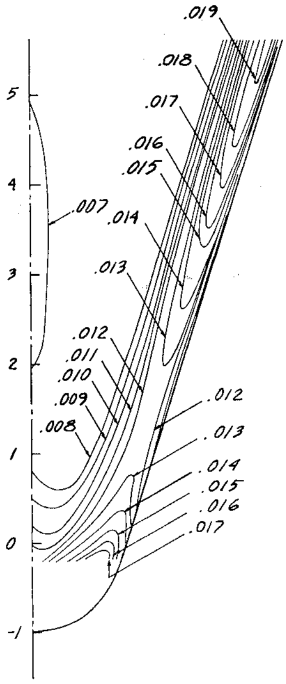

Fig. 1 Computed isobars on windward surface of blunted delta wing at $\alpha = 10°$, $M = 20$ (pressures in atmospheres).

matically changed in the course of the computation according to a scheme prescribed in advance, to follow the geometry of the body.

Full details on the program, which includes techniques for the computation of the shock wave, for the boundary condition on the body, for the evaluation of the cross-derivatives, and for real gas effects, can be found in Ref. 3. Here some significant results will be presented. The following cases have been computed:

1) Delta wing of 70° sweepback, with spherical nose and rounded leading edge, at no angle of attack, $M = 8$ (perfect gas) and $M = 20$ (real gas in equilibrium), length 10 nose radii (January 1961).

2) Blunted cone, 20° semi-apex angle at $\alpha = 5°$, $M = 8$, calculation performed all around the body, length 11 nose radii (June 1961).

3) Dynasoar body (combination of different delta wings, with different sweepbacks, different leading edges, and different inclinations) at $M = 18$, at 10° and 30° angle of attack, length 37 and 5 nose radii, respectively; computations of the windward side (September 1961).

4) Combination of sphere, cone, and cylinder; $M = 22$, $\alpha = 10°$ and 30°, length 7 nose radii, computation of the windward side for the higher angle of attack and of the whole flow field for the lower angle (April 1962).

These computations, besides proving the reliability and effectiveness of the technique, have provided interesting information from the aerodynamical and computational standpoint. Case 2 has given numerical confirmation to the experimental results that an overexpansion takes place behind the nose of the cone, followed by a recompression, and that a practically conical flow is reached at about 6 nose radii from the nose of a blunted cone. Cases 3 and 4 showed the difficulties in stepping away from the initial axisymmetric region in the case of a very high angle of attack. In the same cases the independence of the windward side from the leeward side has been successfully applied to make possible the computation only on the side of interest. In case 4 an additional technique for computing streamlines was applied.[4]

The required IBM 7090 time per step in each meridional plane is about $\frac{1}{200}$ min, using seven points on each radial line. Examples of results are given in Figs. 1 and 2.

Figure 1 shows a sample of computed isobars on the surface of the delta wing at angle of attack. Figure 2 shows the computed shape of the shock surface on the windward side of a delta wing at angle of attack.

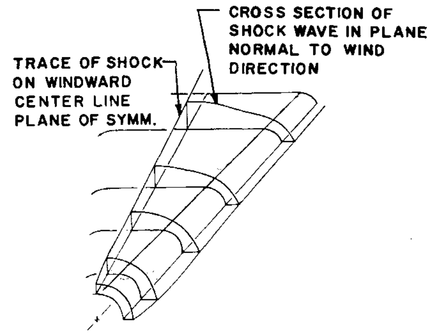

Fig. 2 Computed shock wave envelope about blunted 70° sweepback delta wing at $\alpha = 20°$, $M = 8$.

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Measurements of Heat Transfer Rates in Separated Regions in a Shock Tube and in a Shock Tunnel

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SHOCK tubes and shock tunnels have been used extensively in the last few years for heat transfer studies using their supersonic and hypersonic high enthalpy flows. It has been shown that quasi-steady heat transfer rates are established over a regular model in the shock tube within 10 to 50 μsec (e.g., results in Ref. 1). The flow starting process in the shock tunnel is more intricate. For the tailored interface shock tunnel this starting time has been measured to be about 1 msec out of the 5 or 6 msec available duration of steady flow.[2] The establishment of steady flow conditions in these facilities has been ascertained by schlieren photography and by pressure and heat transfer measurements.[1, 2] The use of these very short duration intermittent operating facilities for studies of separated flows is underway in various laboratories.[3–5] In the case of separated flows one must prove that in addition to the steadiness of the external flow, the intermittent flow duration is sufficient to establish steady mass and heat transfer conditions within the separated region. This problem has been acknowledged by those concerned in shock tube work, and the establishment of steady heat transfer in each case is discussed in Refs. 3–5. How-

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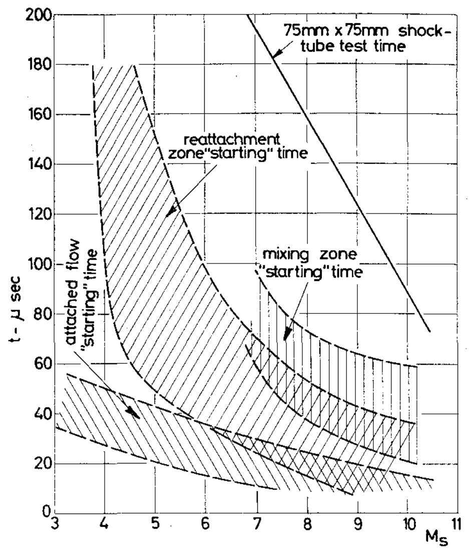

Fig. 1 Time of establishment of steady flow in various flow regions over a backward facing step in the shock tube.

ever, because of the fact that the establishment of steady heat transfer conditions in a separated region is longer than the corresponding attached flow case, there seems to be a feeling that this time may be much longer than available shock tube testing duration. A study, related to this problem, on the adjustment of a separated flow to transient external flows has been conducted by Ihrig and Korst.[6] According to Ref. 6 the adjustment of a separated flow to transient conditions is characterized by three "characteristic times." 1) pressure wave characteristic time $\Delta t_a = L/a_a$; 2) mass transfer characteristic time $\Delta t_m = (L/U_a\Gamma)$; and 3) heat transfer characteristic time $\Delta t_H = (L/U_a\, St)$, where L is a characteristic length of the separated region, a_a = local speed of sound, U_a = local external velocity, Γ = mass mixing parameter, and St = Stanton number. It is realized that of these three characteristic times the slowest adjustment process is the establishment of steady heat transfer. Assuming turbulent heat transfer values of $St \sim 0.01$, one finds that $\Delta t_H = (100/M_a)\cdot\Delta t_a = [100\cdot L/M_a\, a_a]$ where $M_a = U_a/a_a$ = local external Mach number. Let the product $M_a \cdot a_a$ be approximately equal to the free shock tube flow value. This can be justified by the fact that the decrease of a_a behind the expansion fan at the separation point of a base type flow is followed by a comparable increase of M_a. The values of Δt_H for a 2-mm separation region height is then about 190 μsec at $M_s = 4$ and about 70 μsec at $M_s = 10$. These values are not out of the range of testing duration of moderate size shock tubes. However, according to this estimation, studies of laminar heat transfer in separated flow may require much longer testing duration due to the lower values of laminar heat transfer rates. This analysis of Ihrig and Korst[6] is applicable to the case of abrupt changes in external flow conditions such as jump in stagnation pressure during wind-tunnel tests. However, the conditions of flow establishment in the shock tube are different. Up to the arrival of the shock wave there is no flow and the model is at room temperature. The flow over the model is started impulsively immediately after the shock wave passage. With this impulsive start the model surfaces, including the separated region boundaries, are exposed to the high-temperature gas without the benefit of a protective viscous layer. So initially those surfaces are exposed to extremely high heat transfer rates. With the development of a viscous layer, be it a boundary layer or a separation region, the heat transfer rate is adjusted to an equilibrium value that is determined by the aerodynamic parameters. The initial adjustment duration will be much faster than those estimated by the quasi-steady characteristic times of Ref. 6 because of the much higher initial transient heat transfer rates due to the nonexistence of initial viscous layers. The initial process is somewhat similar to the heat transfer to the shock tube wall immediately following the shock front.

The establishment of equilibrium heat transfer rates in a laminar separated region over a backward facing step of 1.5-mm height in the shock tube is discussed in Ref. 5. The measured starting times of steady heat transfer rates at the various flow regions are shown in Fig. 1. It is found that for M_s above 5, steady heat transfer rates are established in the laminar separated regions two to three times slower than the corresponding heat transfer rates for attached laminar flows in the shock tube. Still, this steady heat transfer establishment time is about 40–60% of available testing duration in the 7.5 × 7.5 cm − 7-m-long shock tube. Laminar heat transfer rates can then be studied in a separated region with reasonable range of shock tube operating conditions. The establishment of steady heat transfer rates in turbulent separation regions is of course much faster than the corresponding laminar case. So that one may conclude that although careful attention must be paid to the establishment of steady heat transfer conditions in separated flows, there are ranges of shock tube operating conditions where such equilibrium is reached within the available test duration. The much longer duration of testing time in the tailored interface shock tunnel makes this facility suitable for most separated region studies including laminar heat transfer measurements.

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Comments

Comments on "A Note on the Classical Buckling Load of Circular Cylindrical Shells under Axial Compression"

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THE author's[1] photoelastic pictures of the buckling process are interesting, especially the concrete evidence that the shell passes through intermediate unstable equilibrium states

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