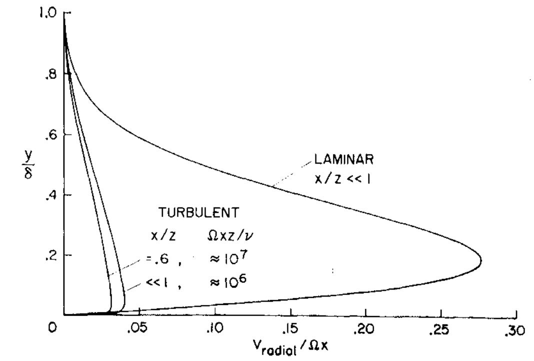

Fig. 3 Radial velocity profiles on a rotating flat-plate blade.

with Ωx; this is the reason for the choice of the abscissa in Fig. 3. A slight decrease in the maximum value of $V_r/\Omega x$ with increasing x/z is predicted by laminar theory,[1] and this also occurs in the turbulent case.

The main conclusion to be drawn from the foregoing remarks is that the turbulent flow on a rotating flat plate is a boundary layer with small crossflow and behaves much as though it were locally two-dimensional, with the appropriate local dynamic pressure and Reynolds number of the local external flow. In other words, the Coriolis and centrifugal effects of rotation appear to be negligible when the problem is cast in potential streamline coordinates. This situation is, of course, quite different from the laminar case, even though the qualitative physical features and parameters are the same.

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Turbulent Boundary-Layer Separation at Low Supersonic Mach Numbers

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Nomenclature

AR = step span-to-height aspect ratio
C_{p2} = plateau pressure coefficient
h = step height
L = distance from leading edge of the flat plate to the face of the step
M_1 = Mach number of flow approaching the separation shock wave
x_s = separation distance measured from the face of the step to the point where separation occurs
$\bar{X}$ = modified separation distance measured from the face of the step to the point where the centerline pressure begins to rise
δ_s = boundary-layer thickness at point of separation

Turbulent boundary-layer separation is a flow phenomena that has been extensively studied both experimentally and theoretically. Its technical importance is well known and it is not necessary here to describe its many practical applications. Zukoski[1] has recently published a summary of experimental studies of turbulent boundary-layer separation in front of a forward-facing step. Based on these experimental results, he suggests a number of very simple empirical relations to describe various separated flow parameters, including separation distance x_s and plateau pressure coefficient C_{p2}. Although Zukoski's correlations were based on a considerable amount of data, it was obvious that very little information is available for the very important low supersonic Mach number case of $M_1 < 2$.

Because of this lack of data and in order to determine the limit of applicability of Zukoski's correlations, a series of wind-tunnel tests has been conducted at the Applied Gasdynamics Institute of the DFVLR at Porz-Wahn, Germany. The tests were performed in a blowdown wind tunnel having a 60×60 cm rectangular test section. Mach numbers ranged from 1.24 up to 2.96 with the emphasis being on the lower (1.24–1.75) Mach numbers. Reynolds numbers were between 0.35×10^6/cm and 0.7×10^6/cm. Using a boundary-layer rake, the boundary-layer thickness in the region of separation could be accurately measured. Natural transition to fully turbulent flow occurred well upstream of separation for all cases. Boundary-layer thickness at the point of separation ranged from 2.75 to 3.75 mm.

The model consisted of a 50×50 cm flat plate and a series of forward-facing steps which were mounted at $L = 350$ mm for all cases studied. The steps were of various sizes having widths of from 100 to 480 mm and heights from 5 to 30 mm. Step span-to-height aspect ratios ranged from $AR = 3.3$ to $AR = 96$. Centerline and spanwise pressure distributions were obtained and schlieren photographs were made for each test condition. A series of oil-flow photographs of the separated region was also made.

Because of the relatively large size of the model and the corresponding tunnel blockage at transonic freestream Mach numbers, it was necessary to introduce an angle of attack of 6° at supersonic freestream Mach numbers in order to study cases where Mach number was less than 1.47. Data obtained with and without angle of attack are distinguished in this note by closed and open symbols, respectively. Further details of the test method are given in Ref. 2.

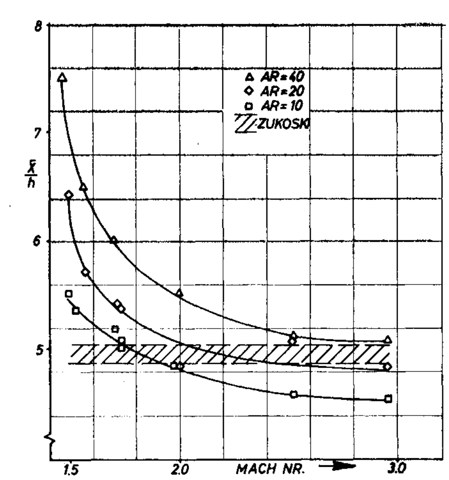

Fig. 1 Effects of Mach number on modified separation distance.

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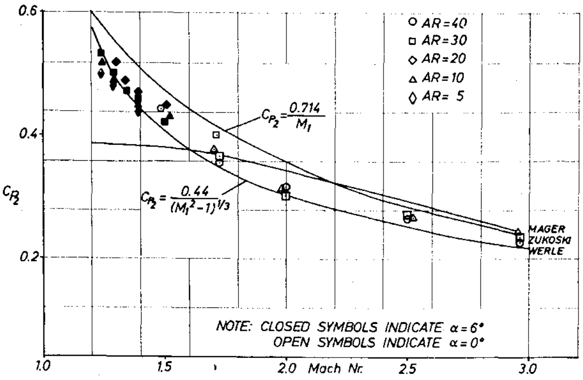

Fig. 2 Effects of Mach number on plateau pressure coefficient.

Figure 1 shows the behavior of the distance $\bar{X}$ as a function of Mach number. All data are for a model with zero angle of attack. The distance $\bar{X}$ is not the usual separation distance x_s measured from the face of the step to the point where separation occurs. It is rather the distance from the face of the step to the point where centerline pressure first begins to rise. This distance was accurately determined from the centerline pressure distributions, whereas the experimental determination of the distance x_s would have required oil-flow pictures of every case studied.

As seen in Fig. 1, at Mach numbers greater than 2, $\bar{X}/h$ is only a weak function of Mach number. However, as Mach number is lowered below $M_1 = 2$, the Mach number dependence becomes increasingly stronger. Separation distance increases with decreasing Mach number. Three different step span-to-height aspect ratios are shown to indicate three-dimensional influences. The point at which the measured separation distance deviates from Zukoski's predicted value is dependent on the degree of three dimensionality. For highly two-dimensional flow where $AR = 40$, the measured separation distance at $M_1 = 2.0$ is already 10% higher than predicted. For the more three-dimensional cases this increase is delayed until lower Mach numbers are reached. Zukoski's simple linear relationship shown in Fig. 1 has been modified to be expressed in terms of $\bar{X}$. In terms of $\bar{X}$, this relationship is

$$(4.2h + 2.25\delta_s) \leqq \bar{X} \leqq (4.2h + 2.75\delta_s)$$

For cases where $M_1 > 2$, this simple relation is reasonably accurate.

The measured plateau pressure coefficients are shown in Fig. 2 as a function of Mach number. Some data obtained with a model angle of attack of 6° is also included. Mager's[3] semi-emperical prediction as well as two empirical predictions of Zukoski and Werle[4] are also shown for comparison. Since Mager's work was based on linearized theory its validity at the lower supersonic Mach numbers is questionable. Indeed, at $M_1 = 1.25$, Mager's predictions are about 20% below the measured values. Werle's correlation best describes the data, but Zukoski's very simple approximation is also reasonably accurate even at the lower Mach numbers.

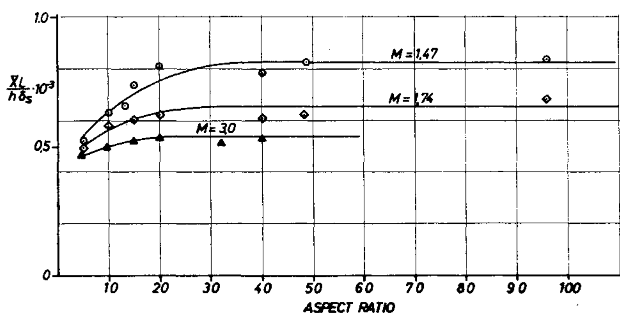

Fig. 3 Effects of step span-to-height aspect ratio on modified separation distance for various Mach numbers.

Figure 3 shows how the chosen separation distance parameter is influenced by three dimensionality at various Mach numbers. In order to eliminate the influence of variation in boundary-layer thickness at the point of separation, the nondimensional separation distance has been multiplied by the quantity L/δ_s. It is seen that the step span-to-height aspect ratio necessary to assure reasonably two-dimensional flow is influenced by the Mach number. As expected, in order to obtain separation distances that are within 10% of the two-dimensional values, a larger aspect ratio is necessary at the lower Mach numbers than at the higher Mach numbers. For flows at $M_1 = 3.0$ an aspect ratio of six or higher produces separation distances that are within 10% of the two-dimensional values, while at $M_1 = 1.47$ an aspect ratio of at least 15 is necessary to produce the same effect.

The wind-tunnel study has shown that: 1) Separation distance becomes an increasingly strong function of Mach number as the Mach number is decreased below 2, increasing with decreasing Mach number. 2) Measured plateau pressure coefficients are most accurately described by a correlation due to Werle but are also quite accurately predicted by the simpler correlation by Zukoski. 3) Three-dimensionality plays an increasingly important role at the lower supersonic Mach numbers. Defining two-dimensional flow solely in terms of step span-to-height aspect ratios is not possible. An aspect ratio that gives nearly two-dimensional flow at $M_1 = 3.0$ may not produce two-dimensional flow at lower Mach numbers.

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A Heated Wire Device for Shock Tube Diaphragm Bursting

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Nomenclature

P_D = ratio of driver section pressure to driven section pressure
P_s = ratio of pressure behind primary shock wave to driven section pressure
R = gas constant for working gas
T_0 = temperature of driven section
u_s = velocity of primary shock wave
γ = ratio of specific heats of working gas

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