Model Wall and Recovery Temperature Effects on Experimental Heat-Transfer Data Analysis

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Theme

THE phase-change coating technique[1] for obtaining quantitative measurements of the heat transfer to bodies in hypersonic wind tunnels offers economies of both time and money when compared to thin-skin thermocouple techniques, and also yields highly detailed heating distributions not possible with previous methods. The procedures required in utilizing this technique result in data being obtained over long test time intervals and, therefore, at model wall temperature levels and gradients not normally encountered in thin-skin testing. During a phase-change coating test, data at various model locations are obtained at different times, with time intervals sufficiently large to allow significant temperature gradients to exist on the model when the data are obtained. Increased model wall temperature results in an increased sensitivity of phase-change-derived heat-transfer coefficients to the adiabatic wall temperature. Basic analytic procedures are used to illustrate the impact of model and reference adiabatic wall temperatures on the accuracy of experimental heat-transfer data. Inaccurate knowledge of adiabatic wall conditions results in measured heat-transfer coefficient inaccuracies which increase as wall temperatures approach the local adiabatic value. High model wall temperatures and wall temperature gradients affect both the level and distribution of measured heat-transfer coefficient.

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Experimental heating data, obtained using either the thin-skin calorimeter or phase-change coating technique, are usually expressed in the form of the aerodynamic heat-transfer coefficient (h). This parameter is defined by Newton's Law of Cooling as the proportionality constant relating the local heat-transfer rate ($\dot{q}$) and the forcing function of the heat-transfer process, i.e., the difference between the local adiabatic wall temperature (T_{aw}) and the local wall temperature (T_w)

$$\dot{q} = h(T_{aw} - T_w) \tag{1}$$

Both techniques assume a step heat input, usually obtained by rapid injection of an isothermal model into the airstream. For the thin-skin technique, heat-transfer coefficient is based upon heat conduction into a *finite* solid of known thermal properties:

$$h = \rho c_p \lambda [\partial T_w/\partial t][1/(T_{aw} - T_w)] \tag{2}$$

where ρ, c_p, and λ are model material density, specific heat, and thickness, respectively. The measured quantities are the wall temperature (T_w) and its time-rate-of-change ($\partial T/\partial t$). The corresponding equation used to reduce phase-change data is based upon heat conduction into a *semi-infinite* solid of known thermal properties:

$$h = \left[\frac{\rho c_p k}{t_{pc}}\right]^{1/2} \theta \quad \text{where} \quad 1 - e^{\theta^2} \operatorname{erfc}(\theta) = \frac{T_{pc} - T_i}{T_{aw} - T_i} \tag{3}$$

The measured quantity is the time (t_{pc}) required for the model surface temperature to increase from some initial value (T_i) to a known coating phase-change temperature (T_{pc}).

The adiabatic wall temperature is rarely measured in thin-skin tests, and the phase-change technique is incapable of indicating this temperature. Computed heat-transfer coefficients are extremely sensitive to excursions of an assumed value of the adiabatic wall temperature. This is illustrated in Fig. 1 where the ratio of heat-transfer coefficient to that value computed assuming $T_{aw} = T_t$ (freestream total temperature) is presented as a function of T_{aw}/T_t for constant values of phase-change temperature ratio and model initial temperature ratios. The curves clearly indicate the sensitivity of heat-transfer coefficient to the adiabatic wall temperature estimate. The initial model-to-stream temperature ratios of 0.10 to 0.65 are representative of conditions for a room temperature model and current hypersonic wind tunnels. Comparison of the plots for this range of T_i/T_t illustrates the magnification of the coefficient sensitivity (to T_{aw}/T_t) with increasing initial temperature.

Local adiabatic wall temperatures can be adequately estimated for simple shapes by use of "exact" numerical computation techniques; however, for complex geometries, such "exact" numerical solutions are beyond the "state-of-the-art." Consequently, in configuration studies, it has become common practice to base experimental data on a nominal adiabatic wall temperature ratio (T_{aw}/T_t) assumed constant over an entire configuration. The use of a nominal value of $T_{aw}/T_t = 1.0$ in the data reduction results in data which are in error as indicated

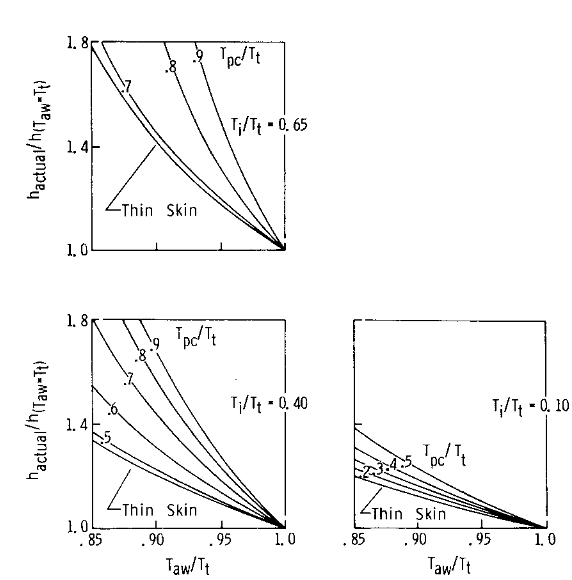

Fig. 1 Effect of adiabatic wall temperature assumption on computed heat-transfer coefficient.

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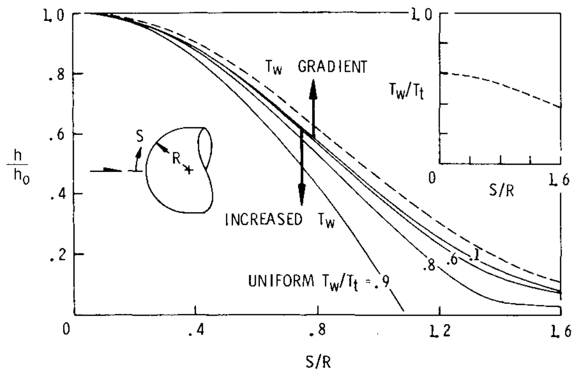

Fig. 2 Theoretical heat-transfer distributions on a hemisphere cylinder at Mach 10.0 in air.

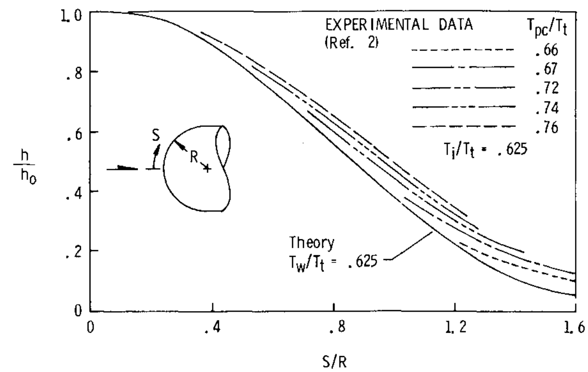

Fig. 3 Effect of wall temperature variation on measured heat transfer on a hemisphere-cylinder at Mach 20.3 in helium.

in Fig. 1. Attempts to reduce this error by assuming a compromise ratio of 0.95 or 0.90 diminish the maximum potential error; however, the functional relationship of heat-transfer coefficient to deviations of the assumed adiabatic wall temperature from the actual value is unchanged.

The effect of wall temperature on heat-transfer coefficient is illustrated in Fig. 2 by solutions to the laminar boundary-layer equations on a hemisphere-cylinder. For a uniform temperature wall, the local heat-transfer coefficient decreases as the wall temperature is increased. This decrease is negligible for low values of the wall-to-total temperature ratio, but becomes significant as wall temperature approaches the adiabatic condition. In contrast, a negative gradient of surface temperature along the wall, results in an increase in the local heat-transfer coefficient. The combined effect of an increase in wall temperatures and the temperature gradient (dashed curve in the insert of Fig. 2) is illustrated by the increment in heat-transfer coefficient from the $T_w/T_t = 0.1$ value; the temperature gradient effect dominates and the heat-transfer coefficient increases.

Phase-change test derived heating distributions on spheres have been frequently used in an inverse method for determining phase-change model material thermophysical properties. This procedure requires comparison of the experimental heating distribution with a theoretical distribution to obtain that value of the phase-change thermal properties parameter, $(\rho c_p k)^{1/2}$, which results in the best correlation. The quality of the measurement is a direct function of the sophistication of the theoretical method utilized. Figure 3 presents experimental phase-change heating data for a hemisphere-cylinder at Mach 20.3 in helium.[2] The measured heat-transfer data were reduced using an adiabatic wall temperature distribution obtained by nonsimilar solution. Also shown is the theoretical heat-transfer distribution for a constant wall temperature equal to the model initial temperature. As can be seen from Fig. 3, the use of a constant wall temperature theory with phase-change data may result in a derived thermal property value which is substantially in error. Thermal properties experimentally derived will be accurate only if the theory adequately models the nonisothermal nature of the phase-change test itself. Conversely, if experimental heating data are to be used to verify theoretical calculation procedures, it is important that the theory accurately model the experiment which produced that data. Data which may exhibit significant wall temperature effects should not be used to verify a theory which lacks the sophistication to account for them.

References

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[2] Stone, D. R., Harris, J. E., Throckmorton, D. A., and Helms, V. T., "Factors Affecting Phase Change Paint Heat Transfer Data Reduction With Emphasis on Wall Temperatures Approaching Adiabatic Conditions," AIAA Paper 72-1030, Palo Alto, Calif., 1972.