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High-Resolution Heat-Transfer-Coefficient Maps Applicable to Compound-Curve Surfaces Using Liquid Crystals in a Transient Wind Tunnel

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Summary

Tests were performed in a transient heat transfer tunnel in which the model under test was preheated prior to allowing room temperature air to be suddenly drawn over the model. The resulting movement of isothermal contours on the model is revealed using a surface coating of thermochromic liquid crystals that display distinctive colors at particular temperatures. A video record is obtained of a temperature and time data pair for all points on the model during a single test. Experiments on a duct model are reported in which the model was preheated using a hot air stream. A manner in which initial model temperature nonuniformities could be taken into account was investigated. The duct model was also tested with a steady-state measurement technique and results were compared with the transient measurements, but recognizing that differences existed between the upstream thermal boundary conditions. The steady-state and transient measurements were shown to be consistent with predicted values. The main advantage of this transient heat transfer technique using liquid crystals is that since the test model need not be actively heated, high-resolution measurements on surfaces with complex shapes may be obtained.

Introduction

This paper describes experiments undertaken with the aim of confirming the use of liquid crystal techniques to measure heat transfer coefficients in a transient cold heat transfer tunnel. The cold heat transfer tunnel was described in reference 1 and is a short-duration heat transfer wind tunnel in which the model or working section is precooled or preheated prior to the start of the tunnel run. The airflow is started quickly within the tunnel and the subsequent history of the model temperature enables the heat transfer coefficient on the model to be determined (ref. 2). The testing is simplified if the airflow is introduced from atmosphere as no supply reservoir is required and working section access is simpler. Thermochromic liquid crystals are a method whereby the model temperature may be measured (refs. 3 and 4).

Short-duration heat transfer wind tunnels have been used for several decades and the major growth in their use occurred when heat transfer measurements in simulated reentry environments were required (ref. 5). Such high enthalpy flows could only be sustained for short periods and techniques to measure heat transfer rates within these short times were developed. Subsequently these techniques were so successful (ref. 5) that, even in situations where steady-state conditions could be readily sustained, the transient techniques were employed by injecting the model into the flow or switching of steady flows (ref. 6).

The cold heat transfer tunnel has great advantages when large mass flows are required because the power requirements to heat the flow, as opposed to preheating the model, would be prohibitive even in a transient test.

The transient measurement techniques are described in reference 5 and can be roughly divided into two categories: calorimetric and semi-infinite. The latter is considered in this paper and it is required that the thickness of the model is such that the heating or cooling pulse which propagates into the model, when flow is established, penetrates only a small distance compared to the model wall thickness. In this case the model may be considered to be semi-infinite, and the model surface temperature history may be analyzed to determine the surface heat flux. Usually the surface temperature is monitored continuously using fast response thermocouples or resistance thermometers. However if a step function in flow and hence heat transfer coefficient may be assumed, then a single measurement of surface temperature rise after a measured time will enable the heat transfer coefficient to be found (refs. 3 and 4). This last possibility enables liquid crystals to be employed in the measurement. Thermochromic liquid crystals are sprayed onto a surface to form a very thin coating ($\sim 10\ \mu m$) which displays distinctive colors at particular temperatures. Thus it is possible to measure the temperature at all points on a model surface during a single test. The particular thermochromic liquid crystals used in this study were chiral nematic liquid crystals (refs. 7 and 8) which have a fast response to temperature changes (ref. 9).

In the work reported here a continuous-flow wind tunnel was adapted such that flow could be switched suddenly through the working section. The wind tunnel was also run in the continuous mode and steady-state heat transfer measurements were made on the same model. The steady-state techniques used also allowed measurements to be made at all points on the model and also employed liquid crystals for temperature measurements as in references 10 to 12. Cholesteric liquid crystals were used in this case. Thus the transient results could be compared with steady-state measurements, but recognizing that differences existed between the upstream thermal boundary conditions. The model tested was a duct which had a transition from a 20.8 cm square to a rectangular cross section. The heat transfer on one wall within the transition was measured. The inlet velocity was generally 37 m/sec. One wall was used for the transient test and a different wall was used for the steady-state measurement.

Symbols

c	specific heat
D	duct inlet width
h	heat transfer coefficient
k	thermal conductivity
P	pressure
$\dot{q}$	surface heat flux
T	temperature of model
t	time
x	distance along the surface
y	distance into the surface
α	diffusivity
β	nondimensional time $h\sqrt{t}/\sqrt{\rho ck}$
Δ	difference
θ	nondimensional temperature $\dfrac{T_i - t_s}{T_i - T_g}$
ρ	density

Subscripts

g	gas
i	initial
s	surface

Description of the Measurement Techniques

The basic transient method of measurement of the heat transfer coefficient using liquid crystals has been described in references 3 and 4. The penetration depth of the thermal pulse into the model wall is assumed to be small compared to the wall thickness or local radius of curvature. Therefore the heat conduction into the wall may be considered to be one-dimensional into a semi-infinite medium. The governing equation is the diffusion equation

$$\frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

and the boundary conditions for heat flux at the surface and at large distances,

$$\dot{q} = h(T_s - T_g) = -k\frac{\partial T}{\partial y_{y=0}}$$

$$\text{Initial condition: } t = 0,\ T \rightarrow T_i,\ y \rightarrow \infty \tag{2}$$

The equation may be solved for the case of a step function of flow to give the surface temperature as

$$\theta = 1 - e^{\beta^2}\, erfc\, \beta \tag{3}$$

where θ and β are nondimensional temperature and time,

$$\theta = \frac{T_i - T_s}{T_i - T_g} \quad \text{and} \quad \beta = \frac{h\sqrt{t}}{\sqrt{\rho ck}} \tag{4}$$

The heat transfer coefficient and gas temperature are assumed constant in the above. Hence it can be seen that if the model wall properties are known then a measurement of wall surface temperature at a certain time enables the heat transfer coefficient to be found when the gas and wall initial temperatures are also known. This is the principle of the transient method utilizing liquid crystals to measure the surface temperature. The model material chosen was acrylic which has suitable thermal properties.

In the tests reported here a liquid crystal which displayed the color display within a temperature band of ~1 °C was used. As the model surface temperature changed a line of color moved across the surface indicating an isotherm. If the model were initially isothermal these color lines would also correspond to contours of constant heat transfer coefficient. Great detail in the history and distribution of surface heat transfer coefficient may be observed under this circumstance (refs. 3 and 4). When the model is preheated before the test such uniformity of model temperature may be difficult to achieve and it is one of the objectives of this paper to show how the technique may be modified to account for nonuniform temperature. It should be noted that the wall-temperature variation referred to above is not so severe that it significantly effects the heat transfer coefficient due to upstream wall thermal-boundary condition effects. Also it is inherent in the method that any spatial variation in heat transfer coefficient will produce a corresponding variation in surface temperature which varies throughout the run. This surface temperature variation does not cause the heat transfer coefficient to vary significantly in time as discussed in detail in reference 4.

Calibration of the liquid crystal was effected by installing thin-foil thermocouples (less than 20 μm thick) on the model surface at particular locations. As the color line moved over the thermocouple a calibration was performed on each run.

Although the times considered ranged from approximately 0.2 to 40 sec it was important that the liquid crystals had an adequate time response. The chiral nematic liquid crystals satisfied this requirement (refs. 3, 4, and 9) and were therefore used.

Returning to the question of the uniformity of the initial model temperature, it was decided to eliminate this from the measurement by employing multiple liquid crystal coatings. Such coatings are possible, for the liquid crystals are encapsulated and two or more may be mixed together with a single binder and sprayed onto the model surface. Each liquid crystal will act independently therefore and a series of color lines at different temperatures will pass over the surface. Such multiple liquid crystal coatings have been used previously in reference 4. From equation (3) it can be seen that if two wall temperatures are measured at the same model location at two different times, then this will suffice to find both the initial wall temperature and the heat transfer coefficient. This technique will be referred to as the double crystal method. In the transient tests the model surface temperature changes continuously and it is required that the heat transfer coefficient remains constant. In order to check this assumption the wall surface thermocouples were monitored continuously and it was shown that equation (3) was obeyed locally throughout the run.

An alternative approach was also used whereby the color line of the high-temperature liquid crystal initially resided on the surface. Thus the initial surface temperature was known along this line. During the tunnel run the lower temperature liquid crystal line crossed the position of the former line at different times and thus the heat coefficient was found, but only along the initial line. This last technique will be referred to as the single crystal method.

The steady-state measurements were conducted using the methods described in references 10 to 12. Again an acrylic model wall was used and this was covered by a thin-foil electrical heater. The heater in turn was covered by a layer of cholesteric liquid crystal contained within thin plastic sheets. The heater electrical power was supplied via bus bars so as to produce uniform ohmic heating over the surface. The conduction into the acrylic wall was small compared to that lost in convective cooling and hence the heat flux into the flow was constant. The temperature that the surface subsequently achieved was measured using the liquid crystal indicator. Isotherms were thus displayed on the surface in the steady state and the heat transfer coefficient determined from

$$h = \frac{\dot{q}}{T_s - T_g} \tag{5}$$

The isotherms (constant heat-transfer coefficients) could be moved over the surface by varying the electrical heater power. The thermal boundary condition in this test was one of constant heat flux which differed from that in the transient testing. This difference will be discussed in the results section. The main advantage of the transient technique is that since the test model need not be actively heated, high-resolution measurements on surfaces with complex shapes may be obtained.

Apparatus

The wind tunnel is shown in figure 1. Room-temperature air was drawn from the test cell, through the working section, and into ducting connected to the main laboratory vacuum system. Mass flow was controlled by an adjustable valve downstream. The inlet velocities were measured with a pitot static measurement at the inlet probe section. In the transient tests the flow initially bypassed the test duct via a diverter door downstream of the working section as shown in figure 1. This door was suddenly closed to allow air flow through the test section thus initiating the run.

Details of the duct model are given in figure 2 and photographs of the instrumented duct floor are shown in figures 3 and 4. Thermocouples were mounted on the duct surface at the positions shown in figure 2. A bare thermocouple was used to measure the room inlet-temperature. A microswitch was placed so as to operate when the manually operated diverter door was closed and the run started. The microswitch activated a light-emitting diode situated on the working section and also produced an electrical pulse which indicated the start of the run. The thermocouple outputs and the start-of-run pulse were recorded on a chart-recorder.

The chiral nematic liquid crystal color patterns were recorded by a color video camera and video recorder in the transient tests and by color photography for the steady-state tests. The light-emitting diode gave a reference on the video recording whereby the start of the run could be determined and synchronized with the chart recordings. A timer signal was also recorded on the video tape. Careful attention was paid to model illumination.

In the transient tests the tunnel conditions were first established by setting the control valve. The diverter door was then opened, closing off the working section exit. The working section duct was then preheated by introducing a tube into the inlet bellmouth through which hot air was then passed (fig. 1). The working section temperature was monitored by the surface thermocouples and the liquid crystals on the test surface. When the model had been heated above the color display temperatures of the liquid crystals the hot-air duct was withdrawn and the model allowed to stabilize. When the initial temperature through the model wall had reached equilibrium the chart recorder and video recorder were started and then the diverter door was quickly shut to allow air to flow through the test section. This door was operated manually but flow-starting times of order 0.2 sec were achieved which were adequate for the tests undertaken. Test velocity was checked again after the run.

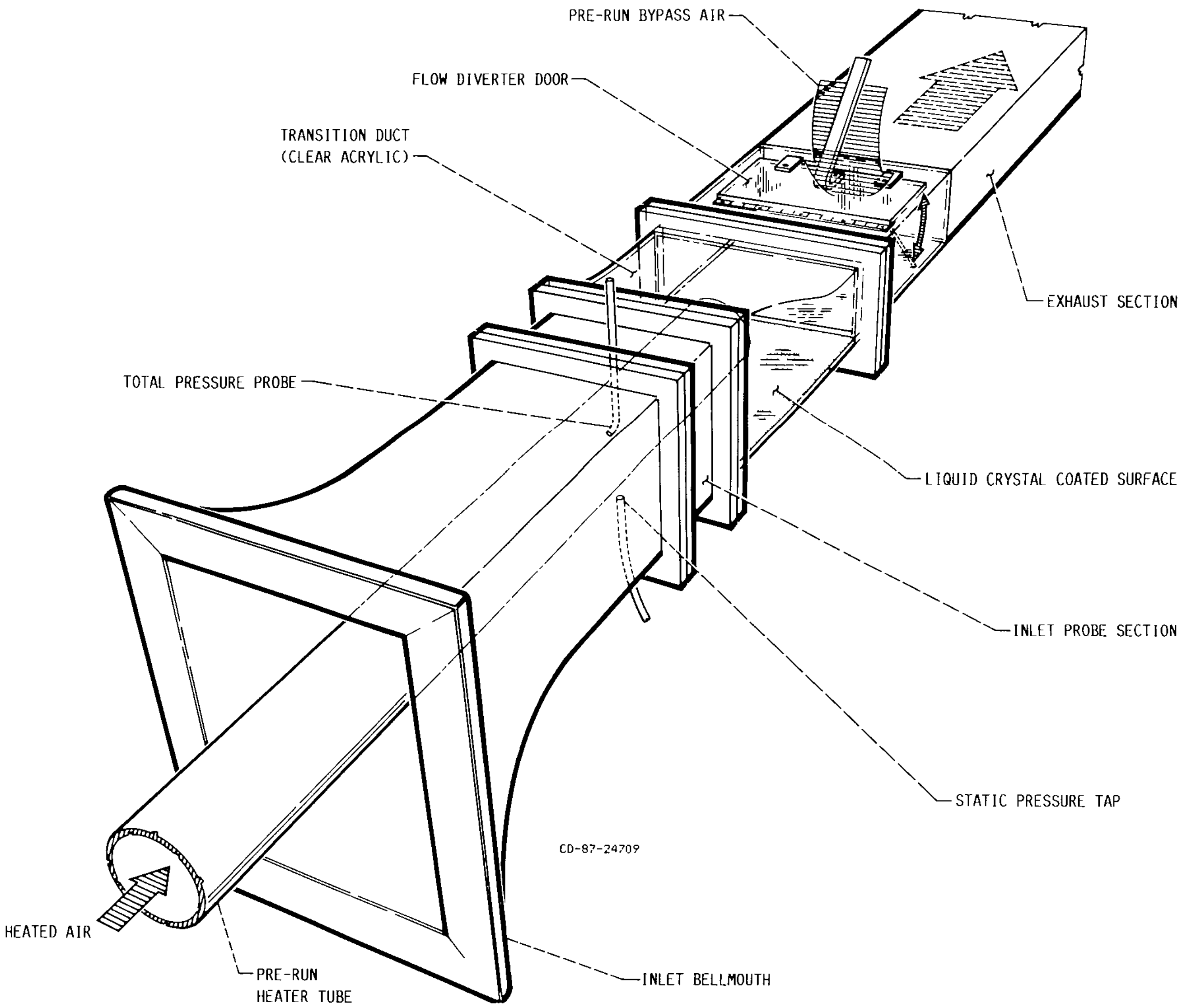

Figure 1.—Transient liquid crystal heat transfer tunnel.

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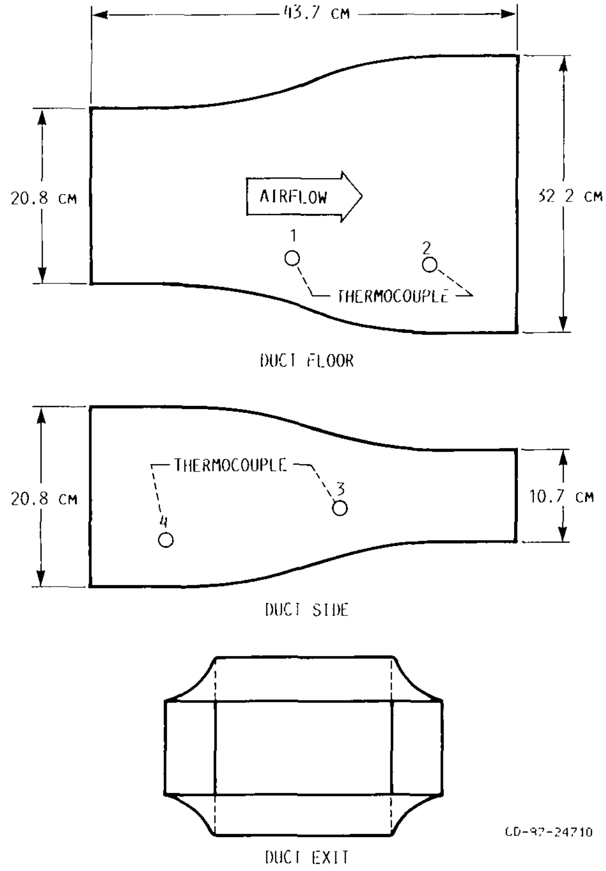
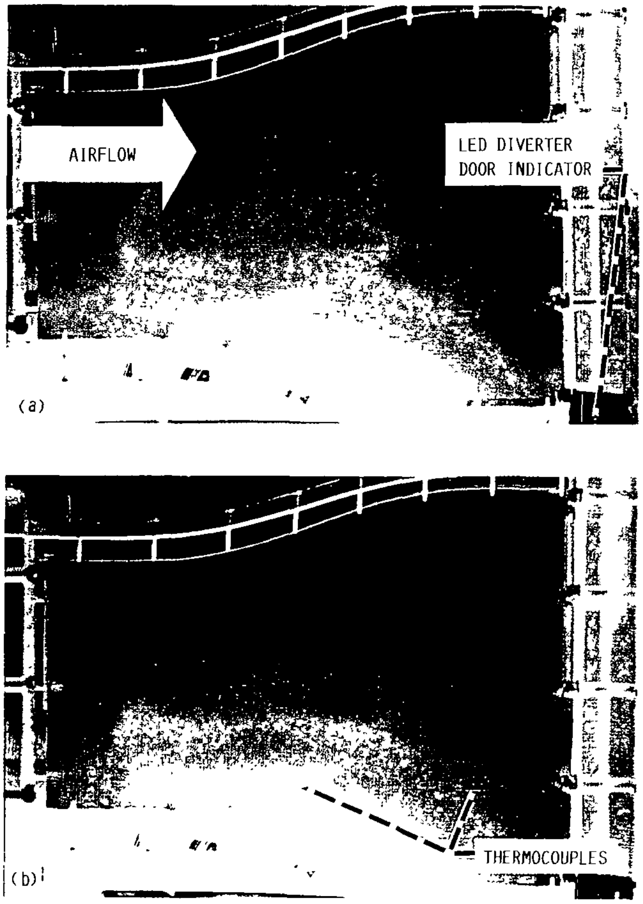


Figure 2.—Duct model details



(a) Higher temperature liquid crystal, early in test run.
(b) Lower temperature liquid crystal, late in test run.

Figure 3.—Photographs of transient liquid crystal patterns on duct floor.

Figure 4.—Photograph of steady-state liquid crystal pattern on duct floor

In the steady-state tests the flow was adjusted as discussed above and the electrical power to the test surface altered to give a liquid crystal color display over the area of interest. A sufficient time was then allowed for conditions to stabilize, the inlet gas temperature was measured, and a photograph of the test surface was taken.

Results

A typical picture of the liquid crystal color lines in a transient test is shown in figure 3 at a certain time within the run. Records of the surface thermocouples and gas thermocouples are shown in figure 5. Together with the pitot static measurement for the flow conditions, the above data represent all that was required to determine the heat transfer coefficient. The movement of a color line with time is shown in figure 6. The two liquid crystals used in these tests indicated yellow at temperatures of 42.4 and 35.6 °C and the times at which they appeared at different positions (e.g., along the centerline of the duct) are shown in figure 7.

From surface thermocouple and gas temperature records a value of θ in equation (3) was determined as a function of time and hence from equation (3) a value of $\beta = h\sqrt{t}/\sqrt{\rho c k}$ found.

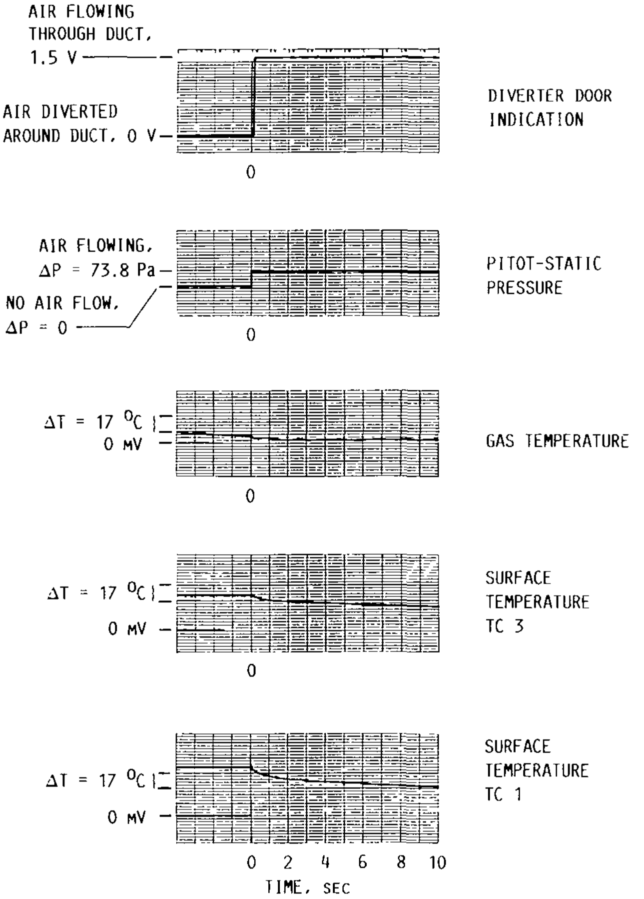
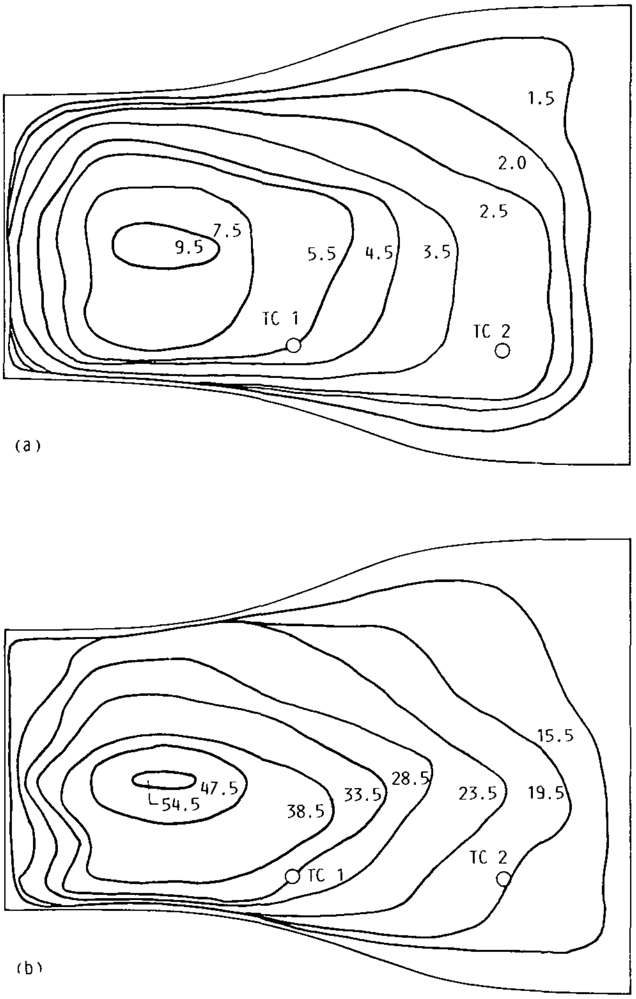


Figure 5.—Chart-recorder records of transient data.



(a) Higher temperature liquid crystal (yellow = 42.4 °C)
(b) Lower temperature liquid crystal (yellow = 35.6 °C).

Figure 6.—Yellow-color line positions shown as function of time (seconds after flow diverter door closed).

A plot of t versus β is shown in figure 8 for two thermocouples and it can be seen that the lines do have a slope of two on a log plot as expected. This confirms that the heat transfer coefficient may be considered constant at any location during the run and a value of h at the thermocouple location may be found from these plots. The value of h thus determined compared favorably with that found from the liquid crystals at this point. The manner in which this was evaluated is explained below.

From graphs such as those in figure 7 the times for the surface to reach given temperatures indicated by the liquid crystals could be found. These two times and temperatures must be consistent with the same value of initial surface temperature and heat transfer coefficient at the point of observation. Therefore the value of the initial surface temperature and the heat transfer coefficients were solved by iteration that satisfied the two times using equation (3). Thus

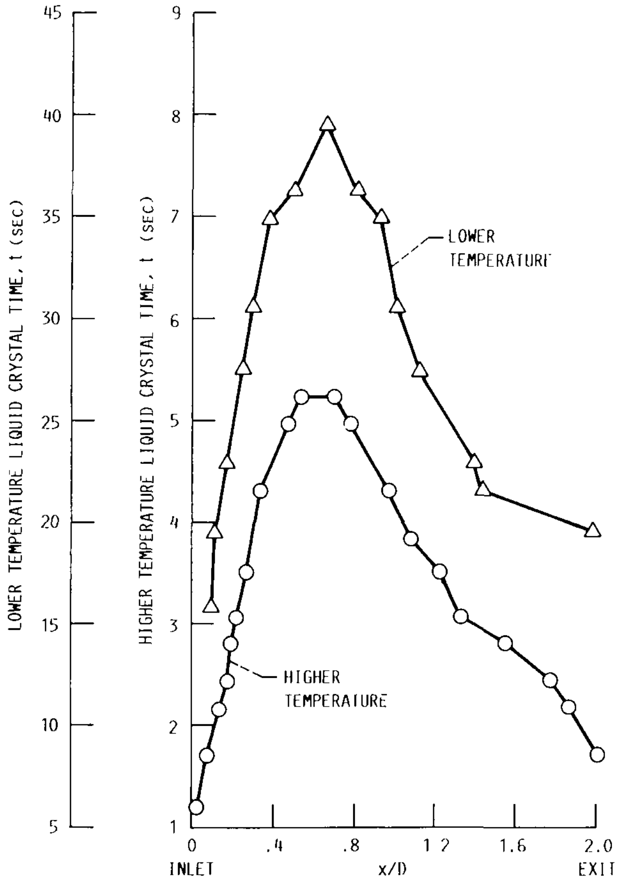


Figure 7.—Times for surface to reach liquid crystal temperatures along duct centerline.

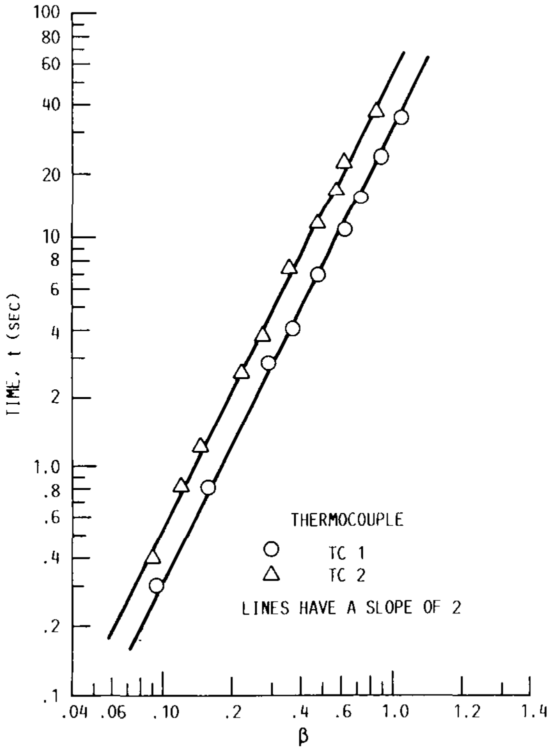
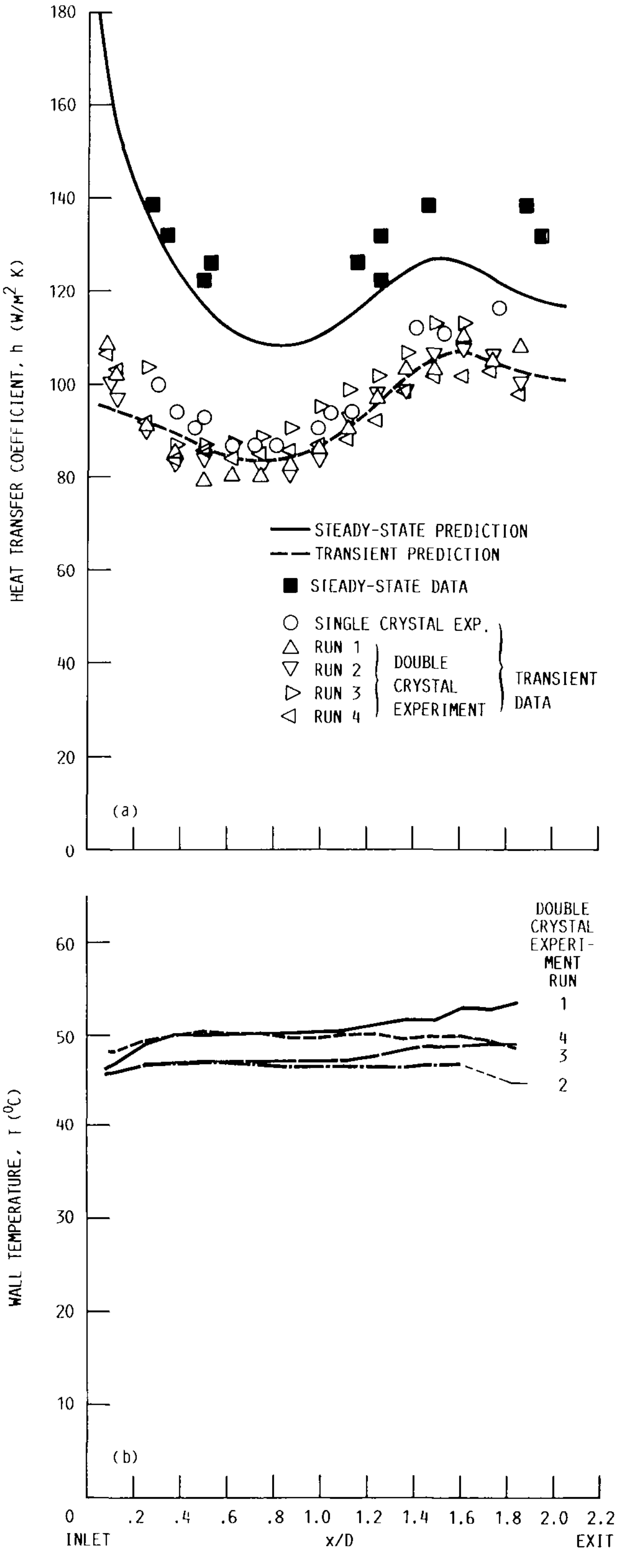


Figure 8.—Time, t, versus beta, β, for two thermocouples.



(a) Experimental and predicted heat transfer coefficients.

(b) Experimental initial wall temperatures.

Figure 9.—Heat transfer coefficients and initial wall temperatures along duct centerline.

the value of heat transfer coefficient and initial wall temperature were found at all points on the model. Plots of heat transfer coefficient versus distance along the centerline of the model for runs where the model initial temperatures were essentially uniform are shown in figure 9, along with results from single crystal tests. Also in this figure is given the distributions of initial surface temperature.

Similar variations of heat transfer coefficients were found using the steady-state results. In this case the total electrical power into the heater film was divided by the total film area to give the uniform local value of heat flux. This in turn was divided by the local temperature difference between the surface and gas to give the heat transfer coefficient. The values of heat transfer coefficient for the steady-state case are also shown in figure 9(a).

It should be recognized that the data scatter in the heat transfer coefficient was found to be significantly effected by the tunnel air temperature and flow pattern. The temperature of the room air drawn into the tunnel inlet bellmouth was found to vary significantly over short periods of time during the testing. Also the tunnel did not have any inlet air-flow conditioning (honeycomb straighteners and screens) installed during the time of testing. During the transient testing by observing the video recording, the yellow isotherms moved, with time, in a somewhat oscillating motion. When selected video frames were used to obtain the yellow isotherm locations, with time, variations in the location caused the heat transfer coefficient h to vary. During the steady state testing, the same variation in h was produced as a function of exactly what time the photograph was taken during the oscillating motion of the yellow isotherm.

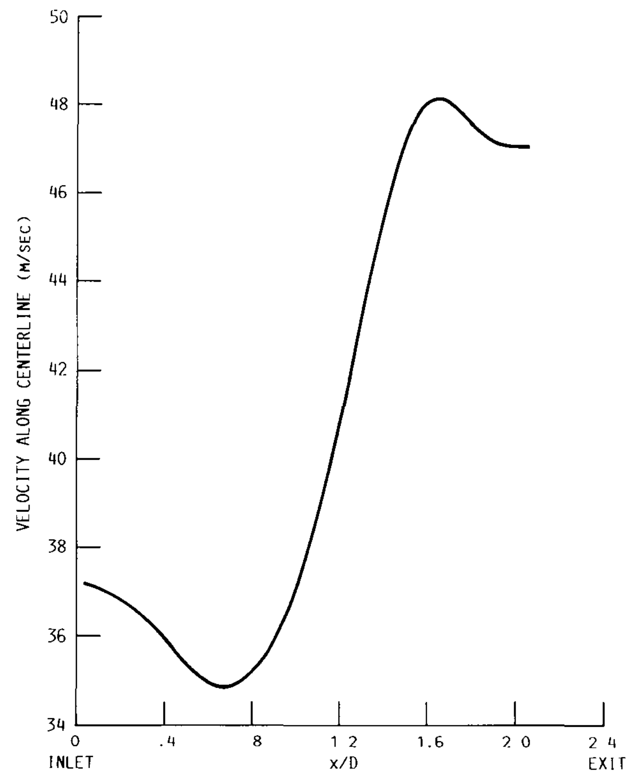


Figure 10.—Velocity distribution along duct centerline predicted by an inviscid 3-D code.

Discussion

From figure 9(a) it can be seen that there is considerable difference between the heat transfer coefficient found from the steady state and transient method. This difference can however be reconciled when the effects of the different thermal boundary conditions are examined. In the transient test in figure 9 the initial surface was essentially isothermal whereas the steady-state test boundary condition corresponded to a constant heat flux. The heater film only existed within the model and hence there was a discontinuity in surface heat flux (unheated starting length) when moving from the inlet section to the model. Along the centerline of the model the boundary layer was developing and surface curvature was small. It was therefore possible to estimate the effects of both the variation of thermal boundary conditions and freestream velocity by using flat plate integral techniques as proposed by reference 13. The results of this simple analysis for the two boundary conditions are shown in figure 9. It can thus be seen that the measurements do correspond closely with the two predictions and hence are consistent with one another. The streamwise edge velocity distribution along the centerline was calculated outside the boundary layer but near the wall of the model and is shown in figure 10. It was obtained from an inviscid three-dimensional computer prediction (refs. 14 and 15).

Concluding Remarks

The main conclusion of the work reported here is that the transient liquid crystal techniques developed at Oxford (refs. 3 and 4) may be used in a cold heat transfer tunnel in order to measure global heat transfer coefficient distributions. The main advantage of the liquid crystal transient measurement is that model construction is simple and models with compound curvature may be tested. Preheating of the model using a subsidiary hot air supply was relatively easy to perform when an acrylic model was under test. The uniformity of the initial temperature was not such that the subsequent isotherms, indicated by the liquid crystals, represented contours of constant heat transfer coefficient. This was the case in the Oxford work with a heated air stream and model at ambient conditions (refs. 3 and 4). However, the use of two liquid crystals enabled the local heat transfer coefficient at all points on the model to be found when used either in the "double crystal" or "single crystal" mode. This is not to exclude the possibility that a sufficiently uniform model temperature might be produced but a complex heating system would probably be required to achieve this. The analysis of such an experiment would be identical to that previously performed (refs. 3 and 4). Simplicity in model construction might be compromised if a system was introduced to ensure the model is initially isothermal. Thus the emphasis in the experiments was placed on the use of two liquid crystals to eliminate initial surface temperature variations from the problem.

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16 Abstract

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