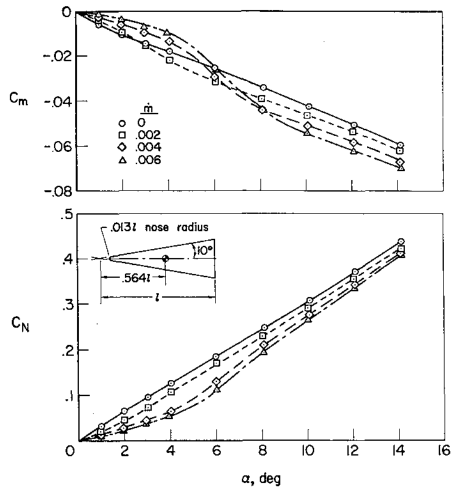

Fig. 1 Effect of mass addition on the normal-force and pitching-moment coefficients for a cone at a Mach number of 21.1 in helium

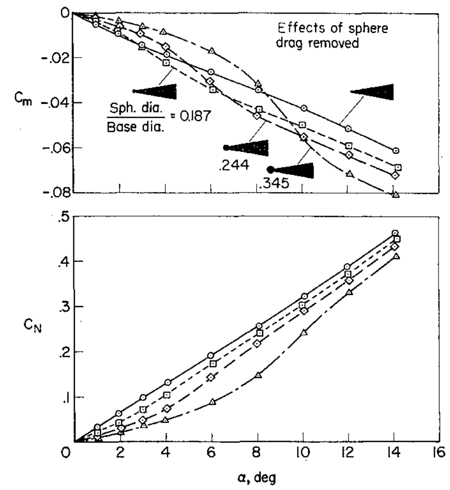

Fig. 2 Effect of oversized spherical bluntness on pitching-moments and normal-force coefficients for a cone at M = 18.1 in helium

1.0; this contribution was subtracted to obtain the results shown in Fig. 2. Note that increasing sphere size has the same effect on pitching moments and normal forces as increasing mass addition rate.

From these latter results, it is suggested that "separation-like" phenomena may be occurring as follows: the injection creates a relatively thick layer of low-energy gas which nearly encases the cone. In many respects this layer behaves as a separated region. When the cone is inclined, the layer cannot support readily the circumferential variation of pressure which produces normal loading. For this reason, both normal force and pitching moment would be reduced, at least at small angles of attack where the cone remains nearly encased in the separated layer. At somewhat higher angles, the separated or low-energy gas will collect on the lee side of the cone. Accordingly, the extent of separation on the windward side will be reduced, and in unseparated regions increased normal loading will be possible. Obviously this trend will occur at lower angles when the separated layer is thinner relative to the body radius. For the test cones, considerations of geometry and continuity indicate that the separated layer is indeed thinner relative to the radius toward the near of the body. From these considerations, it appears that the loading should return to the portions of the body aft of the moment center at lower angles of attack than it returns to the portions forward of the moment center. For this reason, it is suggested that, at some intermediate angles of attack, the moments for a body with separation may exceed in magnitude those for a body without. At these angles, however, the normal forces still will be reduced compared to those for a body without separation. These trends are, of course, those observed in the experimental results.

Use of Transient "Thin-Wall" Technique in Measuring Heat Transfer Rates in Hypersonic Separated Flows

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In the course of an experimental investigation of hypersonic separated flows being carried out at the Gas Dynamics Laboratory in Princeton, several methods of measuring local heat transfer rates were investigated. One of these was the transient "thin-wall" technique, in which a thin-skinned model is subjected to forced convective heat transfer, and the local temperature-time history is used to obtain a measure of the heat transfer rate. This method has been used successfully for many years in the study of attached flows and, more recently, has been applied to separated flows. The model being studied is usually isothermal in the no-flow condition. The tunnel then is started, and the model temperature is recorded as it proceeds toward the recovery temperature distribution. The quantity required is the temperature-time gradient at the instant of starting the tunnel, i.e., when the model was isothermal. In most cases, the heat transfer rate to the model at any point can be expressed usefully in terms of the modified Newtonian Law, and this formulation suggests that the temperature-time variation should be exponential in character for at least the early part of a test run. As a result, an exponential temperature law, or something close to it, usually is anticipated in these experiments. In fact, one common method of reducing the data is to plot the temperature gradient against time from the tunnel start on a logarithmic ordinate scale and extrapolate back to the initial instant using a straight-line law. The reason for extrapolating back to the initial instant is, of course, to avoid the necessity of estimating the conduction effects along the model.

Initial experiments made at this laboratory with laminar cavity-type separated flows at hypersonic Mach numbers have shown that the concepts just outlined must be discarded in certain cases. The temperature-time traces from the section of the model immersed in separated flow in these experiments were very far from exponential in nature, even in the earliest stages of a run. The temperature-time gradient started with a very small value, increased to a maximum, and then decreased again after passing through a point of inflexion. In the reattachment zone and downstream, the traces showed no points of inflexion but still were not exponential in type (see Fig. 1).

Several possible causes of these peculiarities have been considered, and it has been concluded that they were the result of extreme conduction rates along the model. Apparently, the heat transfer rates in the region of separated flow were very low, and the temperature-time traces started

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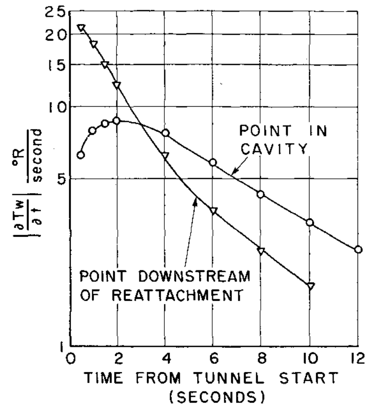

Fig. 1 Typical temperature-history data from cavity model

there with a very small value. Downstream of the cavity, however, the model surfaces changed temperature quickly (particularly in the reattachment region), and the result of this was to draw heat from the cavity surfaces. (Initial wall temperature was greater than adiabatic wall temperature in these experiments.) Later, when some measure of balance had been attained between convection and conduction terms, the entire model continued more slowly to the recovery temperature.

This explanation was checked by carrying out calculations of the conduction terms in the heat transfer equation for the model skin, using polynomials to fit the data at times after the tunnel start. Using these complete calculations, the heat transfer coefficients were calculated over a finite time interval in the early part of a run, and the values were compared with that given by the *initial* gradient of the temperature-time trace. Good agreement was obtained in all cases.

In view of this, it is suggested that caution be exercised in reducing data from experiments using the transient technique in cases where the heat transfer rate varies greatly along the model. Fitting a curve through the data in order to obtain initial temperature gradients is only valid if the form of the curve is known beforehand, and in extreme cases, an exponential variation is not a valid assumption. The need for caution is made greater because of the diffusive nature of the heat transfer equation governing the model temperature distribution. It was found in the present experiments that the temperature traces became roughly exponential in character a few seconds after the tunnel start. This is due to the properties of the parabolic diffusion equation and has no connection with the initial heat transfer rates. There is some danger that an investigator accustomed to exponential temperature traces from more conventional configurations might ignore the initial peculiarities of the curves as due to some initial unsteady effect and use the later exponential sections of the curves for extrapolation purposes. In the case of the present experiments, this would have resulted in the separated-zone heat transfer rates being overestimated by a factor of three. This comment applies particularly to the use of "point-record" potentiometers for recording thermocouple outputs. If the gap between measurement points is too large, the important part of the curve may be missed althogether.

It should be noticed that the initial starting process in a separated-flow configuration may take longer than for an attached flow, because initial transient conditions are not swept immediately downstream. The characteristic time for setting up the steady-state configuration in a cavity flow is of the order of D^2/ν for diffusion of vorticity and D^2/α for diffusion of heat, where D is the depth of the cavity, ν the kinematic viscosity, and α the thermal diffusivity of the fluid. These times were found to be of the order of milliseconds in the present experiments, and the starting process therefore was rejected as a cause of the initial peculiarities in the behavior of the temperature-time traces. (The point of inflexion in the trace from a point in the cavity was found to occur from 2 to 4 sec after the tunnel start.) A more complete discussion of the foregoing is contained in a paper by Nicoll.[1]

[1] Nicoll, K. M., "The use of the transient 'thin-wall' technique in measuring heat-transfer rates in hypersonic separated flows," Princeton Univ. Dept. of Aeronaut. Eng. Rept. 628 (July 1962).

Delaying Effect of Rotation on Laminar Separation

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The experiments of Himmelskamp[1] on an airscrew suggest that the rotation postpones stalling to a higher lift coefficient than would be expected from the two-dimensional characteristics of the airscrew blade sections. In confirmation of the experiments, this note presents a theoretical analysis of a simple case where rotation is found to delay laminar separation and sometimes to prevent it entirely.

Consider a helical surface rotating and advancing at zero incidence, with a straight leading edge perpendicular to the axis of rotation, as in Fig. 1. It is shown in Ref. 2 that the equations for the boundary layer on such a surface are, if the pitch is only moderate, approximately equivalent to those for zero pitch, i.e., for a flat sector of a circle rotating in its own plane, with zero velocity along its axis of rotation. Referred to axes θ, r, y rotating with the sector with angular velocity Ω, the velocity components u and w in the tangential and radial directions are Ωr and zero outside the boundary layer. Suppose now that the helical surface, to which the sector is equivalent, is distorted slightly or operated at a small incidence, so that the pressure over its surface is nonuniform. Consider the special simple case where, for the equivalent sector, the tangential and radial velocity components outside the boundary layer are $\Omega r(1 - K\theta)$ and zero, where K is a constant. The equations of motion become approximately

$$\frac{u}{r}\frac{\partial u}{\partial \theta} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial r} - \frac{w(2r\Omega - u)}{r} = -r\Omega^2 K(1 - K\theta) + \nu\frac{\partial^2 u}{\partial y^2} \quad (1)$$

$$\frac{u}{r}\frac{\partial w}{\partial \theta} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial r} - \frac{(r\Omega - u)^2}{r} = -r\Omega^2 K^2\theta^2 + \nu\frac{\partial^2 w}{\partial y^2} \quad (2)$$

$$\frac{1}{r}\frac{\partial u}{\partial \theta} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial r} + \frac{w}{r} = 0 \quad (3)$$

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