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A note on turbulent shear-layer reattachment downstream of a backward-facing step in confined supersonic two-dimensional flow

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The reattachment of a supersonic jet with a turbulent separating boundary layer abruptly expanding into a two-dimensional parallel diffuser has been experimentally investigated using a surface-flow technique. The reattachment criterion proposed by Mukerjee & Martin (1969) for axisymmetric confined and unconfined flows is found to correlate equally well similar two-dimensional flow measurements in terms of the free-stream Mach number after separation.

1. Introduction

In a recent paper on turbulent shear-layer reattachment downstream of a backward-facing step in confined supersonic axisymmetric flow, Mukerjee & Martin (1969) proposed that the base pressure be evaluated from a reattachment criterion defined in terms of the initial stagnation pressure P_i. In the nomenclature of figure 1, which shows the conventional Korst–Chapman flow model for confined flow, where p is static pressure and subscripts 1, 2 and 3 denote the separating edge, the base region and the region downstream of reattachment respectively, while subscript r denotes dividing streamline reattachment, the reattachment criterion is

$$R_c = \frac{p_r/P_i - p_2/P_i}{1 - p_2/P_i}. \qquad (1)$$

This has the merit over the earlier proposals of Korst (1956), Nash (1962), McDonald (1964), Roberts (1964) and Sfeir (1966) of greater generality in its ability to correlate both unconfined and confined flows, as Mukerjee & Martin (1969) have shown for the axisymmetric case, through its restriction to pressures upstream of reattachment. It, therefore, avoids reference to the non-uniform conditions which may arise downstream of reattachment in confined flows from the presence of reflected waves. Even if it were possible to select a representative normalizing pressure in this region, the evidence of Sfeir (1966), Sirieix, Mirande & Delery (1966) and Roshko & Thomke (1966) shows that within limits perturbations in p_3 have little or no effect on p_r because of a critical condition immediately downstream of dividing-streamline reattachment, which renders the flow at reattachment (and upstream) independent of that further downstream.

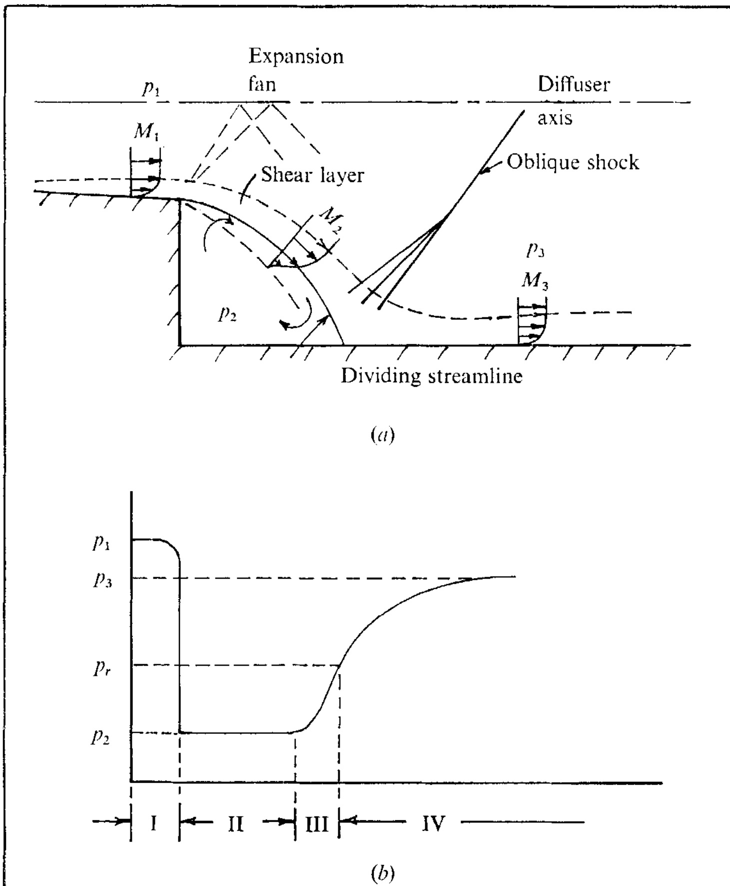

FIGURE 1. Flow and wall pressure distribution at diffuser entry. I, abrupt expansion; II, constant-pressure mixing; III, recompression before dividing-streamline reattachment; IV, recompression after dividing-streamline reattachment.

The equal applicability of (1) to unconfined and confined flows stems also from the substitution of P_i for the static pressure p_1 proposed by Sfeir (1966) which as Rom, Seginer & Kronzon (1967) and Martin & Mukerjee (1968) have shown, is in confined flows subject to the influence of the expansion fan spreading an appreciable distance upstream from the separating edge.

The success of (1) in correlating available axisymmetric flow measurements in terms of the free-stream Mach number after separation suggests that, in the absence of any analytical solution, a corresponding empirical correlation might be established for the two-dimensional flow configuration over a backward-facing step. This is presented below.

2. Experimental apparatus and procedure

Measurements for the confined two-dimensional turbulent flow of air were obtained in a supersonic parallel diffuser 0·91 m in length and 15·24 cm wide, open to atmosphere at the outlet, with a sudden entry enlargement in flow area at the connexion with the upstream generating nozzle, whose exit dimensions were 15·24 cm by 1·27 cm. The two nozzles used had the same throat width of 15·24 cm but throat depths of 1·20 cm and 1·07 cm, corresponding respectively to design exit Mach numbers of 1·26 and 1·50. Adjustment of the diffuser cross-sectional depth allowed a range of base height H from 0·56 cm to 2·49 cm, yielding a minimum diffuser cross-sectional aspect ratio of 12 and ensuring two-dimensional flow over at least the central half of the diffuser width. The side walls were of ground glass for flow observation.

The apparatus, procedure and surface-flow technique used to determine the location of reattachment were otherwise as described by Mukerjee & Martin (1969) for axisymmetric flow, to which the reader is referred for a full description. Operation of the diffuser in the started condition needed for an oblique shock system also ensured flow symmetry in the diffuser; this was confirmed by equality of measured top and bottom wall static pressure distributions, whose accuracy was estimated to be within 3 %.

3. Observations and correlation

As in the confined axisymmetric flow measurements reported by Mukerjee & Martin (1969), the wall static pressure distributions in two-dimensional flow for different M_1 coincide in the region of steepest pressure rise, where reattachment occurs. In this region the pressure is a linear function of distance from the sudden enlargement, the slope becoming independent of nozzle exit Reynolds number $Re_1 = \rho_1 U_1 H/\mu_1$ (where ρ, U and μ are respectively fluid density, flow velocity and fluid viscosity) according to Sfeir (1966) when, as in the present case, where $4{\cdot}9 \times 10^5 \leqslant Re_1 \leqslant 6{\cdot}85 \times 10^5$, the free shear layer is fully turbulent. Elsewhere the present static pressure distributions exhibit similar characteristics to those in confined axisymmetric flow where the wall static pressure diminishes with increasing M_1. Such dependence on Mach number, and also on Reynolds number, well downstream of reattachment does not, of course, affect the upstream flow, because of the critical condition immediately downstream of dividing-streamline reattachment. In the present measurements, the unit Mach number streamline is estimated to be 0·05 times the shear-layer thickness downstream of the stagnating dividing streamline.

Calculated values of R_c are plotted logarithmically against M_2 (obtained from p_2/P_i) in figure 2 together with those derived from the unconfined turbulent flow measurements of Thomann (1959), Sirieix (1960), Carrière & Sirieix (1961), Hastings (1963) and Sfeir (1966). The best correlation is

$$R_c = \frac{1{\cdot}56}{M_2^{4{\cdot}35}} \tag{2}$$

and is equally valid for confined and unconfined flows over the range $1{\cdot}75 \leqslant M_2 \leqslant 4{\cdot}4$. Also included for comparison in figure 2 is the corresponding axisymmetric correlation of Mukerjee & Martin (1969) for $2{\cdot}3 \leqslant M_2 \leqslant 5{\cdot}7$ given by

$$R_c = \frac{6{\cdot}0}{M_2^{4{\cdot}74}}. \tag{3}$$

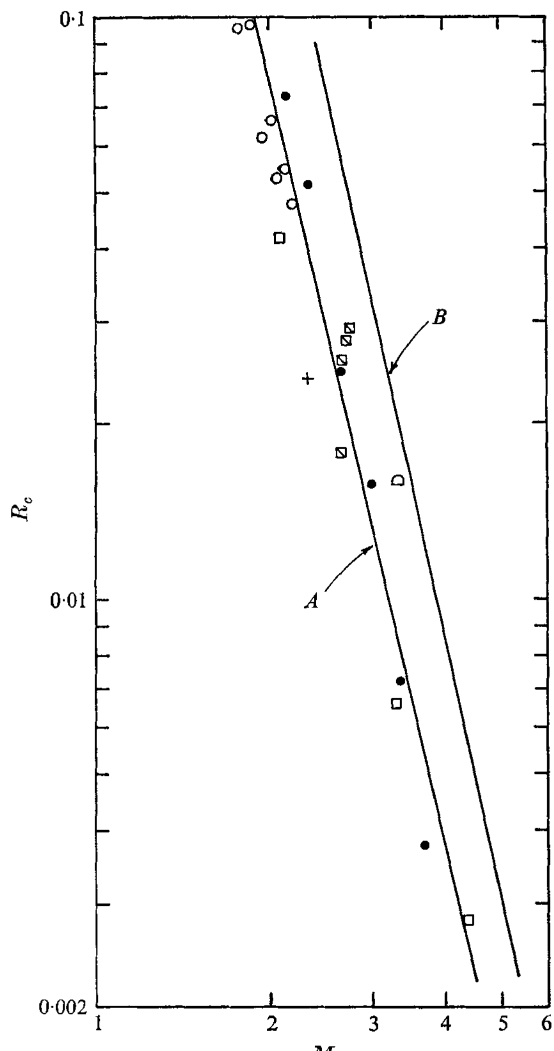

FIGURE 2. Variation of R_c with M_2. ○, present work; +, Thomann (1959); ⧅, Sirieix (1960); ●, Carrière & Sirieix (1961); □, Hastings (1963); ⌓, Sfeir (1966). A, $R_c = 1{\cdot}56 M_2^{4{\cdot}35}$; B, $R_c = 6{\cdot}0/M_2^{4{\cdot}74}$ (Mukerjee & Martin 1969).

Thus in axisymmetric flow, M_2 (and hence the pressure rise to reattachment) for given R_c is greater than in two-dimensional flow. As was found by Baker & Martin (1965), this leads to a relatively lower base pressure for given M_1 and the ratio diffuser cross-sectional area: nozzle throat area.

Since the pressure ratios p_r/P_i and p_2/P_i used to formulate R_c uniquely determine the Mach numbers M_r and M_2 for a given gas, the reattachment criterion may alternatively be expressed as their ratio M_r/M_2. Figure 3 illustrates the resultant dependence of M_r on M_2 for two-dimensional flow. As in figure 2, the correlation

$$M_r/M_2 = 0{\cdot}81 M_2^{0{\cdot}11} \tag{4}$$

covers available measurements in the range $1{\cdot}75 \leqslant M_2 \leqslant 4{\cdot}4$.

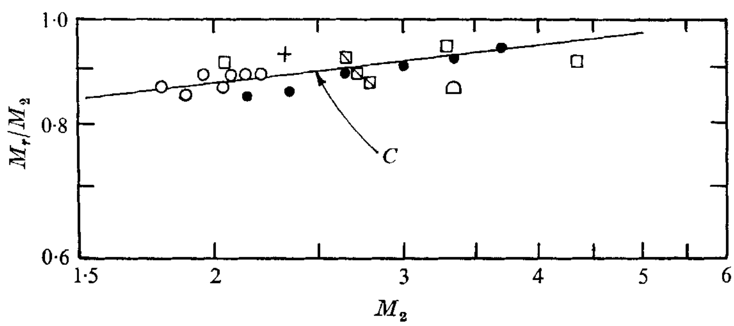

FIGURE 3. Variation of M_r/M_2 with M_2. C, $M_r/M_2 = 0{\cdot}81\ M_2^{0{\cdot}11}$. ○, present work; +, Thomann (1959); ⧅, Sirieix (1960); ●, Carrière & Sirieix (1961); □, Hastings (1963); ⌓, Sfeir (1966).

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