- Measurement of Heat Transfer Coefficient

Measurement of heat transfer coefficient

Heat transfer experiments using LCT are carried out either at steady-state or during a transient phase.

Steady State Approach

For the steady-state technique, the surface is maintained at constant heat flux and sufficient time is allowed to elapse. With the time invariant temperature contours are established, the surface temperature distribution $T_w(x.y)$ can be obtained using liquid crystal thermography. For a given free stream temperature T_∞, the convective heat transfer coefficient is calculated subsequently as

$$h(x,y) = \frac{q_w}{(T_w(x,y) - T_\infty)}$$

With the steady state approach, the temperature range covered is limited by the bandwidth of the LCT sheet. Thus, multiple experiments are to be performed with varying heat flux settings. A wider range of experiments can be performed, however, with a single broadband liquid crystal sheet. Clearly, such experiments are at the expense of loss of temperature resolution. The transient method determines the local heat transfer coefficient from the time sequence of images of the surface temperature when the surface heat flux is prescribed (or zero). Alternatively, the surface may be insulated and the flowing medium might be at a temperature higher than the initial surface temperature. The narrow - and the wide-band technique each may be employed to establish the heat transfer coefficient distribution over the surface. In such an approach, the heat transfer coefficient is taken to be time-independent.

Disadvantages

The steady state approach has a major disadvantage in that the heat flux measurement is in itself a challenge. In most instances, measuring losses either to the back-up substrate or by radiation can have a great deal of uncertainty. When the working fluid is air, the losses may be as large as the energy transferred to the fluid phase.

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These complications are circumvented when the transient approach is used.

Transient Approach

Here, the knowledge of heat flux is not required, though the thermophysical properties of the base that carries the LCT sheet must be available. An elaborate approach where the transient temperature measurements are combined with the physical laws to provide the local heat transfer coefficient is given in the linked publication here.

The main assumption of the transient approach for heat transfer coefficient evaluation is the small penetration depth of the thermal pulse into the substrate. Analytical solutions to the semi-infinite solid heat conduction problem can be used to relate the transient surface temperature to the heat transfer coefficient. When the substrate has a low thermal diffusivity, a one dimensional model for the substrate conduction is often a good approximation, since the surface temperature is limited to a thin layer near the surface and lateral conduction can be shown to be small (Dunne, 1983; Metzger, 1986). Valencia et al. (1995) numerically assessed the influence of lateral heat conduction on heat transfer experiments and concluded that transient tests were less prone to error than those conducted at steady state.

The transient method has a long history and numerous reviews are available (Baughn, 1995; Ireland, 1999; Ekkad, 2000; Ireland, 2000). In the transient method, the difference in temperature between the model and the surrounding fluid is followed in time, starting with a step change at time $t=0$. There are many approaches utilized to accomplish the change in fluid temperature relative to the surface. Clifford et al. (1983), Ireland and Jones (1985, 1986), Metzger and Larson (1986), and Metzger et al. (1991) used a model where the temperature of the fluid was raised suddenly using switching valves. The basic principles and data reduction procedure are described by Ireland and Jones (1985, 1986).

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In subsequent studies (Wang, 1998), the switched flow systems was replaced by a fine, fast response mesh heater fitted to the duct inlet that produces a step change in gas temperature. This approach avoids the complexity of operating fast acting valves and model positioning activators and thus simplifies the construction facility. Ekkad et al. (1997, 1998, 1998) used this heated stream approach for film cooling measurements. Here, two transients were necessary to obtain the heat transfer coefficient and the film effectiveness.

Other approaches to introducing a step response in temperature include rapidly inserting a heated model into the wind tunnel or using the preheated wall of the wind tunnel and initiating flow using a diverter door. O'Brien et al. (1986) used a preheated cylinder and inserted it in place across a channel that carried fluid at the ambient temperature. Jones and Hippensteele (1987) preheated the wall of their wind tunnel and then initiated flow by using a diverter door. Baughn and Yan (1991a) described a preheated wall method for the study of heat transfer from a surface to an impinging jet. Baughn (1991b) also developed a duct insertion technique to measure the local heat transfer coefficient.

Vogel et al. (2002) carried out a comparative study of various heater-foil configurations for LC based experiments. The authors introduced a new transient heater-foil method for film cooling. Thus, the film cooling effectiveness and heat transfer augmentation could be simultaneously obtained. Baughn et al. (1998) introduced the periodic transient method for heat transfer measurements. Here, the free stream is periodically heated while the changes in the local surface temperature of a model are measured. The local heat transfer coefficient is related to the frequency of periodic changes in temperature, the ratio of the change in surface temperature and that of the free stream and the model thermal properties. The primary advantage of this technique is that it approximates quite well a uniform thermal boundary condition which is often not the case for the step transient. On the other hand, it requires a complex heating arrangement for periodically heating the free stream.

In the studies mentioned above, an initially isothermal test surface is exposed to the thermal transient. The color of the test surface coated with the LC sheet starts to change with time. Each pixel will reach the prescribed temperature (color) depending upon the local heat transfer coefficient. The local heat transfer coefficient is calculated, by suitably using the solution of the classical one dimensional transient heat conduction equation. In principle, a few snap shots of the color images are adequate to reconstruct the heat transfer distribution over the surface. However, in practice, the entire cooling duration of the surface is employed so that heat transfer values are retrieved in a statistical sense by the method of least squares. In this approach, the entire calibration range of the liquid crystal sheet is required. The advantage gained by this route is insensitivity to scatter in isolated measurements and hence, a certain robustness in the prediction of the heat transfer rates.

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