Technical Comments

Comment on "Measurement of Aerodynamic Heating of Wind-Tunnel Models by Means of Temperature-Sensitive Paint"

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Nomenclature

h = aerodynamic heat-transfer coefficient
k = thermal conductivity of model material
t = time
T = surface temperature
α = thermal diffusivity of model material
β = $(h/k)\,(\alpha t)^{1/2}$

Subscripts

i = initial condition
aw = adiabatic wall
cc = color change

In a previous note,[1] a method for obtaining quantitative aerodynamic heat-transfer data on complicated models was described. A temperature sensitive paint, which undergoes color changes at certain temperatures, was used in conjunction with a reference sphere for obtaining quantitative aerodynamic heat-transfer data on an X-20 glider model. However, no mention was made of the dependence of the color-change temperature on ambient pressure which could introduce an error into the reference body method unless the pressure on the sphere and the test model were approximately equal at each location where a corresponding color change occurred.

The pink-to-blue color change (one of the three color changes utilized in obtaining data in the note under discussion) for the same type of paint was calibrated by the present authors in 1962 for pressure effects by using the technique described in Ref. 2. The effect of ambient pressure on this color change temperature is shown in Fig. 1, where the color-change temperature is given as a function of the temperature rise rate of the paint for ambient pressures of 3 and 760 mm of mercury. Curves of the form

$$T_{cc} = A + B(dT/dt) + C(dT/dt)^2 \tag{1}$$

are shown as solid lines in this figure. To obtain an indication of the magnitude of the error that could be introduced by neglecting this pressure effect, the surface temperature of the model was assumed to be given by the solution of the partial differential equation governing the transient flow of heat in a semi-infinite slab with a step input in h at time zero. The resulting equation for the surface temperature is

$$(T - T_i)/(T_{aw} - T_i) = 1 - e^{\beta^2}\,\mathrm{erfc}\beta \tag{2}$$

which was differentiated and substituted into Eq. (1) to give

$$\frac{(T_{cc} - T_i)}{(T_{aw} - T_i)} = 1 - e^{\beta^2}\,\mathrm{erfc}\beta - B\left(\frac{\beta}{t}\right) \times \left(\frac{1}{\pi^{1/2}} - \beta\, e^{\beta^2}\,\mathrm{erfc}\beta\right) - C\,(T_{aw} - T_i) \times \left(\frac{\beta}{t}\right)^2 \left(\frac{1}{\pi^{1/2}} - \beta\, e^{\beta^2}\,\mathrm{erfc}\beta\right)^2 \tag{3}$$

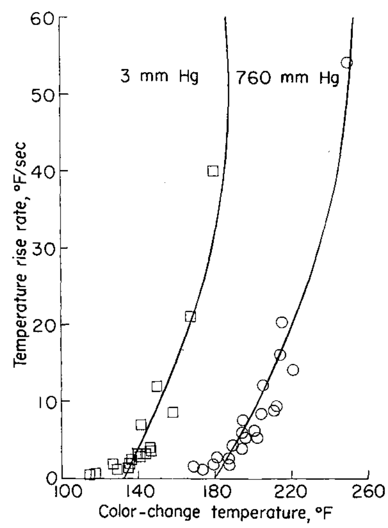

Fig. 1 Calibration curves for pink-to-blue color change.

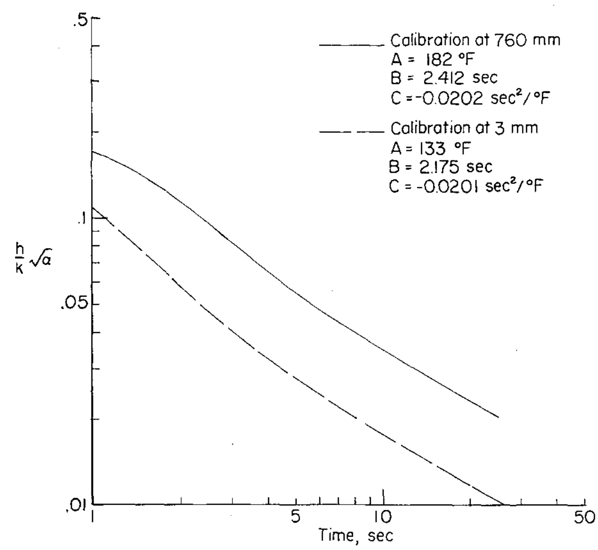

Fig. 2 Solution to Eq. 2 (T_{aw} = 1100°F, T_i = 80°F).

A working form of the solution of Eq. (3) for an initial temperature T_i of 80° F and an adiabatic wall temperature T_{aw} of 1100° F is given in Fig. 2 for the two calibrations at different pressures (Fig. 1) in terms of $(h/k)\,(\alpha)^{1/2}$ as a function of time required for the color change to occur. If the thermal properties of the model (k and α) are assumed constant, the indicated heat-transfer coefficient for the 3-mm-Hg calibration curve is about one-half of that obtained with the 760-mg-Hg calibration curve for test times from 2 to 25 sec. Therefore, if the reference model method were used under conditions for which the pressures of the test model and reference sphere were 3 and 760 mm of mercury, respectively, then at locations where the pink-to-blue color change was observed, the indicated heat-transfer coefficient would be high by a factor of 2.

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Such pressure and heating conditions might occur in interference regions on the lee side of models at angle of attack. However, for certain other test conditions, the error introduced by the pressure effect would be much smaller. Nevertheless, the possibility of large errors caused by the pressure dependence of the color-change paints should always be considered when using this type of coating. In general, the pressure differences between the model and reference sphere should be known and used together with pressure calibrations of the paint.

In Refs. 2 and 3, a different method for obtaining quantitative heat-transfer data with temperature indicating coatings is described. This method uses coatings of pure crystals that undergo clearly visible phase changes at accurately known temperatures that are unaffected by either heating rate or ambient pressure for the range of conditions normally encountered in hypersonic facilities. The isotherms appear as sharply defined lines that progress across the surface of the model as it is heated. These coatings are used, together with theoretical solutions of the transient heat conduction equations [such as Eq. (2)], so that reference bodies are not required. In addition to eliminating the need for tests with reference bodies, the theoretical solutions allow accurate calculation of the magnitude of errors caused by factors such as time required to expose model, error in determining time, error in indicating temperature, etc. This method has been used to measure interference heating effects in the vicinity of protuberances, cavities, and reaction control jets on the Apollo Command Module. Results are believed to be at least as accurate as those obtained from conventional thermocouple models.

References

[1] Kafka, P. G., Gaz, J., and Yee, W. T., "Measurement of aerodynamic heating of wind-tunnel models by means of temperature sensitive paint," J. Spacecraft Rockets **2**, 475–477 (1965).

[2] Jones, R. A. and Hunt, J. L., "Use of temperature-sensitive coatings for obtaining quantitative aerodynamic heat-transfer data," AIAA J. 2, 1354–1356 (1964).

[3] Jones, R. A. and Hunt, J. L., "An improved technique for obtaining quantitative aerodynamic heat-transfer data with surface coating materials," J. Spacecraft Rockets **2**, 632–634 (1965).

Techniques for measuring aerodynamic heat transfer by remote observation are still in development, and the crystalline salt method discussed by Jones and Hunt appears to be another significant contribution to this art.

Comment on "Localization of the Gas-Liquid Interface by Capillary Effects"

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RECENTLY Young[1] has extended his previous results[2] on bubble motion in a temperature gradient to the area of liquid propellant control in low Bond number environments. The equation for the adverse acceleration required to dislodge a bubble is obviously in error. From Eq. (1) in the original paper, the adverse acceleration should be given by

$$g' = \tfrac{3}{2}(dT/dZ)\gamma'/(\rho R981)$$

where 981 cm/sec^2 is the normal acceleration due to gravity. In the author's example, using the given values for the parameters, the calculated g' becomes $-6.53 \times 10^{-6}g$ rather than $-1.17 \times 10^{-4}g$. Although this difference may be significant, it would appear that these calculations, because of the nature of the solution to the original problem, represent gross estimates in those instances where vapor to liquid ratios are large.

References

[1] Young, N. O., "Localization of the gas-liquid interface by capillary effects," J. Spacecraft Rockets **2**, 1010 (1965).

[2] Young, N. O., Goldstein, J. S., and Block, N. J., "The motion of bubbles in a vertical temperature gradient," J. Fluid Mech. **6**, 350–356 (1959).

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Reply by Author to J. L. Hunt and R. A. Jones

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THE problem mentioned by Hunt and Jones has been investigated at The Boeing Company and some of the results have been communicated to R. A. Jones. This investigation has shown that in cases of practical interest, the pressure effects turn out to be of much smaller significance than the preceding comment would suggest. In particular, the color changes from blue to yellow and yellow to black appear to be unaffected practically by pressures ranging from 0.35 mm Hg to atmospheric. The length of exposure to reduced pressure also was of significance in affecting the pink-to-blue transition. Full details of this research, which was carried out by Sartell and Lorenz, will be published shortly.

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Reply by Author to W. J. Masica

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INDEED W. J. Masica and the original article[1] give the correct equations for the poising of a free gas bubble stationary within a large container of liquid. This author's purpose was to show by gross estimate that the location of a gas-liquid interface in some circumstances is controlled by temperature gradients. Temperature gradients can cause gradients of surface tension at the interface and set up fluid circulation. A result is that small free bubbles within a tank will tend to move toward the hottest part of the tank. The feature is that the location of free bubbles can be controlled by temperature gradients.

Reference

[1] Young, N. O., Goldstein, J. S., and Block, N. J., "The motion of bubbles in a vertical temperature gradient," J. Fluid Mech. **6**, 350–356 (1959).

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