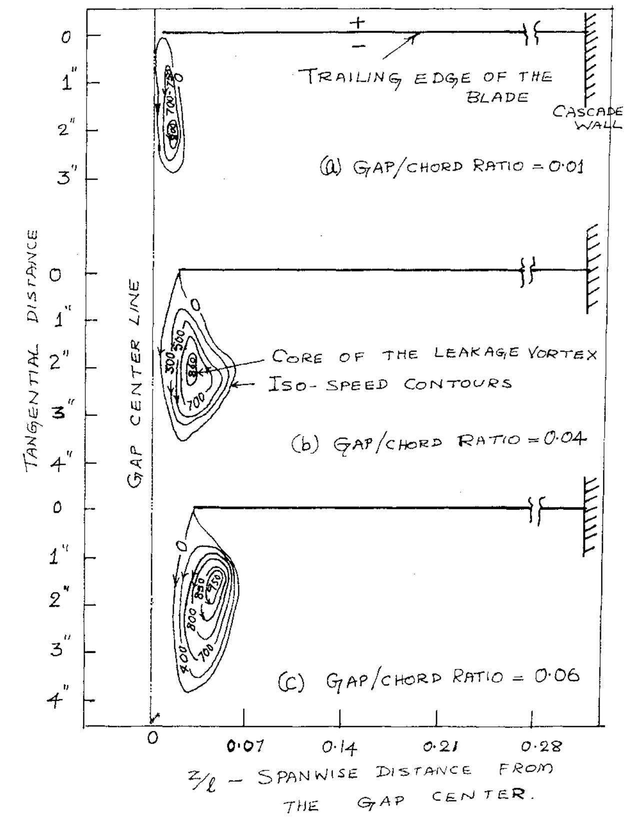

Fig. 3 Comparative strength and location of leakage vortices in a cascade as observed by a vorticity meter for various values of gap/chord ratio. Numbers on the iso-speed contours denote the revolutions per minute of the rotor, and the arrows indicate the sense of rotation.

aluminum and vary from a minimum of three blades to a maximum of six blades, one of $\frac{3}{16}$-, one of $\frac{1}{4}$-, one of $\frac{3}{8}$-, and one of $\frac{1}{2}$-in. diam. All of the rotors have removable shrouds around them. The blades are of aerofoil shape. This, in combination with suitable hub shape, prevents the rotation of the vane in irrotational flow. The constructional details are similar to those used by Todd.[3] The rotors are interchangeable and can be press-fitted to the spindle.

The speed of the rotor was measured by means of a stroboflash. The speed of rotation of a very thin nylon tuft attached to a thin wire was measured in a vortex field and compared with the speeds obtained from the vorticity meter. Nearly identical values confirmed the accuracy of the instrument.

Use of Vorticity Meter for Qualitative Assessment of Leakage Vortices in a Compressor Cascade

The instrument just described was used for measuring, qualitatively, the strengths of the leakage vortices in a compressor cascade at various gap/chord ratios. The instrument was mounted on a traverse gear[4] to enable measurements to be made at various spanwise and passage positions. The iso-speed contours so obtained for various gap/chord ratios are plotted in Fig. 3. The numbers on the contour denote the speed of the rotor in revolutions per minute, and the arrows denote the direction of rotation. The information provided by such contours was found to be very useful. The detailed investigation and conclusions derived therefrom are beyond the scope of this note.

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Use of Temperature-Sensitive Coatings for Obtaining Quantitative Aerodynamic Heat-Transfer Data

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Nomenclature

A = temperature of phase change
$\hat{A}$ = $(A - T_i)/(T_r - T_i)$
h = aerodynamic heat-transfer coefficient
k = thermal conductivity of model material
l = thickness of model surface or allowable depth of heat penetration
M = freestream Mach number
p = parameter used in Eq. (5)
r_d = nose radius
R = Reynolds number based on model diameter and freestream conditions
s = surface distance measured from center of face of model
t = time
t_d = thermal diffusion time
T = temperature
T_i = initial temperature of model
T_r = recovery or adiabatic wall temperature
x = distance normal to model surface
α = thermal diffusivity of model material

SINCE the time that a temperature-sensitive coating was first used at the NASA Langley Research Center for determining qualitative aerodynamic heating rates (early 1959[1]), a development program has been underway to perfect a technique whereby quantitative data could be obtained by this method. It was suggested in Ref. 1 that motion-picture photography could be used to map isotherms at successive times and that this information could be used to estimate the value of the heat-transfer rates. The coating used in Ref. 1 undergoes color changes at certain temperatures. These temperatures are known to be functions of time or heating rate.[1, 2]

Several methods for obtaining quantitative data with this type of coating have been considered. One method would be to measure the time required for the surface to reach the known temperature as indicated by the coating and to calculate the corresponding heat-transfer rate from the transient heat-conduction equation. Another method might be to test a reference body made of the same material as the model (e.g., a sphere for which the heat-transfer rates could be easily calculated) either simultaneously with the model or at the same test conditions, and then to assume that areas on the model and sphere which had color changes at equal times had equal surface temperatures. If the depth of heat penetration is small compared to model dimensions, then these areas would also have equal heat-transfer rates, as indicated by the solution to the heat-conduction equation for a semi-infinite slab. In Ref. 3, the reference sphere method was used with a color-change coating, and heat-transfer rates were determined for a rather complex shape.

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However, the present authors have had considerable difficulty using either of the forementioned methods with coatings that undergo a color change. From wind-tunnel tests with a color-change coating using either of these methods, the indicated heat-transfer rates were different from those of thin-skin thermocouple-calorimeter measurements by factors as large as three. In order to find the reason for these differences and to develop a technique that would give useful results, a calibration rig was built which allowed the accurate measurement of temperature required for a color change for a wide range of heating rates and ambient pressures.† The results showed that these color-change coatings were sensitive to ambient pressure as well as heating rate or time. In fact, a few of these materials were observed to change colors with no change of temperature at all over a range of pressures commonly encountered in hypersonic test facilities. The manufacturer's literature describes this material as metallic salts, which at certain temperatures liberate water vapor, carbon dioxide, or ammonia and, in so doing, change color; therefore, it is possible that the temperature of color change may even depend on local velocity as well as ambient pressure and heating rate. Consequently, in order to use such a material for direct quantitative measurements in a wind tunnel by a reference sphere method, the local pressures on the model and sphere must be equal, as well as the time required for the color change to occur. If transient heat-conduction solutions are used to relate time and surface temperature to heat-transfer rate, extensive calibrations of color-change temperature as a function of heating rate and pressure would have to be made, and the local pressure on the model would have to be known.

With these considerations in mind, a search for a material that would undergo a visible change at a known temperature independent of heating rate or ambient pressure was made. A readily available commercial product that seemed to meet these requirements was found. These materials undergo a phase change from a solid to a liquid at known temperatures. The materials available have phase-change temperatures that differ by as little as 3°F and cover the range from 100° to 3000°F. Calibrations of some of these materials showed that the melting point was not significantly affected by heating rate or pressure when an extremely thin coating (less than 0.001 in.) was used.‡

A method whereby quantitative heat-transfer rates on arbitrary shapes can be determined without the use of a reference sphere has been developed. In this method, the heat-transfer rates depend upon the time required for the phase change to occur and upon the thermal properties of the model material. Results have been obtained which show that this method can be very useful and that reasonably accurate data can be obtained.

A very thin coating of this phase-change material is sprayed over the model, and then the model is rapidly injected into the steady airstream, and the times at which the phase change occurs for various locations on the model are determined by motion-picture photography. When the model is sprayed with a very thin coat of this material, it appears to be covered with opaque-whitish crystals. With care, the coating can be made sufficiently thin so that running of the melted material and errors due to the latent heat of melting are negligible, and yet the contrast between the melted and unmelted areas is adequate for black and white photography. Some examples of patterns obtained by this method are shown in Fig. 1. One set of photographs is of a test made in the calibration rig, which consisted of a thin stainless-steel plate instrumented with thermocouples on the surface and heated from below by a radiant heat source. The other set is of a model tested in the Langley Mach 8 variable density tunnel. The model is a segment of a sphere on which small protuberances were placed to show the detail obtained by the phase-change patterns. The model was tested at an angle of attack, so that the stagnation point is located at the top center of the photographs. The protuberances are small cylindrical pads of about the same thickness as the boundary layer. They are located near the edge of the spherical segment, two near the top and one near the bottom of the photographs. The phase change is taking place at the line separating the light and dark areas.

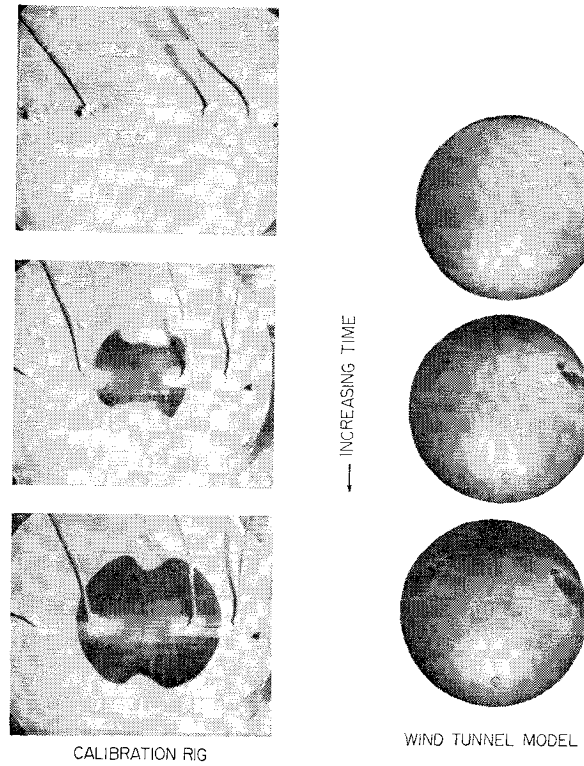

Fig. 1 Photographs of phase-change patterns.

The equation describing the transient one-dimensional flow of heat is

$$\partial T/\partial t = \alpha(\partial^2 T/\partial x^2) \tag{1}$$

with the initial and boundary conditions

$$T(x,0) = T_i \tag{2}$$

$$T(\infty,t) = T_i \tag{3}$$

$$\partial T(0,t)/\partial x = (h/k)[T_r - T(0,t)] \tag{4}$$

It is assumed that the coating is at the temperature $T(0,t)$ and that the value of t is required when $T(0,t) = A$. It is also assumed that the aerodynamic heat-transfer coefficient h is invarient with time, which is a condition normally encountered in the wind tunnel with constant stagnation conditions and a laminar boundary layer. The solution of Eq. (1) with the stated boundary conditions is given in Ref. 4 and can be written in terms of parameters of interest here as

$$\hat{A} = 1 - e^{p^2} \operatorname{erfc} p \tag{5}$$

where

$$\hat{A} = (A - T_i)/(T_r - T_i) \tag{6}$$

$$p = (h/k)(\alpha t)^{1/2} \tag{7}$$

where A is phase-change temperature. The solution of Eq.

† The color change materials tested are called Detectotemp and are sold by Curtis-Wright Corporation, Princeton Division. Some of the materials tested were Detectotemp nos. 915-0907, 915-0910, 915-0923, 915-0950, and 915-0983.

‡ The phase-change materials tested are called Tempilaq and are sold by the Tempil Corporation of New York. Some of the materials tested change phase at temperatures of 113°, 125°, 150°, 175°, 200°, 225°, and 250°F.

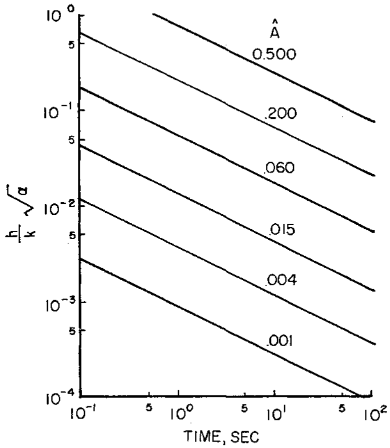

Fig. 2 Solution of one - dimensional transient heat-conduction equation.

(5) for various values of A is shown in Fig. 2 in terms of the parameter $(h/k)\alpha^{1/2}$ as a function of time. The parameter $(h/k)\alpha^{1/2}$ is a function only of the heat-transfer coefficient and the properties of the model material. For a given set of conditions and a time required for the phase change to occur, the value of the heat-transfer coefficient can be read directly from Fig. 2.

The time required for the phase change to occur should be large compared to the time required for the model to reach the proper location in the tunnel, and yet this former time must be short compared with the thermal diffusion time of the model. This thermal diffusion time t_d depends on the thermal diffusivity of the model material and on the allowable depth l of heat penetration and is characterized by the equation

$$\alpha t_d/l^2 \approx 0.2 \tag{8}$$

In practice, the phase-change time can be controlled by selecting a coating with a value A that is suitable for the estimated heat-transfer coefficients to be measured. It may even be desirable to coat different areas of a model with coatings having different values for A. The value of l should be small compared to a model dimension for which accurate data are required, for example, nose or corner radius.

A comparison of some data obtained by this technique with data obtained by the conventional thermocouple-calorimeter technique is shown in Fig. 3 for a blunt re-entry-type configuration at a Mach number of 8. It is thought that data can be obtained by this technique with accuracy approaching that of data obtained by more conventional techniques. In addition, data obtained in regions of interference from protuberances, holes, reaction control jets, and shock impingement show this to be a particularly useful technique for configurations that would be difficult to instrument with thermocouples or for which it is not known exactly where the instrumentation should be placed.

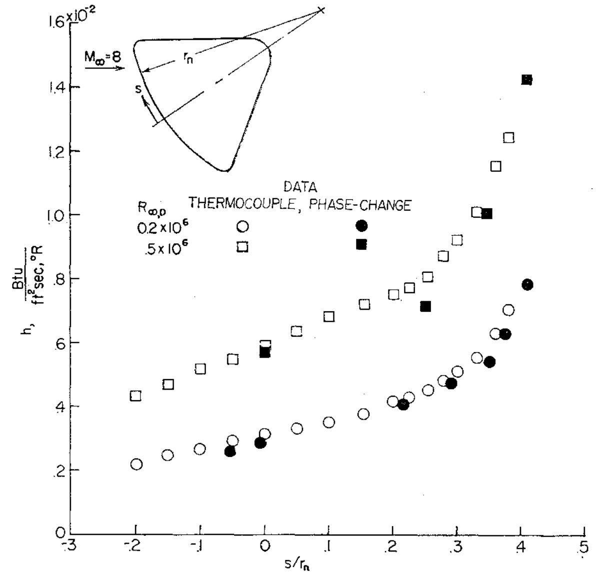

Fig. 3 Comparison of thermocouple-calorimeter and temperature-sensitive phase-change data.

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