High Reynolds Number Wedge-Induced Separation Lengths at Mach 6

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Introduction

ALTHOUGH many studies have been performed on the character of the interaction region, most of these works have been limited to supersonic flows. In the majority of these studies the Mach number was varied between 2 and 4.5, with unit Reynolds number (*Re*) up to 98×10^6/m tested. This Mach number limitation is a result of the small- to medium-sized supersonic tunnels available for such basic research. The purpose of this Note is to present for the first time experimental data that clearly demonstrate the behavior of the separation region in high Reynolds number turbulent boundary layers at hypersonic speeds.

Past works[1-5] have indicated that the upstream extent of the separation zone decreases with increasing Mach numbers and Reynolds numbers, and increases with increasing ramp angle. Others[6-8] indicate the upstream movement of the separation point as the Reynolds number is increased. This disagreement may be due in part to the nature of the boundary layer flow. In this note, the reaction of the separation zone to changes in the Reynolds number from 33 to 98×10^6/m at Mach 6 will be presented.

Model and Experimental Facility

A smooth flat plate of approximately 45.7 cm in streamwise length and 35.6 cm in lateral extent was machined to a number 32 surface finish. A sharp 10 deg asymmetric leading edge was also machined into the model. Approximately 39.4 cm downstream from this leading edge was the intersection point of the instrumented ramp. This ramp was easily adjusted to angles of 22, 28, and 34 deg.

The model was then mounted downstream of a 30.5 cm open jet, high Reynolds number, Mach 6 blowdown wind tunnel.[9] By adjusting the total pressure and stagnation temperature, unit Reynolds numbers ranging from approximately 33 to 98×10^6/m were obtained.

Model instrumentation consists of 46 surface pressure ports and 7 type K (chromel/alumel) thermocouples. These ports were spaced streamwise in x along the plate at its center ($y = 0$) and ± 9.5 mm off the center through the interaction region. All pressure transducer signals and thermocouple amplifiers/reference junction signals were acquired using a Prime 650 mini-computer. Calibration checks were performed on all instrumentaiton prior to each test sequence.

Boundary-layer Parameters

Using a pitot pressure probe and a Winkler-type temperature probe, distributions of both the total temperature and total pressure in the boundary layer were obtained. To allow accurate measurements near the wall, the pressure probe tip was flattened such that its overall height was 0.51 mm. For the same reasoning a miniature Winkler probe was fabricated measuring 1.52 mm in diameter. A recovery factor of 0.984 was determined for this temperature probe. Traverses were performed at two streamwise locations, $x = -16.47$ cm and $x = -5.52$ cm upstream from the ramp/plate intersection point. A third traverse, perpendicular to the ramp surface at a distance along the surface equal to $+3.97$ cm downstream from the intersection point, was also performed. From these measurements, the Mach number, velocity, and static temperature through the boundary layer were obtained. Using numerical integration, the momentum thickness (θ) was computed for each unit Reynolds number and was found to be in good agreement when compared to the empirical correlation of Roshko and Thomke[1] for a supersonic turbulent boundary layer.

Surface Pressure Characteristics

To verify two-dimensionality, surface pressure readings were obtained from several taps displaced laterally across the plate. To further ensure a two-dimensional flow, a fence was installed on both sides of the ramp/intersection region. Initial tests with and without the fences demonstrated excellent agreement and two-dimensionality at all Reynolds numbers tested. In Fig. 1 the surface static pressure distribution is presented with and without fences for the smooth plate with a 22 deg ramp fixed at the trailing edge. Except for some data scatter at the trailing edge of the ramp, excellent two-dimensionality was obtained.

In the present study, the separation point was defined as the approximate location where the first inflection point occurred in the surface pressure distribution. Upon examination of the surface pressure distribution in Fig. 2, the effect of ramp angle

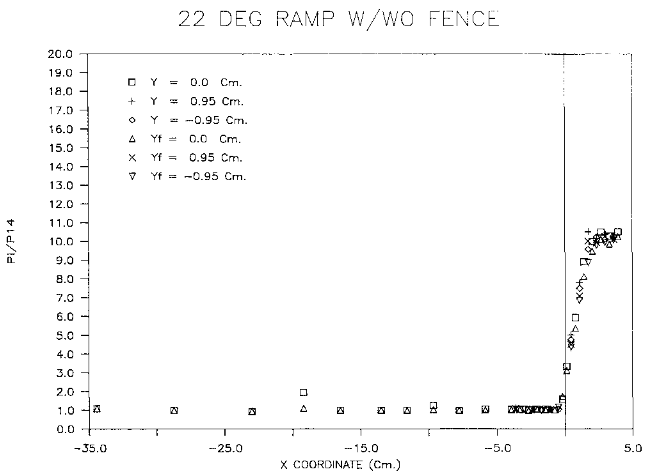

Fig. 1 Flat plate static pressure distributions for a 22 deg ramp with and without a side fence.

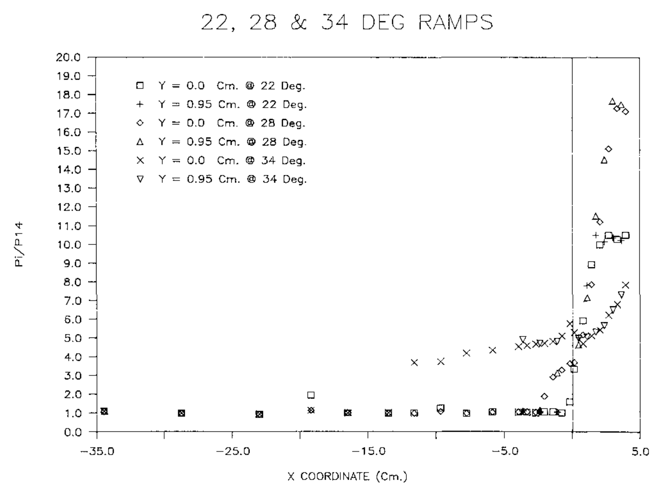

Fig. 2 Flat plate pressure distributions for ramp angles 22, 28, and 34 deg at unit Reynolds number of 32 million/meter.

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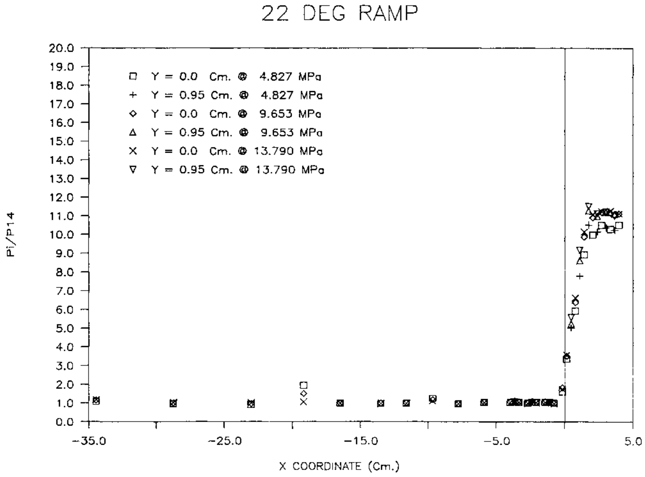

Fig. 3 Static pressure distributions on a flat plate with 22 deg ramp combination.

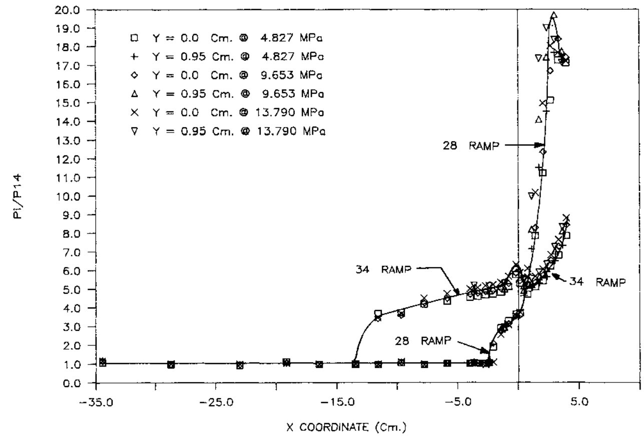

Fig. 4 Static pressure distribution on a flate plate with 28 deg ramp and 34 deg ramp.

on the upstream location of the separation point becomes apparent. That is, at a constant Reynolds number, as the adverse pressure gradient is increased the position of the interaction region moves upstream. For example, in the low unit *Re* case, as the ramp angle was increased from 22 deg to 28 deg, the separtion point moved from -2.0 mm to -20.3 mm, which indicates a change by a factor of 10. Similarly, when the angle was changed from 28 deg to 34 deg, the separation length increased by a factor of 60 to approximately -12.7 cm.

The upstream movement of the interaction region at various unit *Re* and at a fixed ramp angle indicate a critical state has been achieved. Specifically, increases in unit *Re* from 33 to 98 million/meter did not appear to significantly affect the location of the separation point. Because of the subjective nature of determining the point separation, Figs. 3 and 4 are included to demonstrate this asymptotic state, whereby the separation point as indicated by the surface pressure distribution does not appear to be noticeably different over the range of unit *Re* numbers tested.

Similar experimental results were weakly observed by Todisco and Reeves[6] for unit *Re* between approximately 33 and 49 million/meter at Mach number 6.5. Further, a closer examination of previous supersonic studies[15] appears to indicate that an asymptotic state may also be approached when the unit *Re* in their studies were increased to 82 or 98 million/meter.

In summary, the present work appears to indicate that the extent of separation is independent of Reynolds number in the range tested. That is, for unit Reynolds numbers between 23 and 98 million/meter the upstream location of the separation line appears to have reached an asymptotic state and is relatively unaffected by increases in Reynolds number.

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Mechanism of Sidewall Effect Studied with Oil Flow Visualization

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Nomenclature

M = Mach number
S = entropy
T = temperature
$\bar{u}$ = velocity vector
α = angle of attack
$\bar{\omega}$ = vorticity vector

Introduction

SIDEWALL effect has been one of the major uncertainties in airfoil experiments. In contrast with the research on conventional wall interference, the sidewall problem is less investigated and remains basically unsolved. There are research efforts on the subject, theoretical as well as experimental.[1-4] The experimental works usually give only the global effect of the sidewall; so far these results have not provided a clear picture for the mechanism of the sidewall effect. On the other hand, the theoretical studies are all subjected to various assumptions. These simplifications may be necessary

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