfer studies, the thermal resistance of the liquid crystal composite should be measured, and appropriate corrections need to be made as necessary. Table 1 summarizes some of the common properties of liquid crystal. Further information is available elsewhere (Fergason, 1964; Meier *et al.*, 1975).

EXPERIMENTAL TECHNIQUES

Theory

The heat transfer coefficient can be measured using an energy balance on the wall surface. The heat transferred through the surface is equal to the rate of change of its internal energy:

$$Q = hA(T_s - T_f) \tag{1}$$

Thus, if the heat convected by the surface (Q) is known, the heat transfer coefficient (h) can be calculated.

Coating

Encapsulated liquid crystals are commercially available either in the form of an aqueous slurry or sheet with user-specified temperature bandwidth. If the

TABLE 1
Properties of Commonly Available Liquid Crystal (Slurry) Material

Property	*Value*	*Reference (if not measured)*
Temperature range	−30°C to 115°C	Parsley (1987)
Time constant	0·036 s	Parker (1971)
Specific gravity	1·02	Moffat (1990)
Specific heat*	2·301 kJ/kg °C	
Thermal conductivity*	0·626 W/m °C	
Shelf life	Normally 6 months	Parsley (1987)
Calibration error	±0·01°C at best with an average ±0·5°C	Moffat (1990)

*Specific heat by differential scanning calorimetry, and thermal conductivity using the modified Fitch apparatus (Zuritz *et al.*, 1989).

slurry is used, the surface must be precoated with a black paint to absorb light transmitted through the liquid crystal layer. Then the slurry can be applied over the black coated surface by either dipping into solution, brush, air brush, or screen printing. The final coated surface should be smooth and free of debris to avoid scattering of light at rough surfaces. A coating thickness of the order of 0·1–0·05 mm or less is desirable (Moffat, 1990). Improper coating will result in milkiness and should be avoided. Since the slurry deteriorates with time, refrigerated (but not frozen) storage is recommended for long shelf life. Slurries are necessary when the surfaces of interest are curved and sheets cannot be used (e.g. spheres).

Liquid crystals in sheet form are precoated with an adhesive blackened substrate and are covered by a transparent mylar layer. The sheet can be cut into desired sizes and pasted over the surface. The schematic of the composite is presented in Fig. 2. In general, sheets are easier to use on plane surfaces and provide more intense colors than slurries.

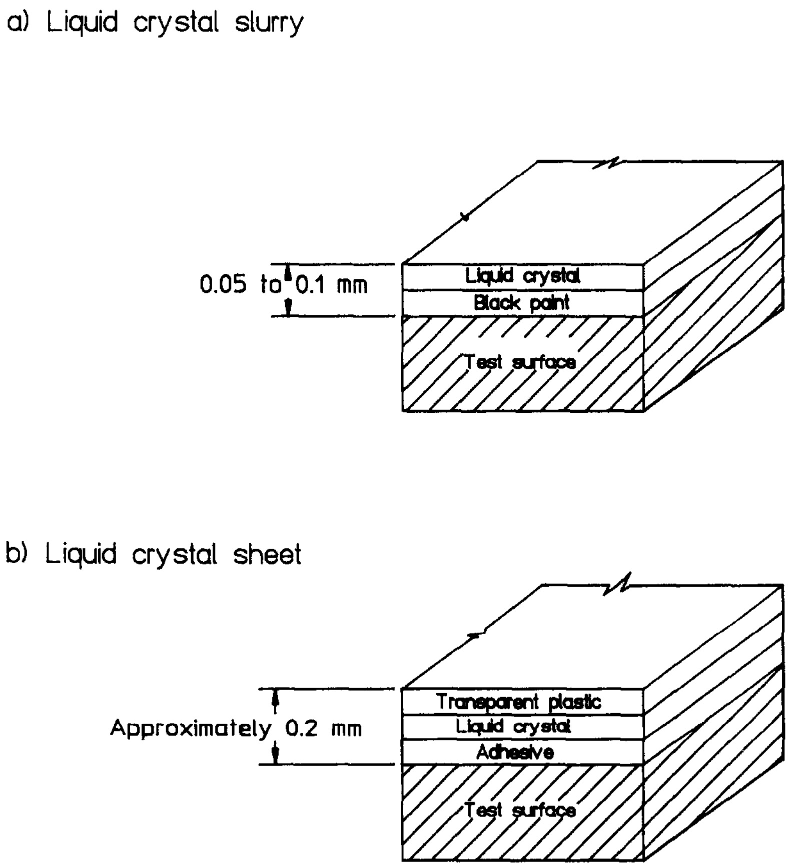

Fig. 2. Schematic diagram of liquid crystal composite.

Calibration

Calibration is most important, since it determines accuracy. It is accomplished by correlating color changes against the temperature as indicated by a standard thermal sensor such as a precision thermometer, thermistor or thermocouple. The color changes can be measured either by using human eye judgement or by using an image analysis system.

Eye judgement. Many researchers (Baughn *et al*., 1986; Cooper *et al*., 1975; Goldstein & Timmers, 1982; Hippensteele *et al*., 1985) used a single color/temperature combination for calibration. Generally a predominantly visible color display (e.g. onset of red, green and blue) was selected to aid in eye judgement. The liquid crystal was introduced into a constant temperature bath (e.g. Cooper *et al*., 1975). The advancement of a selected color over the surface and the corresponding temperature were noted. Human eye judgement was used to determine advancement of color and selected instants were photographed for future reference. Baughn *et al*. (1986) used the green isotherm, corresponding to a temperature of 41·75°C as a calibration color. Hippensteele *et al*. (1985) used the onset of yellow as a calibration color against a precision resistance digital thermometer. Since color measurement by this method is subjective, the calibration and actual experiments need to be performed by the same person (even so, variations may occur). Thus, color changes should be evaluated against pre-determined color values. Stoforos and Merson (1991) used selected colors from the Munsell® scale (red 7·5R 3/8; green 7·5GY 5/10; blue 7·5B 2/6; violet 2·5PB 2·6; black 10Y 2/2) (Munsell, 1976) as standards for calibration, thereby reducing subjectivity to some extent. Nevertheless, the accuracy of quantitative temperature measurement using human eye judgement is questionable, as errors may be caused by the researcher's temporal inconsistency, thus the results may not be reproducible.

Image analysis. A more reliable approach for quantitative measurement is image analysis. Some of the early researchers in this field have been Akino *et al*. (1989) and Moffat (1990). In our studies (Balasubramaniam & Sastry, 1994), we employed a similar image analysis system, a schematic diagram of which is shown in Fig. 3. After videotaping the color changes of the liquid crystal coated specimen, the videotape was played in still mode at selected instants. The still image of the VCR was fed through a red–green–blue (RGB) decoder to a personal computer. An impage analysis software (Image-Pro, Media Cybernetics, Silver Spring, MD, USA) was used to measure the color change values (defined by hue value using the hue-saturation-intensity, or HSI model).

The procedure involves two steps, calibration and experimentation. In the calibration runs, temperatures of liquid crystal-coated particles were measured by thermocouples embedded in the surface of the test specimen. Then the color–temperature response of the liquid crystal (Fig. 4) was regressed to obtain a calibration equation:

$$T=a+bH+cH^2 \tag{2}$$

where a, b and c are the coefficients obtained from regression. This empirical equation is valid only for a particular set of experimental

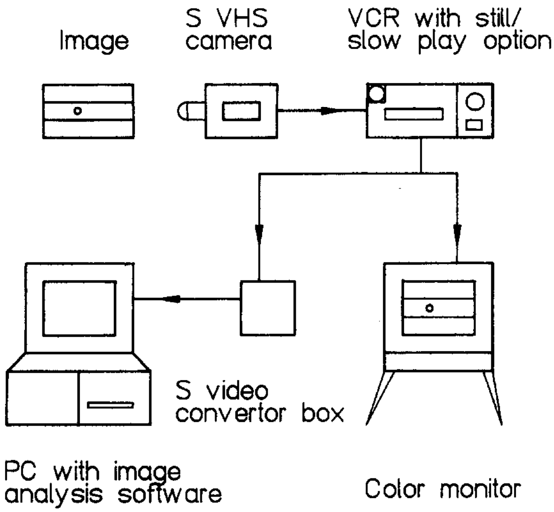

Fig. 3. Schematic diagram illustrating the image analysis interface used to measure liquid crystal hue values.

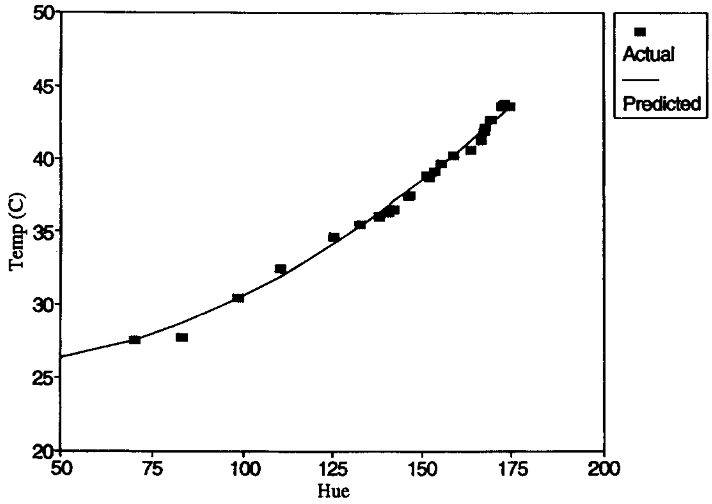

Fig. 4. Sample calibration curve for liquid crystal material against a thermocouple.

conditions and temperature range of the liquid crystal. Extrapolation of color–temperature data may produce erroneous results.

The analysis of images may be conducted in various ways, either by use of optical filters and a black and white camera, or directly from a color camera. Akino *et al.* (1989) used optical filters and an image analysis interface for measuring color changes, using the principle that the light intensity of the liquid crystal layer depends upon the temperature of the specimen and the filter used in the camera. They used a set of 18 interferential band-pass filters in their study. A black and white CCD (charge coupled device) camera with filter mounted in front of the camera lens was used to record the images. The intensity $I_n(T)$ of light filtered by the nth pass band filter is given by eqn (3):

$$I_n(T) = \int_0^{\infty} S(\lambda : T) f_n(\lambda)\ d\lambda \tag{3}$$

As indicated by the above relation, the light intensity depends on both the temperature and the filter. When the liquid crystal layer was observed through one band-pass filter during its heating (cooling), the intensity became maximum around a temperature at which the peak wavelength of the light from the liquid crystal layer coincided with the maximum wavelength of transmittance of the band-pass filter. By using different filters, the peak intensity temperature of each filter could be determined. Using these data, a color–temperature relation (similar to Fig. 1) was obtained. The authors used the above method to study the temperature distribution of a heated plate disturbed by a cylinder under steady state conditions. A pseudocolor image processing technique was used to map the heat transfer coefficients. The heat transfer coefficient values so determined were in agreement with previously published results. This approach necessitates considerable time and effort to determine the wavelength–intensity relation (and hence the wavelength–temperature relation) for the optical filters and in image processing of the recorded color changes. Hence, the approach may be useful only under steady state conditions, where time is not an issue. Unfortunately, most food processing applications require rapid transient measurements, thus this method may not be suitable.

Experimentation

The liquid crystal is applied over the specimen over which the spatial temperature distribution needs to be mapped. Color changes are videotaped and measured using the image analysis software. The temperature of the unknown specimen can be determined from the hue value at selected instants of time, using eqn (2). Heat transfer coefficients (h) can then be calculated from the temperature history. Since color measurements are optical properties, experimental conditions should be identical to those of calibration. The accuracy of temperature predictions using eqn (2) is limited by the resolution capabilities of the imaging and the quality of video pictures. Since liquid crystal deteriorates gradually over time, frequent *in situ* calibration before experiments is recommended. Detailed analyses of surface temperature field distributions is possible but requires considerable manual labor.

APPLICATION OF LIQUID CRYSTAL

Engineering applications

Many applications of liquid crystals have focused on obtaining qualitative and quantitative heat transfer information on heated surfaces in forced convection environments. Some researchers (e.g. Cooper *et al.*, 1975; Davies *et al.*, 1986) have found that liquid crystal data were in agreement with previously published results indicating the validity of the technique. Some interesting applications in engineering research include the following:

(1) Mapping of convective heat transfer coefficients (Cooper & Petrovic, 1974; Cooper *et al.*, 1975; Hippensteele *et al.*, 1981; Simonich & Moffat, 1982; Hippensteele & Russell, 1988, Jones & Hippensteele, 1988).
(2) Heat transfer in fully developed flow in ducts and tubes (Davies *et al.*, 1986).
(3) Overheating in electronic components (Dowden, 1967; Davis, 1967).
(4) Microwave field intensity detection (Magura, 1970, cited by Meier *et al.*, 1975).
(5) Study of effectiveness of wind shield heater (Champa, 1972).
(6) Transition of boundary layer over a flat plate (McElderry, 1970).
(7) Flow blockages in heat exchangers (Woodmansee, 1968).

Applications in food processing research

Thermal processing of particulates. One promising application is in non-invasive measurement of the liquid to particle heat transfer coefficient (h_{fp}) in flow situations commonly encountered in the thermal processing of particulates. Stoforos and Merson (1991) reported h_{fp} values for spherical particles in axially rotating cylindrical vessels using liquid crystals. The Munsell® color chart (Munsell, 1976) was used in calibration. An h_{fp} value of 2326 W/m^2 °C was reported for a 1·27 cm diameter teflon particle processed at 102·2 rpm with deionized water. Balasubramaniam and Sastry (1994) indicated that the order of magnitude of liquid to particle heat transfer coefficient values obtained in hold tubes using the liquid crystal method, compared moderately well with other techniques used under similar conditions (Table 2). The principal reasons for divergence from other methods was that the liquid crystal method was the only truly non-invasive heat transfer based technique. The other techniques included a moving thermocouple approach which shows lower h_{fp} values due to restriction in

TABLE 2
Sample Values of h_{fp} in 0·0508 m Diameter Hold Tube Flow Using Different Experimental Techniques (temperature range 20–45°C)*

Fluid CMC concentration (%)	*Particle diameter (m)*	*Flow rate (m^3/s)*	*h_{fp} (W/m^2 °C)*†		
			MT	*RV*	*LC*
0·2	0·0128	0·00041	1193	1229	1316
0·5	0·0159	0·000315	750	878	1358
0·8	0·0223	0·000315	701	729	1085

*From Balasubramanian and Sastry (1994).
†Means of three replications.
MT, moving thermocouple method; RV, relative velocity method; LC, liquid crystal method.

particle rotation, and a relative velocity measurement approach which calculates h_{fp} from a measured translational relative velocity, but ignores the rotational contribution of relative velocity to h_{fp}. The minimum and maximum values of h_{fp} reported were 363 and 2010 W/m^2 °C, respectively, under the conditions of study. Liquid crystals were useful in determining h_{fp} values in continuous flow through scraped surface heat exchangers, conditions under which the usefulness of conventional sensors such as thermocouples were restricted by the system and flow conditions.

Ohmic and microwave heating. Liquid crystal is unaffected by the presence of electric fields commonly employed by the industry. Only at higher voltages (of the order of thousands), will the field influence the properties of liquid crystal (Parsley, 1992). Hence, it is helpful in visualizing the thermal field of ohmically heated surfaces. The thermal imaging of particulates will be useful in understanding local heating phenomena at the liquid–solid interface (Sastry & Palaniappan, 1992). It may also be worthwhile investigating the application of liquid crystal methods in microwave fields (this has been done in industry).

Other applications. Liquid crystals are useful in visualizing temperature fields within transparent aqueous-based media, which tend to be opaque to infrared thermography. Thermal design of industrial heat exchange surfaces could be facilitated, since vivid and detailed mapping of spatial temperature variation may be obtained. Other applications include studying the thawing phenomenon in frozen products, and free convection current patterns during thermal processing of canned foods.

Limitations

One of the main limitations of liquid crystals in food processing research is the necessity of transparent media between camera and surface, so that color changes may be seen. Thus, applications are restricted to model transparent food systems. An additional limitation is temperature, since liquid crystal is available only in the temperature range of −30°C to 115°C; they cannot be used at higher process temperatures employed by the industry. However, if other techniques which are not subject to the same limitations are found comparable to this approach, then it is possible to use liquid crystals as a means of validation of other techniques. Under conditions where conservative prediction is desirable, liquid crystals can be used by making the model test fluid more viscous than under commercial practice, and using test flow rates that are lower than commercial conditions.

CONCLUSIONS

Thermochromic liquid crystals show promise in developing further understanding of industrially significant heat transfer problems due to their ability to provide continuous and quantitative information about convective heat transfer coefficients for a variety of geometries and flow conditions. The convective heat transfer values obtained using this technique by various researchers have been found in agreement with those obtained using other techniques.

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