pletion of the energy transfer. However, although the "functional relationship" between shock location and time is remarkably close to the prediction of the theory as modified for "variable energy" blast waves, Eq. (1), a modified constant is required for a good match. In the present case with $\beta = 2$, ratios of shock arrival times at two fixed locations are predicted remarkably well by the expression

$$t_2/t_1 = (R_2/R_1)^{4/\beta+2} \tag{2}$$

given by the modified blast wave theory.

References

[1] Taylor, G. I., "The Formation of a Blast Wave by a Very Intense Explosion," *Proceedings of the Royal Society, London*, Ser. A201, 1950, pp. 159–174.

[2] Lin, S. C., "Cylindrical Shock Waves Produced by Instantaneous Energy Release," *Journal of Applied Physics*, Vol. 25, No. 1, 1954, pp. 54–57.

[3] Sedov, L. I., *Similarity and Dimensional Methods in Mechanics*, Academic Press, New York, 1959.

[4] Sakurai, A., *Basic Developments in Fluid Dynamics*, edited by M. Holt, Academic Press, New York, 1965, pp. 309–375.

[5] Freeman, R. A., "Variable Energy Blast Waves," *British Journal of Applied Physics (Journal of Physics D)*, Ser. 2, Vol. 1, 1968, pp. 1697–1710.

[6] Dabora, E. K., "Variable Energy Blast Waves," *AIAA Journal*, Vol. 10, No. 10, Oct. 1972, pp. 1384–1386.

[7] Oktay, E., "Effect of Wire Cross Section on First Pulse of an Exploding Wire," *The Review of Scientific Instruments*, Vol. 36, No. 9, 1969.

Incipient Separation of Axially Symmetric Hypersonic Turbulent Boundary Layers

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Introduction

IN a recent Note, Rose Page and Childs[1] showed that the pressure rise for incipient separation in axially symmetric internal supersonic flow could be considerably lower than for planar, two-dimensional flows. However, for axially symmetric external supersonic flow Kuehn[2] found that the turbulent boundary layer can withstand a slightly larger pressure gradient before separation occurs. The present hypersonic cold wall experiments have confirmed Kuehn's result and have emphasized the close relation between the axisymmetric and two-dimensional cases. This similarity suggests that criteria evolved from the large amount of available two-dimensional data may be used in the design of control surfaces for hypersonic vehicles.

Experimental Details

The experiments were conducted at a freestream Mach number of 9 in the Imperial College No. 2 Hypersonic Gun Tunnel,[3] using Nitrogen as the test gas. The model was a sharp leading edge hollow cylinder of 6.4 cm outside diameter to which could be added trailing edge flares with angles in the range $15° < \alpha < 40°$. Both the cylinder and the flares were instrumented with

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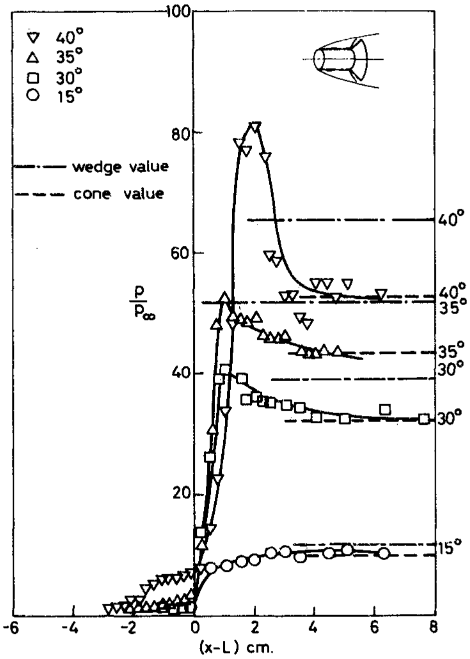

Fig. 1 Pressure distributions on a hollow cylinder-flare; $M_\infty = 9.22$, $Tw/Tr = 0.28$, $Re_{\delta_L} = 2.14 \times 10^5$.

surface pressure tappings and thin film gauges for heat-transfer measurement. The length of the cylinder ahead of the flare was 45.7 cm.

All tests were conducted with the cylinder axis parallel to the freestream. The experimental data have been tabulated by Coleman.[4]

Discussion

The surface pressure distributions (Fig. 1) were similar to the two-dimensional data (Fig. 2) reported by Elfstrom.[5] Elfstrom noted that, for two-dimensional hypersonic flow, the incipient

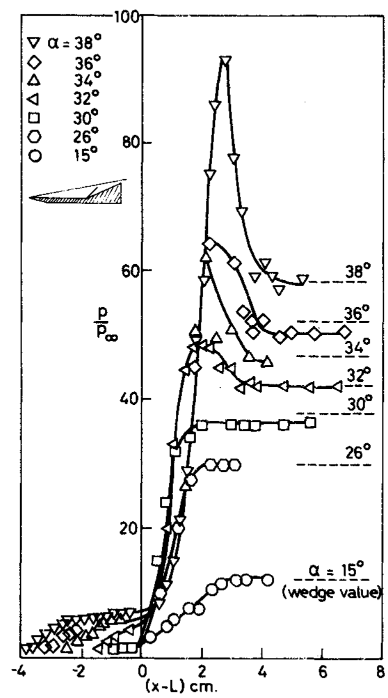

Fig. 2 Pressure distributions on a wedge compression corner (Elfstrom[5]); $M_\infty = 9.22$, $Tw/Tr = 0.28$, $Re_{\delta_L} = 3.4 \times 10^5$.

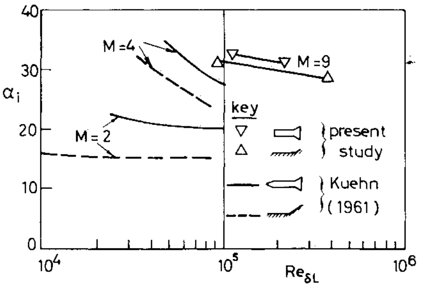

Fig. 3 Comparison of axisymmetric and planar two-dimensional incipient separation results.

separation angle (α_i) could be determined from the disappearance of the pressure overshoot downstream of reattachment on the wedge. This criterion is less reliable for the axisymmetric case because the attached flow pressure distribution is already of this form with a locally two-dimensional pressure rise at the corner followed by a gradual decay to the cone value far downstream on the flare.

Incipient separation was determined here by three methods which had given good agreement for the two-dimensional configuration.[4,5] These were 1) looking for the onset of an increase in pressure and heat-transfer rate ahead of the flare; 2) looking for a change in the shape of the pressure and heat-transfer distributions on the flare; and 3) by plotting the separation length (l) as measured from schlieren photographs, against flare angle and extrapolating to $l = 0$. The answers from these three methods agreed to within $\frac{1}{2}°$. The results (Fig. 3) are compared with the wedge compression corner experiments of Elfstrom and Coleman.[4,6] The results of Kuehn[2] for Mach numbers of 2 and 4 are also shown. All of the data exhibit the trend of decreasing α_i with increasing Re_{δ_L} where δ_L is the undisturbed boundary-layer thickness at the cylinder-flare junction. This is opposite to the trend noted by Rose, Page, and Childs in their nozzle wall experiments and may be the result of different upstream histories of the boundary layers in the two cases.

Data are presented by Rose, Page, and Childs[1] "which indicate that separation occurs in axially symmetric flows at much lower pressure rises than would be expected on the basis of previous data for planar two-dimensional flows." This conclusion is in direct contrast to the information given here and to that given by Kuehn,[2] both of which compare planar and axisymmetric external flows. Either there is a great difference between incipient separation on internal and external surfaces, or the determination of incipient separation is very sensitive to the detection method employed, as found for example by Spaid and Frishett.[7] From a practical viewpoint, the designer needs to know when significant changes in pressure and heat-transfer rate distributions will occur as a result of separation so there is considerable merit in using such measurements to define incipient separation whenever possible.

To summarize, our results have shown that for axisymmetric external flow the incipient separation angle is slightly higher than for the planar two-dimensional case. There is a close similarity between the surface pressure and heat transfer rate distributions for the two cases.

References

[1] Rose, W. C., Page, R. J., and Childs, M. E., "Incipient Separation Pressure Rise for a Mach 3.8 Turbulent Boundary Layer," *AIAA Journal*, Vol. 11, No. 5, May 1973, pp. 761–763.

[2] Kuehn, D. M., "Turbulent Boundary Layer Separation Induced by Flares on Cylinders at Zero Angle of Attack," TR R-117, 1961, NASA.

[3] Needham, D. A., Elfstrom, G. M., and Stollery, J. L. "Design and Operation of the Imperial College No. 2 Hypersonic Gun Tunnel," Aero Rept. 70-04, 1970, Imperial College, London, England.

[4] Coleman, G. T., "Hypersonic Turbulent Boundary Layer Studies," Ph.D. thesis, 1973, Dept. of Aeronautics, Imperial College, Univ. of London, London, England.

[5] Elfstrom, G. M., "Turbulent Hypersonic Flow at a Wedge Compression Corner," *Journal of Fluid Mechanics*, Vol. 53, Pt. 1, 1972, pp. 113–127.

[6] Coleman, G. T. and Stollery, J. L., "Heat Transfer from Hypersonic Turbulent Flow at a Wedge Compression Corner," *Journal of Fluid Mechanics*, Vol. 56, Pt. 4, 1972, pp. 741–752.

[7] Spaid, F. W. and Frishett, J. C., "Incipient Separation of a Supersonic Turbulent Boundary Layer, Including Effects of Heat Transfer," *AIAA Journal*, Vol. 10, No. 7, July 1972, pp. 915–922.

Strong Spherical Blast Waves in a Dust-Laden Gas

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Nomenclature

C_D = drag coefficient (gas flow drag on dust particle; based on cross-sectional area of sphere)
E_o = energy of blast, joules (sphere); joules/m (cylinder)
M' = $|v_p - v|(\gamma p/\rho)^{-1/2}$—Mach number of flow relative to dust
p = gas pressure, N/m^2
r = spatial coordinate measured from center of blast, m
r_p = coordinate of dust particle, m
$r_{p\,min}$ = coordinate of inner boundary of dust layer, m
R_s = coordinate of shock wave, m
R_{s_1} = initial value of r_p for a particle trajectory, m
Re' = $2\rho|v - v_p|\sigma_p/\mu$—Reynolds number based on flow relative to dust
t = time, sec
t_1 = time when shock reaches particle located at R_{s1}, sec
T, T_p = gas temperature, dust particle temperature, °K
v, v_p = gas velocity, dust particle velocity, m/sec
γ = ratio of specific heats of gas
μ = viscosity coefficient, kg/(m sec)
ρ, ρ_p = gas density, material density of dust particle, kg/m^3
σ_p = radius of spherical dust particle, m

Subscript

∞ = initial undisturbed condition

Statement of Problem

WHEN a blast wave passes through a dust-laden gas, the ensuing motion of the dust particles may produce noticeable effects on the loading and abrasion experienced by structures in the vicinity of the explosion. This Note discusses a simplified treatment of the two-phase flow produced by a spherical blast wave traveling through a uniform dust-laden gas.‡ The assumptions made here permit us to neglect interaction of particles and the effect of the particles on the gas flow; the problem reduces then to the computation of trajectories of individual dust particles (considered point masses) in a known unsteady flow-field.

The following assumptions are made for the dust: 1) the particles are spheres of uniform size and material density,

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‡ A more detailed account is found in Ref. 1.