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Transition in Compressible Free Shear Layers

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Nomenclature

l = shear-layer length to transition point
Re_T = $\rho_2 u_2 l/\mu_2$ transition Reynolds number
u = velocity
λ = $(1 - u_3/u_2)/(1 + u_3/u_2)$
μ = dynamic viscosity
ρ = density

Subscripts

o = value when $u_3 = 0$
1 = conditions behind generator shock
2,3 = conditions on high and low velocity side of shear layer
∞ = freestream conditions

Introduction

CURRENT interest in shock-on-shock interaction flows is prompted by the associated increase in surface heat transfer. In 1968, Edney[1] identified six basic types of flow produced by unequal shock interactions. Here, we consider only one of these flows, identified as Type III by Edney. This flow, which results from the interaction of a strong and weak shock, produces a single shear layer with supersonic flow on one side and subsonic flow on the other. It has been shown[2] that the surface heat transfer in the attachment region strongly depends on whether or not this shear-layer flow is turbulent. It is, therefore, of interest to establish the transition Reynolds number Re_T for shear layers produced by these interactions, since no such data appear to be available.

Results

The results presented here are based on two separate studies using the Langley 20-in. (Mach 6) and 11-in. (Mach 6.9) Hypersonic Tunnels.[3] In each case, a variable angle wedge generates a planar shock wave which interacts with the bow wave of a bluff body. The interaction geometry obtained in the two facilities differed in that the bluff body used in the 11-in.-tunnel was two-dimensional, 7.62 cm (3-in.) long, and 6.35 cm (2½-in.) wide, whereas that used in the 20-in. tunnel was a hemisphere/cylinder, 5.08 cm (2-in.) in diam. A side view of the model used in the 11-in. tunnel is shown in the schlieren photograph in Fig. 1, and further details of the apparatus used in the 20-in. tunnel are given in Ref. 4. The transition length l is defined as the length along the shear layer from the shock interaction to the point at which turbulence became visible on schlieren photographs. An average value of l based on a series of photographs was used to determine the transition Reynolds number Re_T, and these results are given in Table I.

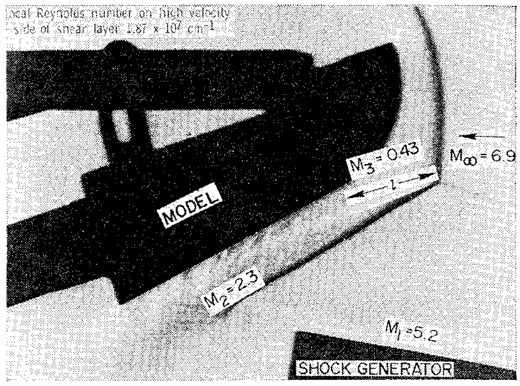

Fig. 1 Shear layer produced by unequal shock interaction.

Most of the published results on transition in free shear layers are based on shear layers with a velocity u_3 of zero or close to zero. For the present work, the velocity ratio u_3/u_2 is substantial ($u_3 \neq 0$), and its effects cannot be ignored. If these results are to be compared with previously published data obtained for separation geometries where $u_3 = 0$ approximately, it is necessary to extrapolate the measured values of Re_T to the values they would have for a zero-velocity ratio. The literature contains no experimental results for the variation of Re_T with the velocity ratio u_3/u_2, and the variation in the present results is too limited to justify any definite conclusions. Edney[1] suggested that an Re_T based on the velocity difference across the shear layer would be more appropriate when the velocity $u_3 \neq 0$. However, it appears that, unless the transition process is a function of the absolute velocity, the transition length l must increase with u_2 and u_3, simply because of the increase in the average convection velocity in the shear layer, even if M_2 and $(u_2 - u_3)$ are held constant. Thus, as a first approximation, an increase in transition length might be assumed to be proportional to an increase in the average velocity or

$$l_0/l = u_2/(u_2 + u_3) \tag{1}$$

where l_0 is the transition length when $u_3 = 0$. Based on Edney's suggestion that u_2 be replaced by $u_2 - u_3$ and Eq. (1), Re_{T_o} may be written as

$$[\rho_2(u_2 - u_3)/\mu_2][lu_2/(u_2 + u_3)] = \rho_2 u_2 l\lambda/\mu_2 \tag{2}$$

Table 1 Summary of experimental results

M_2	Re_T	u_3/u_2	λ	Re_{T_o}
1.79	3.0×10^4	0.360	0.470	1.41×10^4
1.99	6.1×10^4	0.270	0.574	3.50×10^4
2.06	5.7×10^4	0.289	0.552	3.20×10^4
2.17	5.2×10^4	0.256	0.592	3.10×10^4
2.22	5.6×10^4	0.259	0.589	3.30×10^4
2.22	6.5×10^4	0.259	0.589	3.80×10^4
2.30	4.3×10^4	0.265	0.580	2.50×10^4

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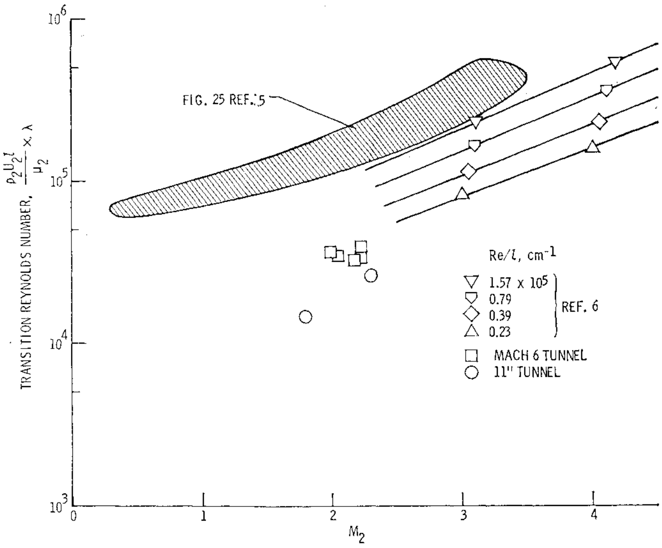

Fig. 2 Variation of transition Reynolds number with Mach number.

Note that Eq. (2) ignores the dependence of Re_T on M_3. This is probably justified when u_3 is subsonic, but it cannot be expected to hold when the velocity on both sides of the shear layer is supersonic.

The transition Reynolds numbers for the present study are plotted in Fig. 2 as a function of Mach number on the high velocity side of the shear layer, and compared with experimental values obtained for both two-dimensional[5] and axisymmetric[6] separated shear layers. Even though the variation with Mach number is roughly the same in all three cases, a direct comparison of the absolute values of Re_{T_0} is not justified, since the Reynolds numbers in Ref. 5 are based on conditions ahead of the separation shock rather than on local values, and the shear-layer studies in Ref. 6 are for separated axisymmetric rather than planar boundary layers.

From the limited results on transition in separated boundary layers, Edney concluded that the correlation of transition Reynolds number with Mach number, given by Chapman et al.,[5] was valid for shear layers produced by Type III interactions. Results presented here do not justify this conclusion and show that predictions of length to transition based on this correlation can be in error by as much as a factor of 5. This is ascribed to the small initial shear-layer thickness (presumably of the same order of magnitude as the shock thickness).

For one case ($M_2 = 1.79$) where Re_{T_0} is measured over a unit Reynolds number range of $1.16 \times 10^4 \text{cm}^{-1}$ to 5.83×10^6 cm^{-1}, there appeared to be no measureable change in Re_{T_0}.

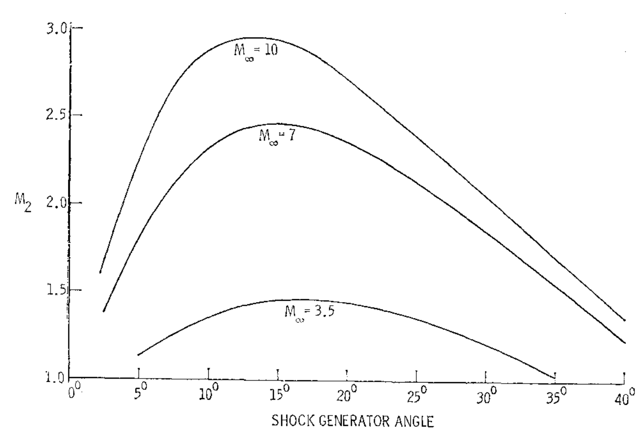

Fig. 3 Variation of M_2 with shock-generator angle for a range of freestream Mach numbers.

In contrast, Fischer[7] reported a strong unit Reynolds number effect in the same tunnel for transition in a boundary layer. This suggests that the differences between the measured values of Re_{T_0} in the 11-in. tunnel and the Mach 6 tunnel may be due to differences in model geometry rather than a unit Reynolds number effect. However, the available results are too meager to justify definite conclusions.

Although the data presented here cover a fairly limited range of Mach numbers, the results apply to a wider range of conditions than is at first apparent. The variation of M_2 with generator-shock angle, for a range of freestream Mach numbers, is given in Fig. 3. It can be seen that M_2 has a maximum value of only 2.9 for freestream Mach numbers up to Mach 10; thus, with a little extrapolation, the present results can be used to predict Re_{T_0} over most of this range.

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Errata

Erratum: "A Combustion Stability Analysis for Catalytic Monopropellant Thrusters"

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In Fig. 4 of the above paper, the terms for the abscissa and ordinate are reversed. The abscissa should read $\bar{P}_c/\overline{\Delta P}_B$, and the ordinate $\bar{P}_c/\overline{\Delta P}_L$.

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