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REVIEW

Liquid crystal methods for studying turbulent heat transfer

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Liquid crystals that can accurately measure temperature and are relatively stable are now available. There are exciting new opportunities to apply these liquid crystals to the investigation of important and interesting heat transfer/fluid flow problems. Five methods of using narrow-band liquid crystals for the measurement of local heat transfer coefficients are reviewed in this paper. These methods have been developed and used at the University of California, Davis and include the heated-coating method, three variations of the transient method (preheated-wall transient, duct-insertion technique, and shroud-heating technique), and a uniform coating method. Some examples of applications for these methods are described. The examples include cylinders in cross-flow, pin fins, impinging jets, turbine blades, smooth and ribbed square ducts, and spirally fluted ducts.

Keywords: liquid crystals; turbulence; heat transfer

Liquid crystals

A general description of liquid crystals, their physical and chemical properties, and other characteristics (including color and image processing) is given by Kasagi et al. (1989). Only a brief review is given here. Liquid crystals are substances which have the properties of both liquid and solid crystalline states. Although they were first observed more than 100 years ago, studies of liquid crystals were confined to material laboratories until the 1960s, when applications to "science" and engineering began (Fergason 1964).

Liquid crystals are categorized according to their molecular structure into three groups: smectic, nematic, and cholesteric. The molecular ordering is different for these different categories and changes under the influence of electromagnetic fields, shear stress, pressure and temperature. This change in molecular order changes the optical properties. Fergason (1964) notes that the most significant optical characteristic of cholesteric liquid crystals is their color change with temperature. This change is reversible and is the basis for the applications in heat transfer/fluid flow studies described here. Due to their color changes with temperature, the cholesteric liquid crystals are also called thermochromic liquid crystals (TLCs).

Liquid crystals are organic compounds that degrade when exposed to chemical contamination and to ultraviolet UV light. This degradation is reduced by microencapsulation. This process encloses the liquid crystal in polymer spheres which can be as small as a few microns. Microencapsulated TLCs have improved stability, since they are somewhat isolated from atmospheric contamination and UV light. Microencapsules of different liquid crystal formulations can be mixed together to produce coatings and films with multiple color ranges (Parsley 1987).

Commercial microencapsulated TLCs for use as coatings usually come in the form of a water base slurry ready to be applied to a surface. There are many ways to apply this slurry to surfaces including screen printing, brushing, dipping, rolling, and airbrushing. The author has found airbrushing (using an airbrush with a well-controlled pressurized air source) to be an excellent means of obtaining a good coating on both flat and nonflat surfaces. The thickness of the coating must be controlled carefully, since a layer that is too thin produces poor color, while a layer that is too thick results in a milky appearance and slow response. Brilliant colors can be achieved by using a black background (we use a layer of black paint, which is also applied by airbrush).

In experimental heat transfer, one of the most interesting and demanding parts of using liquid crystals is the color/temperature interpretation. This depends on the calibration method and the recording method being used. It also depends on the lighting source and angle of illumination and viewing angle (Kasagi et al. 1989), since the color is from reflected light. If possible, the calibration should be done under the same lighting conditions and at the same angle that will be used in the measurements. For the narrow-band liquid crystals used in the methods described here, the calibration is less sensitive to the illumination and viewing angle. There is also some drift with time, so temperature calibration should be done both prior to and after a measurement.

The author has had good success using a calibrated video system from which an experienced human observer selects a distinguishable color or color transition (e.g., green to yellow). This works especially well with the narrow-band liquid crystals, which are less sensitive to lighting and angles, used in the methods described in this paper. Akino et al. (1989) describe methods for excluding the human color sensation. Moffat (1990) discusses color image processing and describes some applications of TLCs in heat transfer and fluid-flow measurement. Camci et

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al. (1991, 1993) describe a hue-based technique for calibrating TLCs. Wilson et al. (1993) describe image-processing techniques applied to wide-band TLCs. Wang et al. (1995) have described a method for processing TLC video signals from transient heat-transfer experiments.

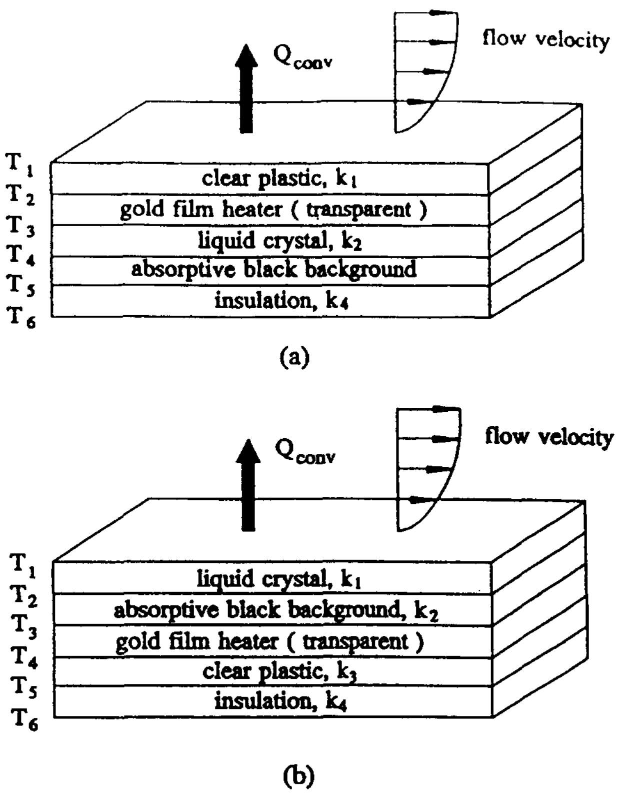

Figure 1 Liquid crystal/heater packaging arrangements; (a) integral heater-internal location; (b) integral heater-surface location (from Baughn et al. 1986)

The time constants for the color changes are not very well known. Ireland and Jones (1986), who have made considerable and significant contributions to the use of liquid crystals in heat transfer studies, report a response time of approximately 3 ms for

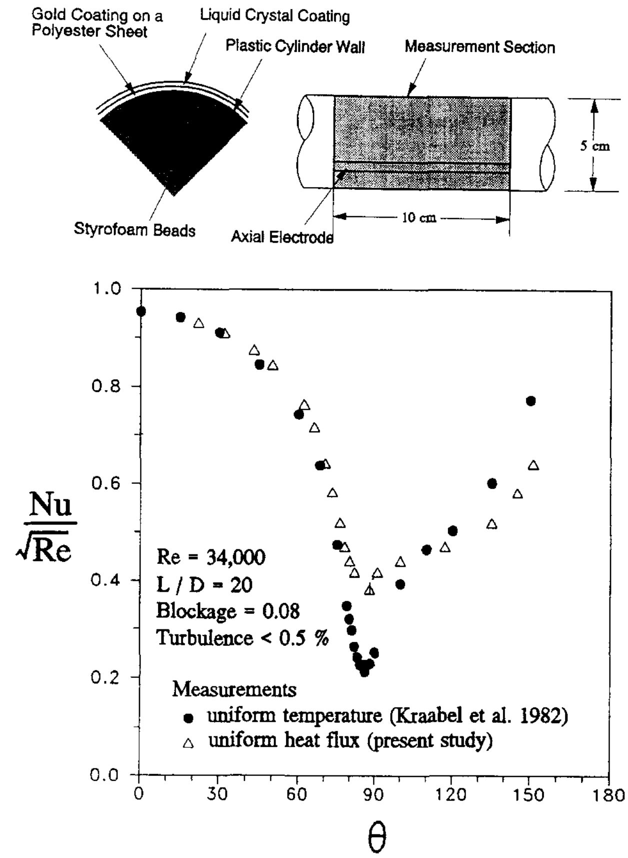

Figure 2 Heated-coating example — cylinder in cross-flow showing the effect of the thermal boundary condition (from Baughn and Saniei 1991)

Notation

A	area of the gold film
bx	turbine blade chord
C_{PW}	specific heat of wall (Plexiglas)
D	diameter of nozzle (or hydraulic diameter of duct)
h	local heat transfer coefficient
I	current across the gold film
k_a	air thermal conductivity
k_c	thermal conductivity of coating
k_w	thermal conductivity of wall
L	jet exit to surface distance
Nu	local Nusselt number, hD/k_a
Nu	circumferential average Nusselt number
q_c	local convective surface heat flux
q_l	conduction loss
R	radial coordinate of surface
Re	Reynolds number (based on D)
R_t	thermal resistance of coating
s	distance from leading edge
T^*	nondimensional surface temperature
T_{aw}	local adiabatic wall temperature
T_{awo}	adiabatic wall temperature at stagnation point
$T_b(x)$	air bulk temperature at x
T_j^*	nondimensional jet temperature
T_{lc}	liquid crystal color temperature
T_r	local recovery temperature
T_w	local wall temperature
T_{wi}	initial wall temperature
T_{wo}	wall temperature at stagnation point
T_∞	ambient air temperature
t	time
V	voltage across the gold film
x	coordinate or axis in flow direction

Greek

γ	variable in Figure 7
δ	coating thickness
ε	surface emissivity
η	effectiveness
θ	angle from stagnation point
ρ	density of Plexiglas
σ	Stefan–Boltzmann constant

materials which have their color play near room temperature. The time response is also discussed by Kasagi et al. (1989).

A more thorough discussion of liquid crystals for heat transfer studies can be found in Kasagi et al. (1989) and in a recent report by Jones (1994).

Some methods for heat transfer measurements

This paper describes five methods for heat transfer measurements, with examples of applications for each. These methods have been used in research by the author and colleagues at the University of California at Davis. Only single-phase experiments are described for some two-phase methods and applications (see Oker and Merte 1981 and Yan et al. 1995). There are, of course, many other methods and important contributions by other researchers which are not described or referenced in the present paper. Each of the methods described here uses the liquid crystal to identify a particular isotherm (a particular color) on the surface at some time or under some condition (as opposed to using different colors to map the surface temperature distribution). When this is done, it is generally desirable to use a narrow-band liquid crystal and a yellow (transition from red–green) color, since it is easily identifiable and provides a relatively low uncertainty in the temperature of the isotherm.

Heated-coating method

The heated-coating method has a long history, and space does not allow a complete review here. It has been described by Baughn et al. (1985, 1986). In the heated-coating method, a very thin conductive coating (vacuum-deposited gold on the surface of a thin polyester sheet in the examples given) is electrically heated. Conduction in the gold, plastic sheet, and insulated substrate is generally quite small (less than 1% of the surface heating) so that the surface boundary condition is very close to that of a uniform heat flux. Several methods for measuring the surface temperature have been used with this method, including thermocouples (Baughn et al. 1985). Hippensteele et al. (1981, 1985, 1987). Simonich and Moffat (1982) and Baughn et al. (1986) have all used liquid crystals to map the surface isotherms. The arrangement may place the liquid crystals behind the plastic sheet and the gold coating (Simonich and Moffat) or directly on the surface (Baughn et al. 1986), as shown in Figure 1. Since the heat flux can be adjusted by changing the electrical voltage on the electrodes, the surface temperatures can be increased or decreased.

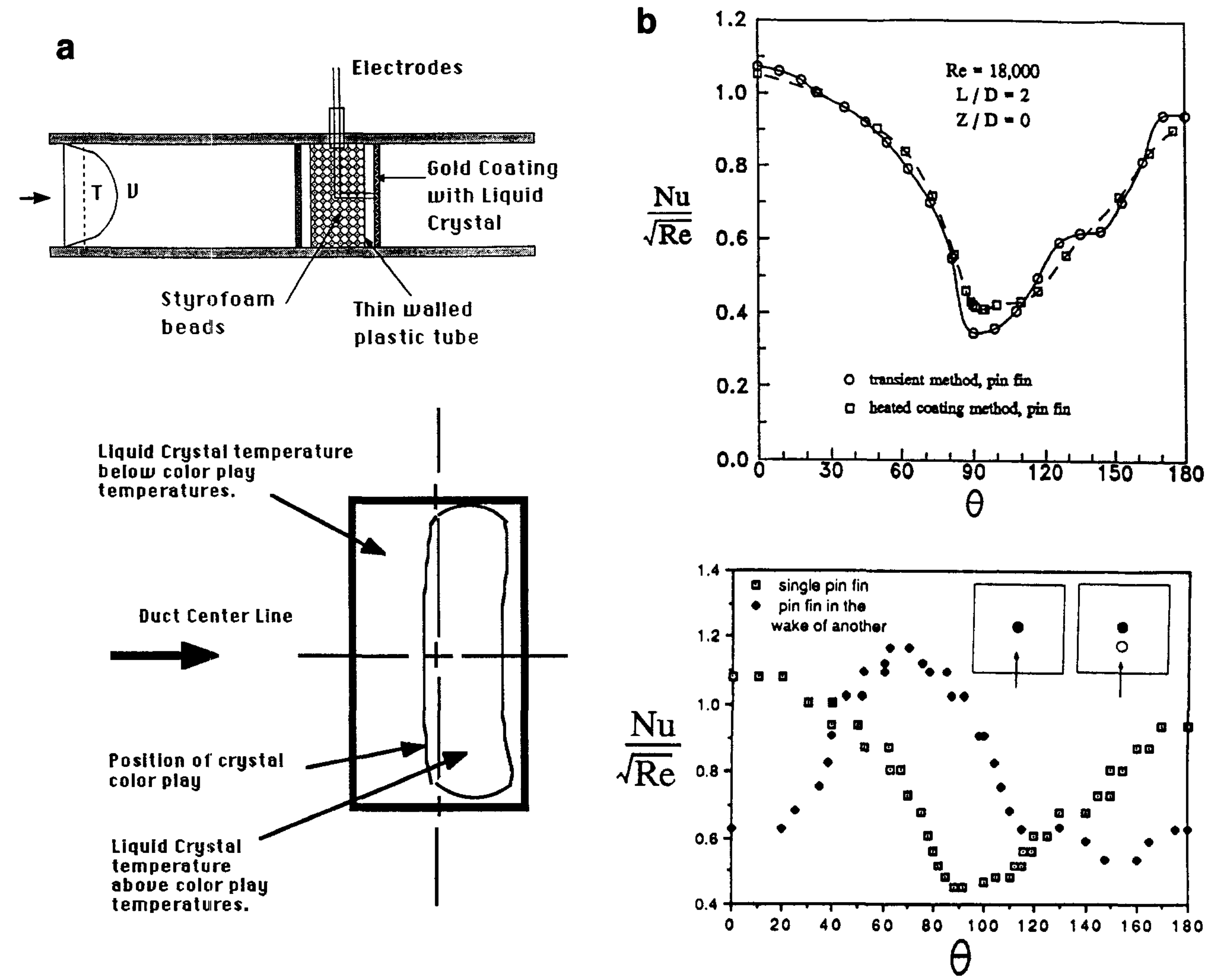

Figure 3 (a) Heated-coating method example, pin fin diagram (from Baughn et al. 1989); (b) Heated-coating method example, pin fin results (from Baughn et al. 1989; Baughn and Saniei, 1990)

The local heat transfer coefficient at the position of a particular color (temperature) is given by the following:

$$h = q_c/(T_{lc} - T_\infty) \quad (1)$$

where q_c is given by the following:

$$q_c = IV/A - \varepsilon\sigma(T_w^4 - T_\infty^4) - q_L \quad (2)$$

In this method, a line of constant color represents both an isotherm and a line of constant heat transfer coefficient, the value being given by Equation 1.

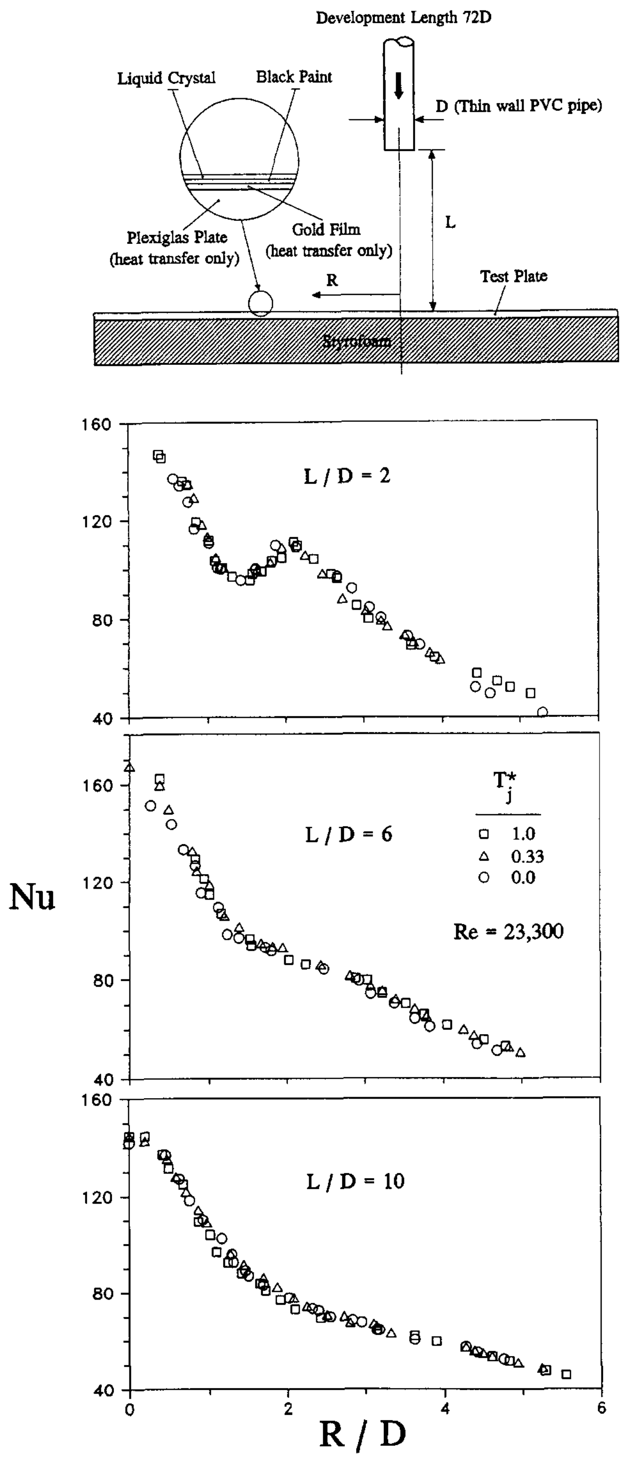

Figure 4 Heated-coating method example, impinging jet (from Baughn and Shimizu 1989; Baughn et al. 1991)

The heated-coating method has been used by the author and colleagues for studies of curved circular and square duct flow (Baughn et al. 1987), cylinders in crossflow (Baughn and Saniei 1991), pin fins (Baughn et al. 1989; Baughn and Saniei 1990), impinging jets (Baughn and Shimizu 1989; Yan et al. 1992), and most recently for turbine blades (Baughn et al. 1995).

Cylinder-in-cross-flow example. One example of the heated-coating method using liquid crystals is the measurement of the heat transfer distribution on a cylinder-in-cross-flow by Baughn and Saniei (1991). They compare their measurements with the heated-coating method (which provides a uniform heat flux) to earlier measurements in the same wind tunnel which used a uniform wall temperature boundary condition. The wind tunnel produced a uniform velocity air flow with low turbulence (less than 2%) in a rectangular duct. The cylinders were mounted across the duct producing a blockage of 8%. The gold-coated sheet was mounted on a long plastic cylinder filled with Styrofoam beads, as shown in Figure 2. By careful selection of the gold-coated sheet the nonuniformity in the gold coating was held to within approximately 2%. Larger sections have been found by the authors and others to have a nonuniformity up to 8%. The radiation correction was small (1–3%). The liquid crystal used in this example had a narrow band with a color play of 0.7°C at approximately 42°C. The ambient temperature was approximately 25°C. The uncertainty in the measurement of the heat transfer coefficient was estimated at approximately 5%.

The results of the uniform heat flux measurements on the cylinder in cross-flow are compared to those of the uniform wall temperature in Figure 2. The effect of the cylinder wall thermal boundary condition on the heat transfer coefficient distribution around the cylinder is significant. The heat transfer for the uniform temperature case is as low as half that of the uniform heat flux case near the separation point. At the rear of the cylinder, the heat transfer coefficient for the uniform temperature boundary condition increases rapidly and becomes greater than that for the uniform heat-flux boundary condition on the far back side. This behavior is a consequence of the difference in the growth of the thermal boundary layer (on the front) and the difference in the temperature of the separated recirculating flow (on the back). It is apparent that caution must be taken when making measurements of the local heat transfer on a surface with a thermal boundary layer, since different methods have different thermal boundary conditions, and this may significantly affect the results.

Pin fin example. In this example of the heated-coating method, the gold-coated sheet was mounted on pin fins (Baughn et al. 1989; Baughn and Saniei 1990). In these studies, local heat transfer coefficients were measured on a single pin fin (a short cylinder mounted across a duct), on a pin fin in the wake of another, and on a pin fin in a bank of in-line and staggered arrangements (see Figure 3a). The pin fins were two diameters in length and were arranged with a pitch-to-diameter ratio of 2.0. The Reynolds number was 23,000. The measurements showed the effect of the duct turbulence, of flow separation, and of impingement on the distribution of heat transfer.

The pin fins used in this study were plastic tubes with a 5.08-cm outside diameter and were 10.16-cm long with a wall thickness of 0.635 cm. One pin fin was modified and instrumented for the measurements, as shown in Figure 3. Electrodes for the gold film were made by cutting two narrow lengthwise grooves. The electrodes (0.07-cm copper wire) were buried in the grooves and were attached to two lead wires which exited from the top out of the cylinder's hollow center. Silver paint was used to provide an electrical contact between the electrodes and the gold film. The microencapsulated liquid crystal was sprayed on the gold film using an airbrush.

The procedure in this experiment involved adjusting the electrical heating until the liquid crystal color play temperature occurs at the position of minimum heat transfer coefficient. The apparatus was allowed to operate in this condition for 1 hour. The voltage was then increased slowly until the color of green appeared on the surface of the pin fin. In most cases, the first colors occur near $\theta = 90°$ at the position of minimum heat transfer. The apparatus was again allowed to come to equilibrium, after which the pin fin electrical power, ambient temperature, and the position of the green color on the surface of the pin fin were recorded. An illustration of the color distribution is also shown in Figure 3a. To map the entire surface of the pin fin, the voltage was progressively increased and data recorded as the green color moved to a different location.

This study also used a narrow-band liquid crystal with a color play of 0.7°C at approximately 42°C. The ambient temperature was approximately 20–25°C.

The uncertainty in the measurement of the heat transfer coefficient was estimated at 4.7%. The radiation loss can be as high as 3–7% in these measurements and contributes to the total uncertainty in the heat transfer coefficient.

Results for a single pin fin are shown in Figure 3b (from Baughn et al. 1989) along with those for arrays of pin fins (from Baughn and Saniei 1990).

Impinging jet example. The heated-coating method with liquid crystals has also been used for measurements of the local heat transfer coefficient on flat surfaces with an impinging jet for both an ambient-temperature jet (Baughn and Shimizu 1989) and for a heated impinging jet (Baughn et al. 1991).

The liquid crystal used for the ambient temperature jet had a narrow range of approximately 1°C over which the color spectrum occurs. Temperature resolution of the red and yellow colors was better than 0.1°C. The position of the red and yellow lines was shifted by changing the electrical heating of the gold coating on the surface. This allowed mapping of the heat transfer coefficient over the entire surface. Since the temperature differences between the jet and the wall were small (on the order of 10°C), the resulting heat transfer coefficients are independent of the level of heat flux used (fluid properties are not dependent on the temperature).

A diagram of the apparatus used in this example is shown in Figure 4. It consisted of a blower, a long pipe for development of the flow, and a test section. The upstream development length of 72 diameters provided nearly fully developed flow at the jet exit. The test section had a thin (0.64-cm thick) Plexiglas plate on which the plastic sheet containing the gold coating was glued. Styrofoam was used on the back for insulation. The liquid crystal was airbrushed directly on the surface of the gold coating.

For the ambient temperature jet, the data reduction was straightforward and consisted of computing the surface heat flux from the electrical power applied to the gold coating. A radiation correction, usually less than 5%, was made. Conduction losses with this technique were less than 1% and were neglected.

For these ambient temperature jet studies, the uncertainty in the Nusselt number (based on 20:1 odds) was estimated at 2.4% (probably too low). The uncertainty in the Reynolds number was estimated at 2.3%.

For the heated jet, two types of test plates were used, one for effectiveness (see Baughn et al. 1991 for a discussion of the effectiveness)) and one for the heat transfer measurements. The test plate for the effectiveness measurements was a smooth foam plate (a photo-mounting board) which was painted black and airbrushed with a thin layer of liquid crystals. As the jet was heated, circular rings of color (isotherms) form on the surface. At equilibrium, these rings measure the local adiabatic wall temperature from which the corresponding local effectiveness of the heated jet can be calculated. The test plate for the heat transfer measurements was the same as that used for ambient temperature jets.

For the heated jet, two different types of microencapsulated liquid crystals were used. For the effectiveness measurements, a narrow-band (1°C-wide) liquid crystal calibrated with a yellow/red transition at 34.95 ± 0.13°C was used. For the heat transfer measurements, a broader band (4°C-wide) liquid crystal calibrated with a red of 29.6°C ± 0.1°C and a yellow of 30.1°C ± 0.1°C was used.

For the ring (isotherm) at the liquid crystal temperature T_{lc} for a particular jet temperature, the local adiabatic wall temperature was determined by an energy balance. Radiation and conduction corrections were small.

The effect of the jet heating can be seen by defining a nondimensional jet temperature T_j^* in terms of the jet temperature, ambient temperature, and wall temperature. When the jet is unheated, T_j^* is 0.0. As the jet is heated, the value of T_j^* increases for a given surface heat flux (which determines the difference between the stagnation point wall temperature and the adiabatic wall temperature).

For the heated-jet measurements, the uncertainty in the Nusselt number ranged from 2.3% (at the stagnation point) to 3.0% at

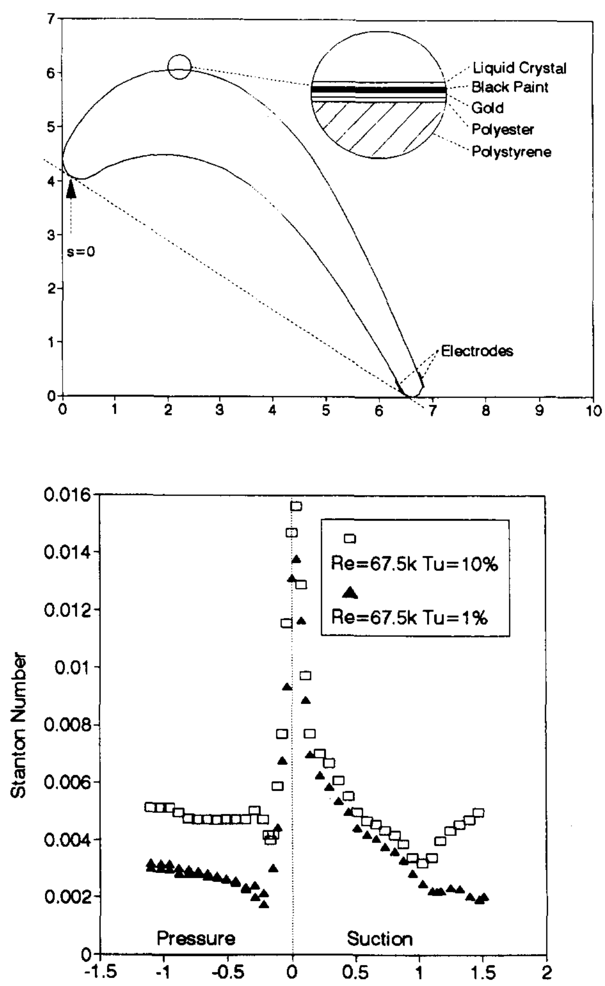

Figure 5 Heated-coating method example, turbine blade (from Baughn et al. 1995)

the maximum R/Ds (again, probably too low an estimate). The uncertainty in the Reynolds number was typically 2%, and the uncertainty in T_j^* was typically 4%.

A sample of the results for these jet studies is shown in Figure 4. Note that by using the adiabatic wall temperature in the definition of the heat transfer coefficients, the ambient temperature and heated jet results compare well.

Turbine blade example. Our most recent application of the heated-coating method was in an experimental investigation of heat transfer, transition, and separation on turbine blades at low Reynolds numbers and high turbulence intensities. This investigation was conducted in cascade wind tunnels at both the USAF Academy and UC Davis. In this application, the gold-coated plastic sheet was glued to a Styrofoam blade which had been cut in the shape of a turbine blade. Electrodes at the trailing edge of the blade were used to heat the gold coating. A diagram of this arrangement is shown in Figure 5 along with typical results of the heat transfer distribution on the turbine blade. The heat transfer coefficient distribution in this case provides insight into boundary-layer transition and separation, and thus represents a form of flow visualization. The uncertainty in the heat transfer coefficient for these measurements was estimated to be 5.5%.

Preheated wall transient method

The next three methods are all variations on the transient method. The transient method also has a long history, and a complete review is beyond the scope of this paper. It was used for many years at high temperatures in shock tunnels for the measurement of surface heat flux (Schultz and Jones 1973). In these applications, the surface was usually a ceramic, and the surface temperature was measured with a film resistance thermometer (usually platinum). Although some early external thermal-paint measurements are reviewed in Schultz and Jones (1973) and Jones (1977), the use of the transient technique at lower temperatures for internal flows has been developed more recently. Clifford et al. (1983) used phase change paints on acrylic models to study heat transfer within gas turbine blade cooling passages, and Metzger and Larson (1986) used melting point coatings to study heat transfer in rectangular ducts with turns. More recently, Ireland and Jones (1985, 1986), Jones and Hippensteele (1987), Metzger et al. (1991), and Baughn and Yan (1991a–c) have used liquid crystals on the surface as the temperature sensor. The liquid crystals have been found to be particularly suitable, since their response is repeatable, and their color play can be easily recorded with a video system (Ireland and Jones 1986). A video recording provides the time and location of the color play on the surface. The transient method can be used for very complex geometries, including curved ducts (Metzger and Larson 1986) and complex gas-turbine, blade-cooling passages (Clifford et al. 1983; Saabas et al. 1987). O'Brien et al. (1986) used the transient method on cylinders which were preheated and inserted into a cross-flow stream. Metzger et al. used the transient method for local heat transfer measurements on a rotating disk with jet impingement. The basic principles and the data reduction for this method are described by Ireland and Jones (1985, 1986) and Ireland (1987). The transient method uses the surface temperature transient in response to a fluid temperature change as a measure of the surface heat flux and the corresponding heat transfer coefficient. When the surface has a low thermal diffusivity (e.g., Plexiglas) a one-dimensional (1-D) assumption is often a good approximation, since the surface temperature response is limited to a thin layer near the surface and lateral conduction is small (Dunne 1983).

A variety of techniques are used to accomplish the fluid temperature change relative to the surface. For example, Clifford et al. (1983), Ireland and Jones (1985, 1986), Metzger and Larson (1986), and Metzger et al. (1991) all use an ambient temperature wall and then suddenly raise the temperature of their flow by using switching valves. Jones and Hippensteele (1987) preheat the wall of their wind tunnel and then initiate their flow by using a diverter door. O'Brien et al. (1986) use a preheated cylinder and insert it into place across a channel with an ambient temperature flow field. Baughn and Yan (1991a) remove a shield blocking a heated flat surface from an impinging jet.

The heat transfer coefficient in the transient method is determined from the response of the surface temperature to a step

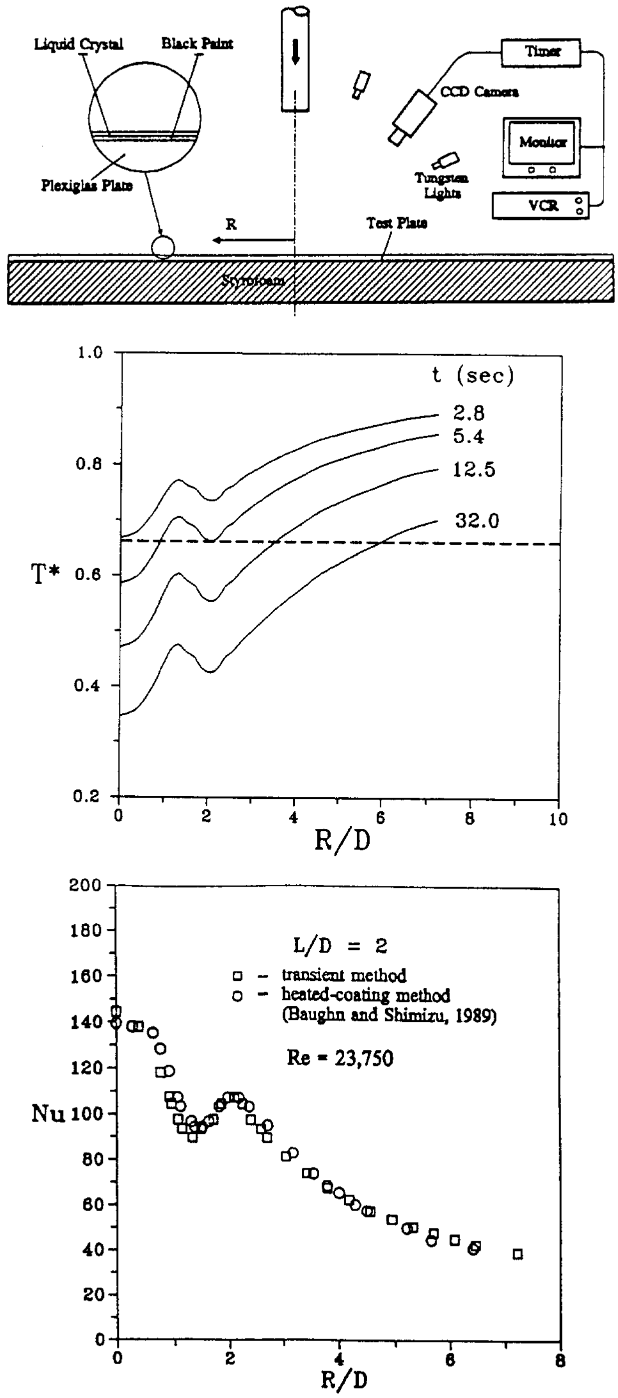

Figure 6 Preheated wall transient method, impinging jet example (from Baughn and Yan 1991a; Yan et al. 1992)

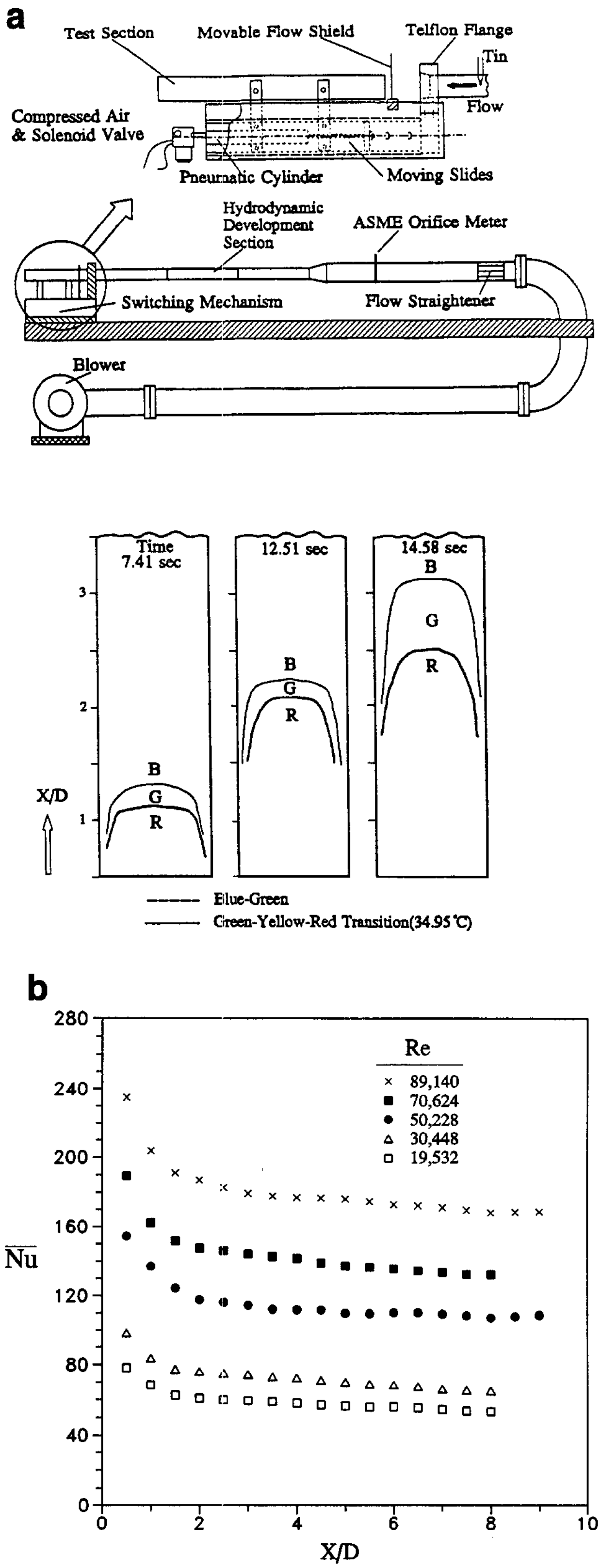

Figure 7 (a) Duct insertion technique, diagram of apparatus and smooth square duct example (from Baughn and Yan 1991b; Baughn and Yan 1992; Baughn et al. 1994); (b) Duct insertion technique, smooth square duct example results (from Baughn and Yan 1991b; Baughn and Yan 1992; Baughn et al. 1994)

change in the local temperature which, for a 1-D, semi-infinite body, is given by the following:

$$T^* = (T_w - T_\infty)/(T_{wi} - T_\infty)$$

$$= e^{\gamma^2}\,\mathrm{erfc}(\gamma) \tag{3}$$

where T_∞ is the ambient air temperature (or the local bulk temperature in case of a duct).

The parameter γ is defined as follows:

$$\gamma = h\sqrt{t}\,/\sqrt{\rho C_{PW} k_W} \tag{4}$$

The time t for the surface temperature $T_w(t)$ to change to that of a liquid crystal color temperature is obtained from a video record and used with Equation 4 to obtain the local heat transfer coefficients.

Impinging jet example. The transient method has been used for measurements with an impinging jet at UC Davis using the

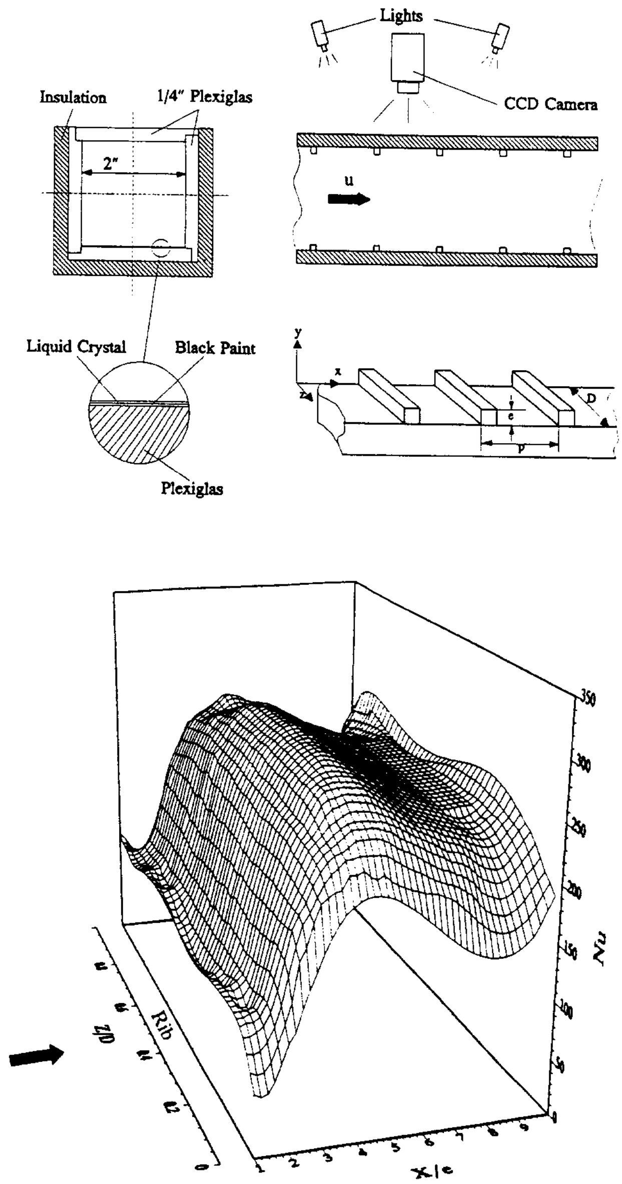

Figure 8 Duct insertion technique, square ribbed duct example showing heat transfer distribution on ribbed side of duct (from Baughn and Yan 1992)

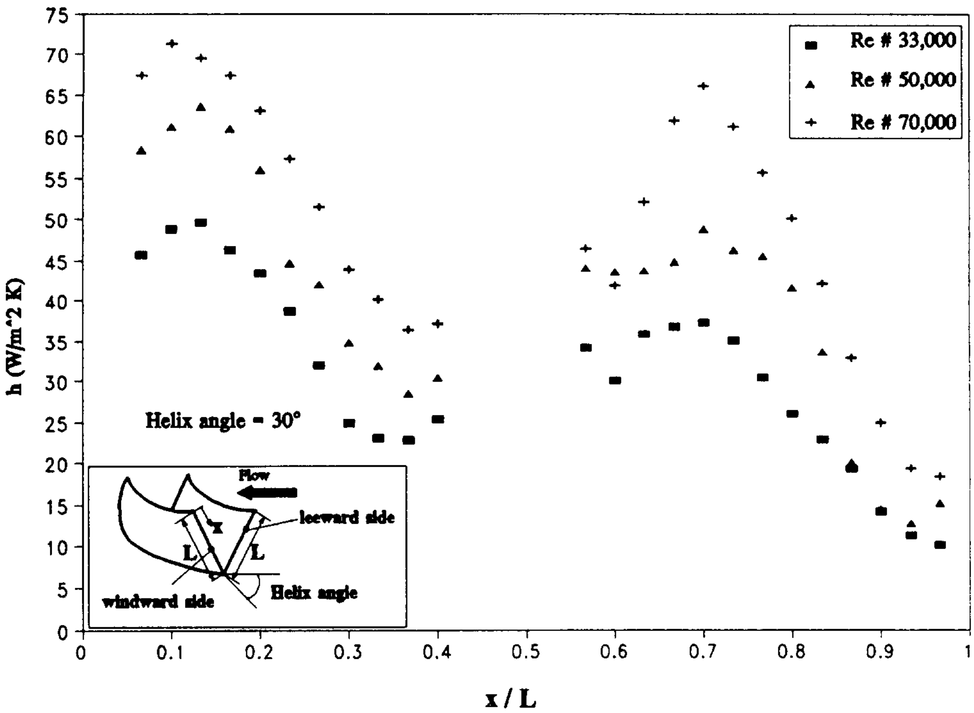

Figure 9 Duct insertion technique, spirally fluted tube example results (from Perera and Baughn 1994)

same apparatus described above for the heated-coating method but with a different test plate (Baughn and Yan 1992; Yan et al. 1993). The test plate used with the transient method has neither gold coating nor plastic sheet. The black paint and liquid crystal are applied directly to the surface, as shown in Figure 6. When ready to test, the plate is heated in a uniform and constant temperature oven to a selected temperature. In general, the transient method can be used with either a heated fluid or a heated wall. In this application, however, the heating of the fluid would produce entrainment effects, so the fluid cannot be heated without affecting the results. This method has also been used for impinging jets on pedestals (Baughn et al. 1993) and is currently being used for impinging jets on curved surfaces.

A video system records the response of the surface. A typical temperature response of the surface is shown in Figure 6. When the temperature is at the liquid crystal color temperature, the time is recorded and the data reduced using Equations 3 and 4. In Figure 6, the results are compared to those from the heated-coating method. The results compare very well for distances less than six jet diameters from the stagnation point. Due to the different thermal boundary conditions, the results should diverge at larger distances.

Pin fin example. The transient method has been used on a variety of geometries (including a pin fin) by T. V. Jones at Oxford University. The heated-coating and transient method results for pin fins are compared in Baughn et al. (1989) (see Figure 3b). The two methods compare well, especially the value obtained near the center stagnation point of the pin fin where the difference in the thermal boundary condition of the two methods has no effect. They are close but differ somewhat in other regions. This comparison increases the confidence in both of these powerful methods. The transient method (which can approximate a uniform temperature boundary condition) is very useful for handling very complex geometries. The heated-coating method (which provides a uniform heat flux boundary condition), is restricted to geometries with curvature in one direction.

Duct insertion technique

Another variation on the transient method is the duct insertion technique (Baughn and Yan, 1991b; Baughn et al. 1994). The duct insertion technique is used to measure local heat transfer coefficients inside ducts. It involves the sudden insertion or attachment of a heated section of duct on the end of a duct which has an established flow at ambient temperature. The transient temperature on the surface of the inserted section is measured using the liquid crystals and recorded with a video system. Prior to insertion, the section of duct to be inserted is preheated in a uniform temperature oven for 8–12 hours until it is at a selected uniform temperature (uniform within 0.15°C) above that of the ambient temperature flow. It is then fired into position with a switching mechanism using a pneumatic cylinder. This technique allows control of upstream hydrodynamic and thermal boundary conditions. The data reduction is similar to that used with the transient method, except that an iterative procedure is used for the calculation of the local bulk temperature. A diagram of the apparatus used in the insertion technique is shown in Figure 7a.

Smooth square duct example. Initial experiments with the duct insertion technique used a smooth square duct. The duct test section size was 5-cm square with a wall thickness of 0.64 cm and 50-cm long. After preheating the test section to the desired temperature, it is attached to a switching mechanism and suddenly inserted into place using a pneumatic cylinder. A Teflon flange is used for mating the test section to the hydrodynamic development section. The switching mechanism fires the test section into place in less than two frames on the video recording (each frame is 0.03 s)

A typical video record (VHS recording) of the data from a run is shown in Figure 7a for the smooth duct. The location of the transition between red (R) and green (G) is used to determine the location of the liquid crystal transition temperature. A calibration system with a known linear temperature gradient was used to establish the color appearance on the video monitor. For the R–G transition (yellow) in these experiments, the calibrated temperature was 34.95°C ± 0.13°C.

The local heat transfer coefficients in this case require that the local bulk temperature be known. The local fluid bulk temperature is obtained by an energy balance. This requires an iteration, since it depends on the upstream heat transfer coefficients. Convergence is rapid, since the increase in bulk temperature is small compared to the difference between the wall and fluid temperature. The axial distribution of the circumferential average Nusselt number for this example is shown in Figure 7b.

The uncertainty in the local Nusselt number for these measurements was estimated at 7.1%. The largest contributor to the uncertainty is the wall thermal properties. As better properties are determined, it is expected this source of uncertainty will be reduced.

The duct insertion technique provides a complete mapping of the heat transfer coefficients on the inside surfaces of complex ducts, while allowing excellent control of the upstream hydrodynamic and thermal boundary conditions.

Ribbed square duct example. The arrangement and results for a ribbed square duct example are shown in Figure 8 (from Baughn and Yan 1992). The procedure is essentially the same, although data reduction is more complex due to the heat transfer contours. The color patterns at any time look much like those of the heat transfer coefficient contours.

Spirally fluted tube example. The spirally fluted tube has been the most complex internal geometry used with the duct insertion technique. Spirally fluted tubes are of great interest for heat transfer enhancement. A knowledge of the local heat transfer distribution in the flutes will be valuable for understanding and optimizing such ducts. Producing a spirally fluted tube of Plexiglas and coating the inside with black paint and liquid crystal is very difficult. The method for achieving this is described in Perera and Baughn (1994). In this case, the inside surface is painted with liquid crystals first, and then the black paint is applied. This allows the liquid crystals to be seen from the outside. The small flutes were observed with a video camera mounted on a dissecting microscope. Since the flutes are small, the assumption of 1-D conduction is no longer valid, and a two-dimensional (2-D) conduction solution is necessary. This required an iterative process. The heat transfer coefficient distribution of a flute is shown in Figure 9.

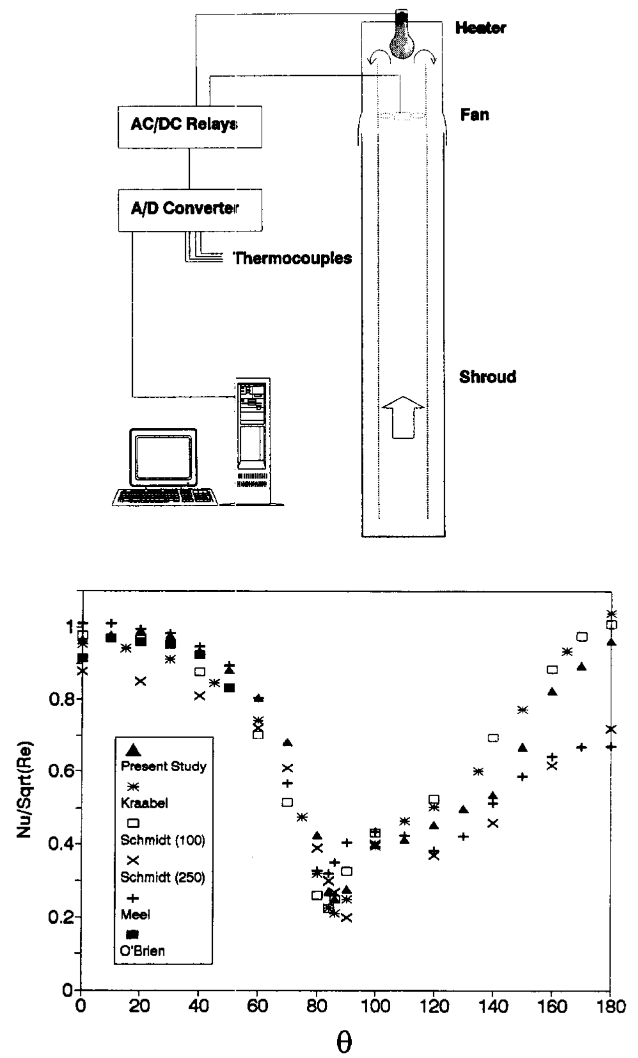

Figure 10 Shroud-heating method (in-situ heating), cylinder in crossflow example (from Butler and Baughn, 1994)

Shroud-heating technique

Another variation on the transient method is to use in-situ heating as described by Butler and Baughn (1994, 1995). In this case, a shroud over the object to be tested acts as an in-situ heater, as shown in Figure 10. A control program operates a fan and heater (light bulb) to heat the sample to a uniform constant temperature. When ready, the shroud is suddenly removed exposing the heated sample to the wind-tunnel flow.

This method has been validated using a cylinder in cross-flow, and the results are shown and compared to other methods in Figure 10. This method produced very good results at a Reynolds number of 34,000. At a Reynolds number of 110,000, the results are good except in the wake region, where the heat transfer is effected by the duration of the flow development time. It was also found that end cavity effects can change the shedding frequency and have a strong effect on the heat transfer on the rear of the cylinder.

This method has been used to evaluate the differences between uniform wall temperature, uniform heat flux, and transient thermal boundary conditions.

Uniform coating method

The author has tried another method recently. In this method, a thin uniform surface coating is applied to a highly conducting wall or substrate, as shown in Figure 11. The black paint and liquid crystal are then applied to the outside surface of the coating. A heater in the highly conducting substrate is used to change its temperature, which is measured with a sensitive temperature sensor. When there is heat transfer from the surface, the thermal resistance of the coating will result in a temperature difference between the surface (the liquid crystal) and the highly conducting substrate. The surface heat flux is then given by the following:

$$q_c = (T_{lc} - T_w)/R_t \qquad (5)$$

where R_t is the thermal resistance of the coating given by the following:

$$R_t = \delta/k_c \qquad (6)$$

The value for R_t can be found by calculation or by calibration. It can also be adjusted to put $(T_{lc} - T_w)$ in the right range by selecting the coating thickness.

The procedure for this method involves adjusting the heater (substrate temperature) until an isotherm (color) or series of colors appear on the surface. The local surface heat flux can then be calculated from Equation 5 and the local heat transfer coeffi-

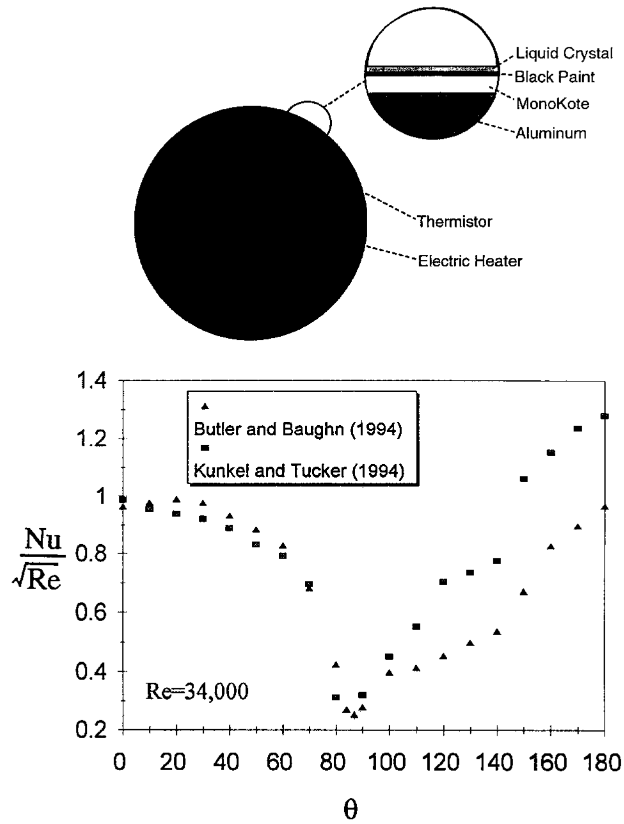

Figure 11 Surface-coating method, cylinder in cross-flow example

cient determined from the local surface temperature T_{lc}. This method can map the heat transfer distribution on 2-D surfaces. It is robust and can provide a nearly uniform temperature on the surface.

Cylinder-in-cross-flow demonstration. Proof-of-principle demonstration tests of this method were performed on a cylinder-in-cross-flow. These tests were done by two cadets (Kunkel and Tucker 1994) at the USAF Academy under the direction of the author. For these demonstration tests, the substrate was an aluminum cylinder. The surface coating was a thin plastic film with adhesive called MonoKote (it is used in model airplanes and was suggested by Maj. H. G. Schneider of the USAF Academy). Multiple layers (5) of the MonoKote were used to adjust the coating thermal resistance so as to maintain a small temperature difference across the coating (0.5–2°C). The thermal resistance of the coating was calculated from the stagnation point heat transfer, which is well known for a cylinder-in-cross-flow. The results are shown in Figure 11, where they are compared to those of Butler and Baughn (1994).

Kim and Reynolds (1994) have also demonstrated this method (using an expoxy coating) for an impinging air jet on a flat surface.

Conclusion

This paper has described five methods and techniques for using liquid crystals in experimental heat transfer. It is clear that liquid crystals are an exciting and powerful new tool for studying many important heat transfer and fluid-flow problems and that there are many methods and techniques for their use. Each method and technique has its own advantages and disadvantages. Continued innovation in the methods and techniques for using liquid crystals in heat transfer experiments can be expected.

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