Lecture 35: Introduction to liquid crystal thermography

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Introduction

Liquid crystal thermography is a convenient technique that can provide temperature distribution over the entire test surface. It can be configured to yield the heat flux variation as well. Since the liquid crystals employed have a reasonable temporal response, temperature and heat flux variations can be measured, in many contexts, as a function of time. Since the response to changes in temperature originates from laser-matter interaction, LCT is also classified as a light scattering technique. Traditional techniques employing sensors such as thermocouples and resistance thermometers can measure temperature at individual locations. Hence, a large number of sensors are required for complete mapping of the surface. Since physical sensors occupy space, the measurements are to be interpreted as spatial averages. This route may prove to be disadvantageous in regions of localized peaks and valleys of heat transfer. Liquid crystal thermography proves to be useful under these circumstances.

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Liquid crystals have been extensively used in recent years for studies related to fluid mechanics and thermal engineering. They can be used to identify the hot spots in high power density electronic components such as processors in high performance computing.
Other applications include

- ergonomic studies and
- medical thermograph.

The latter is a diagnosis technique known since the Greek civilization. Physicians would apply thin mud slurry on to areas of the bodies of patients. The pattern of drying and determines the abnormal distribution of heat release. For example, if there is damage in the nervous system, a temperature variation is observed around the injured nerve. Similarly, temperature patterns over the skin provide information related to arthritis and breast cancer. LCT uses encapsulated liquid crystal material and may be employed as temperature sensing layers on surfaces or microspheres suspended within liquids. Independently, liquid crystals may also be used to measure shear stress over surfaces exposed to a flowing fluid.

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Liquid Crystals

Liquid crystal is a unique organic material which exists between the solid and the isotropic liquid phase. In the context of temperature measurement, the material is in the amorphous solid phase below a certain temperature and a pure liquid beyond an upper limit. In between these temperature limits, it shows a certain molecular structure that resembles the crystalline state. Here, the incident light is scattered selectively and forms the basis of temperature measurement.

Liquid crystals possess a helical structure with a characteristic pitch. The pitch length of the helix is in the range of the wavelength of visible light. The pitch length changes with an external stimulus such as temperature. In a second family of liquid crystals, the molecular structure responds to the applied shear stress. The fundamental chemical structure is unaffected by the external stimulus and a liquid crystal coating can respond repeatedly to the physical change and can be used reliably as a temperature sensor. Since the technique involves using a (white) light source for illumination and a detector for recording the scattered light, LCT classifies as an optical technique.

There are two families of liquid crystal materials that have helical structures and are referred to as chiral-nematic and cholesteric. The molecular ordering here are quite distinct and change under the influence of electromagnetic fields, shear stress, pressure and temperature. Cholesteric crystals are suited for temperature measurement. Both the extent of the temperature range and its location in the temperature scale can be controlled by selecting the appropriate cholestric esters and their proportions in a given formulation. Liquid crystals are presently available for a temperature spectrum ranging from a few degrees below zero to several hundred degrees Celsius. A mixture can be obtained with event temperature spans as small as 1^{o} C to as large as 50^{o}C. Owing to their color changes with temperature, the cholestric liquid crystals are also called thermochromic liquid crystals (TLCs).

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The properties of temperature sensitive liquid crystals are reported in terms of the event temperature and the clearing point temperature. The lowest temperature where liquid crystals scatter visible light is called the event temperature. At a temperature below the event temperature, liquid crystals will be in the solid state and will appear transparent. At a temperature above the clearing point temperature, it will enter the pure liquid state and will revert back to being transparent. Outside this range, the scattered light is negligible and, when viewed through a camera, the sheet would appear black. At the clearing point temperature, the helical pitch of the liquid crystals exceeds the wavelengths of visible light. The reflected color spectrum of liquid crystals will vary continuously from the longer wavelengths (red) corresponding to event temperature to shorter wavelengths (blue) corresponding to the clearing point temperature. At intermediate temperatures, the surface would take on a green color. Liquid crystals transmit a significant amount of the incident light with virtually no modification. Therefore, they are viewed against a non-reflecting (black) background. This precaution prevents the transmitted light from getting reflected without adversely affecting the interpretation of selectively scattered light from the liquid crystals.

The repeatability and thermal performance of liquid crystals degrade rapidly due to chemical contamination and exposure to ultra-violet radiation. Therefore, a manufacturing process known as micro-encapsulation is used to protect the raw liquid crystal material. Micro-encapsulation is a chemical process that takes raw liquid crystal material and encases it in protective capsules, 5-10 micron diameter. The micro-encapsulation process offers chemical contaminant resistance and radiation protection. Moreover, encapsulated TLCs have been found to be insensitive towards pressure while they were tested up to 133 bar. On the other hand, special care is required to avoid problems associated with over-attenuation of the reflected light coming from the liquid crystal and regeneration of the binder and microcapsules.

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A color/temperature designator describes the response of a typical liquid crystal chemical make up. This helps in selecting the liquid crystal composition for a particular application. For example, R35C5W designates a formulation which signifies that the event temperature of the liquid crystal (where it turns red) is 35^{o}C. The blue start temperature is 5^{o}C above the red start temperature. This provides an estimate of the bandwidth of liquid crystals as 35-40^{o}C.

The liquid crystals can be either

- narrow band or
- *wide band* formulation.

The narrow band formulations have bandwidths below 1 or 2^{o}C while wide-band formulations have bandwidths between 5 and 30^{o}C. Micro-encapsulated liquid crystals are commercially available in prefabricated adhesive sheets, sprayable slurries, and in water-resistant micro capsules. Prefabricated LC sheets, which include a black backing material and a protective clear polyester layer for the LCs are most commonly employed. The primary disadvantage of prefabricated sheets is that they have slower temporal response characteristics and increased thermal contact resistance compared with the sprayed liquid crystal. Still, it has been widely in use due to its ease of application. It is worth noting that thin plastic sheets pre-coated with liquid crystals are not only user-friendly, but often exhibit a very clear color display. The typical wide bandwidth encapsulated TLC sheet (Hallcrest, R35C5W) will be of polyester (Mylar), 125 µm thick coated with black paint and an adhesive layer. The total thickness of the sheet is 200 µm.

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Resolution

The highest spatial resolution achievable with liquid crystal thermography is limited by the type of liquid crystal formulation and resolving capacity of the optical system (namely, camera and lenses). A camera with a pixel array of 1024 × 1024 sensors viewing a 50 × 50 mm^2 surface would be able to record scattered light intensities from a single pixel whose size is approximately 50 × 50 μm^2 .
The encapsulated liquid crystal itself would be smaller than this size and presents the lower limit of area where a unique temperature can be assigned. These dimensions are often acceptable in laboratory scale measurements. The accuracy of temperature measurement and the resolution obtainable in an experiment with LCs is directly related to the accuracy and consistency of their color-temperature response. Inconsistency in lighting and viewing arrangements can contribute significantly to measurement errors in liquid crystal thermography.

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The rate at which the optical properties of liquid crystals respond to the changes in the surface temperature is an important parameter for transient experiments. The time taken for any point within the liquid crystal layer to achieve the heated surface temperature is a function of the distance from the surface, the layer thickness and the film diffusivity. Ireland and Jones (1987) measured the response of TLC material and showed that the delay between the time at which the thin aluminum foil reached the steady-state color display temperature and the occurrence of the color display was no more than a few milliseconds (around 3 ms). Moffat (1990) suggested that the molecular reorientation time of LCs after reaching a steady state temperature is of the order of 5-10 ms for chiral nematics and 50-100 ms for cholestrics. Kobayashi (1998) numerically simulated the thermal response of an individual encapsulated particle by considering both the chiral nematic LC core and the gelatin encapsulation properties and calculated the response time to be as much as 150 ms. Given these numbers, it is clear that transients that last a few minutes onwards to a few hours will be comfortably time-resolved by liquid crystal thermography. Special treatment would be required if the characteristic timescales are a few hundred milliseconds or smaller.

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