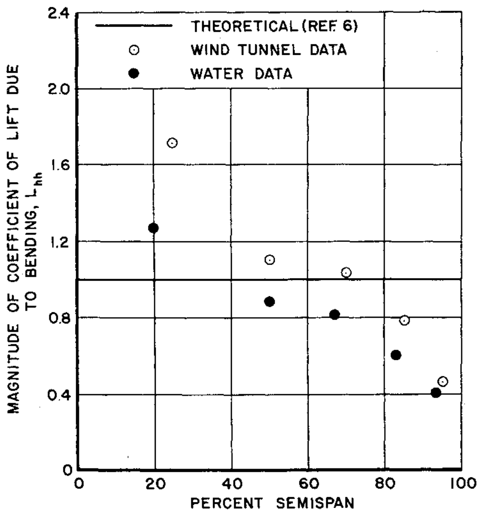

Fig. 5 Lift coefficient due to bending ($1/k = 0$)

Although the data from the tests in water are not of as high quality as from those in air, correlation between the two sets of experimental data is remarkably good, with the exception of the phase angle of moment due to bending (Fig. 3). Agreement between experimental and theoretical lift coefficients is generally good, but that between experimental and theoretical moment coefficients leaves something to be desired. The phase of the moment due to bending (Fig. 3) is puzzling because this is the only instance where the air and water-test data do not appear to correlate well; one could speculate that the experimental data *do* correlate and that any deviation resides with the theory (compare with the phase variation shown in Fig. 4). The moment due to torsion is interesting because the two sets of experimental data correlate very well but differ significantly from theory; for the higher values of reduced velocity, this seems to agree generally with previous investigators. It is emphasized that the selection of 50% semispan as a reference station was entirely arbitrary, dictated only by the fact that this was the only spanwise station at which measurements were made in both air and water tests.

Figure 5 shows that the general effect of the actual finite span on the shape of the spanwise distribution remains significant down to even $1/k = 0$ (the other coefficients show quite similar effects). Of course, theoretical finite span effects[6] begin to diminish rapidly for small values of reduced velocity, reducing to the two-dimensional values of lift and moment at $1/k = 0$. More detailed comparisons with finite span theory over the range of reduced velocities are given elsewhere.[4]

Although few final conclusions should be drawn from the limited data on hand and the few correlations with theory that have been made, the extent of the differences between the classical theory and the measured coefficients at low reduced velocities appears to be significant. This applies particularly to the moment coefficients, where the phase of the moment due to bending requires additional data, and both the magnitude and phase of the moment due to torsion depart from theory rather significantly, on a percentage basis, as reduced velocity decreases.

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Turbulent Mixing of Compressible Free Jets

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THE effect of Mach number on the spreading rate of turbulent free jets (in the half-jet mixing region) is not clearly defined. Estimates[1, 2] of σ, jet-spreading parameter, as a function of Mach number differ by a factor of 2 at $M = 2$.

An experimental investigation[3] of the turbulent mixing of axisymmetric jets with quiescent air at nozzle exit Mach numbers of 0.70, 0.85, 0.95, 1.49, and 1.96 was conducted at Sandia Laboratory. Radial Pitot and static pressure surveys were made at 0.5, 1.0, 2.0, 3.0, and 3.84 nozzle diameters downstream of the 3-in.-diam nozzles. The 0.042-in.-diam Pitot and static probes were mounted on a lathe bed assembly. Probe position was measured with a 10-turn Helipot geared to the lathe bed assembly. Probe position and pressure data, measured by unbonded strain-gage transducers, were recorded in both analog (strip chart recorders) and digital (IBM cards) form. Data reduction with the CDC 1604 high-speed computer greatly facilitated handling the copious quantity of data.

Velocity profiles were calculated, assuming a constant total temperature through the mixing region. The virtual origin of the mixing region (resulting from the nozzle-wall boundary layer) was determined by extrapolating the width of the mixing region $b_{0.1}$ (for the five axial stations) to zero. The width $b_{0.1}$ is defined as the radial distance between 0.1 $(V/V_1)^2$ and 0.9 $(V/V_1)^2$ streamlines, where V/V_1 is the ratio of local velocity to velocity at the inner edge of the mixing region. The measured virtual origins are 0.2, 0.5, and 0.8 in. upstream of the nozzle exit for Mach 0.70, 0.85, 0.95; 1.49; and 1.96; respectively. The data indicated linear growth of the mixing region with axial distance.

The experimental velocity distributions (in the nondimensional form of $\sigma y/x_e$ vs V/V_1) were compared with Crane's[4] and the error-function theoretical profiles. The jet-spreading parameter, σ, is proportional to the spreading rate of the mixing region and is determined by comparison of experimental with theoretical profiles. The coordinates y and x_e are the radial and the axial-plus-virtual-origin dimensions, respectively, with y measured from the $V/V_1 = 0.5$ streamline. Considerable effort was devoted to trying to fit the data (by the right choice of σ) to the error function distribution, since this simple mathematical model is easier to apply to other problems. However, the data correlated well with Crane's[4] (or Gortler's[5]) solution for incompressible flow. The correlation is shown in Fig. 1 for $\sigma = 10.5, 10.8, 11.0, 15.0$, and 20.0 for Mach 0.70, 0.85, 0.95, 1.49, and 1.96, respectively. Data from 16 repeat runs[3] (not presented herein)

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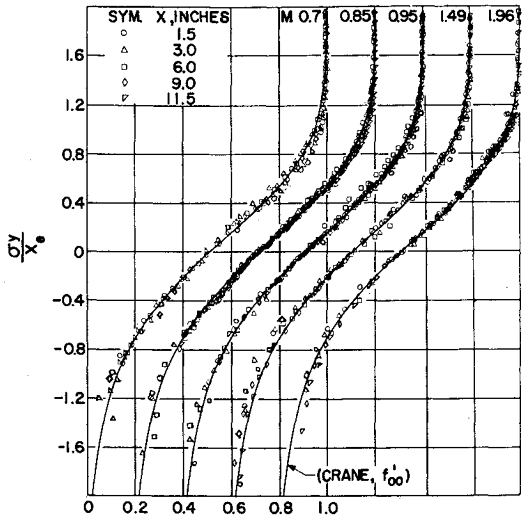

Fig. 1 Normalized velocity profiles

indicate the same results as the data from the 25 surveys shown in Fig. 1.

The nondimensional velocity profiles are similar at axial stations from $0.5 \leq x/D \leq 3.84$ at the five Mach numbers, i.e., there is no discernible effect of Mach number (at $M < 2$) on the shape of the velocity profile. This tends to support Crane's[4] reasoning that (because of compensating effects) the nondimensional velocity profile for compressible flow essentially is unchanged from that obtained for incompressible flow.

These jet-spreading parameter data are presented in Fig. 2, along with the available experimental data[3] from other sources; the estimated variation of σ with M also is shown. A value of $\sigma = 12$ for incompressible flow has been used widely for many years; however, Liepmann and Laufer determined a value of $\sigma = 11$ from comparison of their low-speed data with Gortler's (or Crane's) theoretical velocity profile. Hence, it is concluded that the spreading rate of the mixing region is essentially constant ($\sigma \approx 11$) at subsonic speeds and decreases (with increasing Mach) at supersonic speeds. The estimated error in determining σ in these experiments is $\pm 5\%$.

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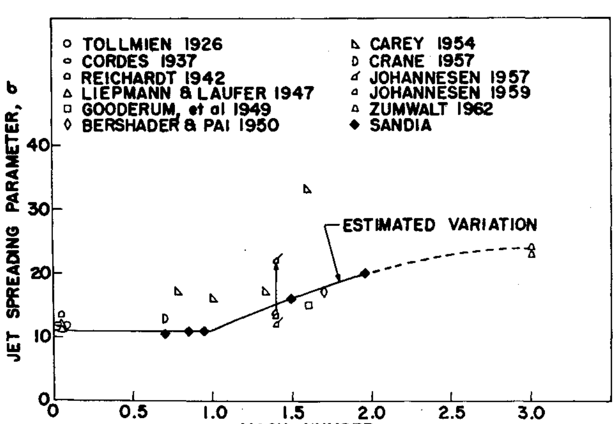

Fig. 2 Summary of jet spreading data

Successful Re-Entry of Space Fragments from a Decaying Earth Orbit

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Nomenclature

A = reference area for drag, ft^2
c = heat capacity, Btu/lb°R
C_D = drag coefficient
g_c = gravitational constant, 32.2 ft/sec^2
R = effective radius, ft
r = actual radius, ft
S = surface wetted by boundary layer, ft^2
T_w = maximum temperature of fragment during re-entry, °R
t = thickness, in.
W = weight, lb
ρ = fragment density, lb/ft^3
ϵ = surface emissivity
σ = Stefan-Boltzmann constant, 0.48×10^{-12} Btu/ft^2 sec °R^4

THE fact that space debris can successfully re-enter the earth's atmosphere has been underlined by the recent orbital decay of a Soviet satellite and of United States space boosters.[1, 2] One of the most publicized Soviet fragments is a thick metal disk weighing about 20 lb. Most of the fragments recovered from the space boosters can be typified as thin metal plates. The idealized fragment whose re-entry heating characteristics are examined in this note is a circular plate oriented perpendicular to the flow.

For cases of negligible heat capacity (very thin plates), Chapman's expression for laminar-convective heat flux[3] may be equated with the radiant heat flux from the fragment to give

$$\epsilon\sigma T_w^4 = 590 K_1 \left(\frac{W}{C_D A R g_c}\right)^{1/2} \bar{q} \qquad (1)$$

For re-entry of nonlifting bodies from a decaying earth orbit, the maximum value[3] of the dimensionless heating rate $\bar{q}$ is 0.218. For this disk geometry, the local-convective heat flux will be assumed equal to the stagnation value (cf., Ref. 4) so that $K_1 = 1$.

For heat-sink fragments (very thick plates), one may equate the total convective heat flux during re-entry to the heat stored in the fragment. Equating the expression for total laminar heat flux, found in Ref. 3, to the stored heat gives (neglecting radiation from the surface and internal temperature gradients)

$$Wc(T_w - T_i) = 15{,}900\ K_2 S \left(\frac{W}{C_D A R g_c}\right)^{1/2} \bar{Q} \qquad (2)$$

For nonlifting re-entry from an earth orbit,[3] $\bar{Q} = 1.36$; the assumption $K_1 = 1$ implies $K_2 = 1$.

In evaluating these equations the authors will take $r = 1$, $C_D = 2$, $\rho = 501$, and $c = 0.17$, which is typical for stainless

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