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RESEARCH MEMORANDUM

PRELIMINARY REPORT ON A STUDY OF SEPARATED FLOWS IN SUPERSONIC AND SUBSONIC STREAMS

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SUMMARY

This paper is a preliminary and brief account of some research conducted during the last two years on the general problem of flow separation. The research is fundamental in nature, being partly theoretical and partly experimental. Measurements have been made at subsonic as well as supersonic speeds for a variety of two-dimensional model shapes, each involving separation. Study is made of the over-all pressure rise for incipient separation, as well as the pressure rise to the separation point and to the first peak (or plateau) pressure in flows where sizable separated regions exist. Detailed cognizance is taken throughout of the location of transition relative to the reattachment and the separation positions, as this relative location was found to be the most important variable investigated.

INTRODUCTION

Flow separation is an unusually common and important phenomenon in aerodynamics. It can occur, for example, on compressor blades, near control surfaces, in rocket nozzles, on airfoils, or near regions of a surface from which a shock wave has been reflected. Separation often limits the effectiveness of various devices which depend on the dynamics of fluid flow for their successful operation.

The purpose of the present research was to obtain fundamental or general information about separated flows. It was hoped that such research would lead to a better understanding of separation phenomena. This approach was taken with the philosophy that, to a designer, one generalization - or one understanding - can sometimes be worth many data points.

Inasmuch as an understanding was a prime objective, the various model shapes selected for study were relatively simple. All were two-dimensional configurations. They included forward facing steps (which would simulate the flow, for example, upstream of a spoiler control), rearward facing steps (which would simulate the flow behind a base or a spoiler), compression corners (which would simulate the flow over an inlet ramp or a deflected flap), curved surfaces (which would simulate the flow over one side of a compressor blade), special models producing leading-edge separation, and configurations producing separation by reflecting a shock wave from a boundary layer.

The experiments were conducted in the Ames 1- by 3-foot supersonic wind tunnel no. 1 at Mach numbers between 0.4 and 3.3. The over-all Reynolds number range investigated (based on characteristic model length) was between 4,000 and 4,000,000. Wall static pressure distributions, surface oil-film observations, and high-speed motion picture studies were made. In the present publication, development of theory and description of experimental details are not included.

SYMBOLS

c_f	local skin-friction coefficient at beginning of interaction
L	characteristic model length
M	Mach number
p	static pressure
Δp	$p - p_o$
q	dynamic pressure, $\frac{\rho u^2}{2}$
Re	Reynolds number
u	velocity
x	longitudinal distance along model chord
ρ	mass density

Subscripts

o	beginning of interaction at outer edge of boundary layer
$'$	just downstream of reattachment zone
d	dead air

RESULTS

The most general result arising from the research is that a single variable appeared dominant throughout in controlling pressure distribution, irrespective of the particular Mach number, Reynolds number, or model shape investigated. This signal variable is the location of transition relative to the reattachment and separation positions. Because transition is so important, classification of the separated flows is made at the outset, as illustrated in figure 1, into three essentially different types, depending on the relative location of transition: a "pure laminar" type illustrated at the left for which transition is downstream of reattachment, a "transitional" type illustrated in the center for which transition is between separation and reattachment, and a "turbulent" type at the right for which transition is upstream of separation. The pressure distributions represent wall static pressures. As is indicated, the particular configuration for this figure is a step model tested at a Mach number of 2.3. The characteristics here exhibited, however, actually are rather general. For the laminar case the separation point S, (which was determined by oil-film observations) is associated with a relatively small pressure rise and is followed by further rise to a plateau pressure which represents the dead-air pressure of the separated region. High-speed motion pictures taken of this pure laminar separation at several thousand frames per second show the flow field to be remarkably steady. These characteristics are in contrast to those of the transitional-type separation in the center portion of figure 1. The pressure rise to separation, and the plateau pressure rise remain small, but an abrupt pressure rise associated with transition, and occurring at about the same streamwise location as transition, now makes itself evident and alters the flow field. High-speed motion pictures showed this transitional type of separation to be unsteady. Random movements of the shock waves were observed as were random changes in the angle of flow separation. Perhaps we should expect this since the transition phenomenon itself, which is of dominant importance to these flows, is known not to be steady. Some of these characteristics of transitional separation are in contrast to those of turbulent separation represented by the example at the right of figure 1. The pressure rise to the turbulent separation point is about five times greater than that to a laminar separation point. There is no plateau pressure, although there is a peak pressure in the separated region. Downstream of this region the pressure rises to a terminal value higher than the peak pressure. It was somewhat surprising to observe in high-speed motion pictures that this turbulent-type separation is relatively steady - not rock-like steady as the pure laminar separations but, nevertheless, quite steady compared to the transitional separations. In passing, it is to be observed that plateaus in pressure are associated with laminar separations and may be thought of as approximating the idealized "dead-air" region; but in turbulent separations an eddying motion keeps the air very much alive so that the term "dead-air" is only a figurative one.

It does not seem necessary to exemplify further the three types of flow separation, although each type has been found and studied for the various other models investigated. They exhibit the same qualitative phenomena, that is, they show the relative transition location to be dominant in controlling pressure distribution throughout the investigation. Although the dominating role played by transition previously does not appear to have been generally appreciated, the recognition of transition as significant to separated flow is by no means new. In studying the flow over a cylinder, for example, Schiller and Linke (ref. 1) noticed the strong influence of transition location within a separated layer relative to the location of separation. Other examples can be cited from experiments, such as the recent ones of Gadd, Holder, and Regan (ref. 2), wherein the importance of transition relative to the location of reattachment also was clearly recognized. It should be noted, further, that Crocco and Lees (ref. 3) attempt directly to include the relative location of transition as an essential variable in their analysis of separated flows. They consider the importance of transition relative to a "critical" station in the wake (this station being determined from mathematical characteristics of their equations), rather than relative to the reattachment location (this being determinable from experiments with oil film or surface shear stress), but these two ways of describing relative transition location may represent essentially the same thing.

By keeping close account of the relative location of transition throughout the investigation, several experimental trends were observed which appeared to be general. These trends can be illustrated from a plot of the dead-air pressure in various separated regions as a function of Reynolds number. Figure 2 represents such a plot: once again, pure laminar separations are on the left, transitional separations in the center, and turbulent separations on the right. The Reynolds number is based on body length. Individual data curves are not identified, as this is unnecessary for the general purpose at hand. Suffice it to say that these curves represent various combinations of Mach number and model shape. They also include one set of data obtained by Love (ref. 4). The ordinate is the absolute value of the pressure change across the reattachment region $p' - p$ divided by the pressure p' just downstream of reattachment; p is measured at an arbitrary fixed point in the separated region. By focussing attention on the pure laminar separations at the left, it is seen that some of these are affected to a negligible extent by variation in Reynolds number. This agrees with a theory described later which indicates no effect of Reynolds number on those pure laminar separations for which the boundary-layer thickness at separation is zero. Other curves show a Reynolds number effect which amounts, at the most, to only about a 1/4 power variation. In these cases the boundary-layer thickness at separation is not negligible. Generally speaking, pure laminar separations are affected only to a small extent by Reynolds number. If focus now is shifted to the transitional separations in the center portion of figure 2, it is seen in contradistinction, that these flows can be affected markedly by variation in Reynolds number. Such effects are particularly pronounced when transition is near reattachment, as is the case for the left portion of each curve. Movement of transition upstream of reattachment (brought about by an increase in Reynolds number) increases the pressure change through the reattachment region. Turning now to the turbulent separations on the right portion of the slide, it is seen that for this type of separation there is no significant effect of Reynolds number discernible from the data.

An explanation can be given as to why transition location is so important to a separated flow. This explanation is based on a theoretical mechanism postulated as fundamental to all separated flows. Very briefly, the mechanism requires that a balance exist between the mass flow scavenged out of the dead-air region by the separated mixing layer and the mass flow reversed back into this region by the pressure rise through the reattachment zone. Inasmuch as the mechanism helps in understanding various results, a digression temporarily is undertaken to present some results of experiments especially designed to test quantitatively this mechanism.

There are certain special conditions for which both the mass flow scavenged from a separated region and the mass flow reversed back into the region can be calculated without empirical information. These conditions are for pure laminar separations with zero boundary-layer thickness at separation. All calculation details will be bypassed and only end results shown. The theory provides an equation in closed form for the dead-air pressure as a function of the Mach number M' and the pressure p' which exist just downstream of the reattachment zone. The equation is not very complicated, as is evident from figure 3. It involves the ratio of specific heats γ, the Mach number, and a number 0.655 which arises from the solution of a nonlinear differential equation with definite boundary conditions. This number involves no empirical information; it cannot be adjusted to take up any slack between experiment and theory. The data points represent both supersonic separations from the present experiments, and low subsonic-speed separations from some experiments of Roshko at the California Institute of Technology (ref. 5). Three different models are represented: A model producing leading-edge separation, a flat plate normal to the stream, and a circular cylinder. It is evident that the strictly theoretical calculation, which indicates the dead-air pressure to be independent of both Reynolds number and model shape, agrees well with the experiments.

With the knowledge that the mechanism postulated has satisfactorily been put to quantitative test, an explanation can be given as to why the location of transition relative to reattachment is so important to a separated flow. Suppose transition were to move suddenly from a position just downstream of reattachment to a position just upstream of reattachment. The introduction of eddies just upstream of reattachment would not affect the scavenged mass flow (since this depends on conditions along the length over which mixing takes place) but would have a pronounced effect of reducing the reversed mass flow (since the eddies would energize the low velocity portions of the mixing layer just before reattachment and thereby would enable more air to excape downstream). Consequently, balance of the two mass flows would occur at considerably different pressure when transition moves upstream of reattachment. Whether the flow upstream of reattachment is laminar or turbulent is just as fundamental to a separated flow as whether the flow upstream of separation is laminar or turbulent.

In regard to the quantitative test of the theoretical mechanism, reference is made to the recent researches of Korst, et al. (ref. 6). Korst considered the case of fully turbulent (rather than fully laminar) separation with zero boundary-layer thickness at separation. Comparison of his calculation method with the one used above for fully laminar separation reveals some differences in detail, but essentially the same physical idea as to the mechanism which determines the pressure of the separated region. Good agreement is obtained by Korst between his calculations and measurements of base pressure for thin turbulent boundary layers at separation. The results of the two independent researches appear complementary in substantiating the common physical idea employed.

While distinction need not be made between subsonic and supersonic separations when considering qualitatively the importance of transition, it is necessary to make such distinction when considering most other aspects of flow separation. There is a basic difference between subsonic and supersonic separation which should be recognized before discussing such questions as "What pressure rise will separate a given boundary layer?" Figure 4 illustrates the pressure distribution upstream of a compression corner in subsonic flow at various Reynolds numbers. The dotted line represents the calculated distribution that would exist in inviscid flow. Variation in Reynolds number is seen to bring about only small departures from this distribution. Moreover, the separation point (indicated by the filled symbols) and the pressure rise to separation are essentially independent of Reynolds number. These results indicate, as is well known, only a minor interaction of boundary layer with an external subsonic flow. The situation is quite different in supersonic flow, as first anticipated by Oswatitsch and Wieghardt (ref. 7), and as illustrated in figure 5. These data are for the same model as that in figure 4, tested in the same wind tunnel, and investigated over the same Reynolds number range, only at a supersonic Mach number of 2. In this case the dotted line representing pressure distribution in inviscid flow bears little resemblance to the experimental distributions; moreover, both the location of separation and the pressure rise to separation depend considerably on the Reynolds number. Such results indicate a dominant interaction of boundary layer with an external supersonic flow. Local interaction of this type near supersonic separation can dominate the picture to the exclusion, for example, of effects of downstream object shape. Such supersonic separations can be termed "free interactions."

Free interactions are subject only to the boundary-layer equations and the external-flow equations; it turns out that they are amenable to a simple dimensional analysis, the details of which will not be presented here. The end result of such analysis, for both laminar and turbulent separation, is that any distinguished pressure rise in a free-interaction flow is proportional to the square root of the local skin-friction coefficient existing at the beginning of interaction. Comparison of this theoretical result with experiment is made in two figures: figure 6 for laminar separation, and figure 7 for turbulent separation. In figure 6 both the plateau pressure rise and the pressure rise to the separation point are plotted as functions of Reynolds number for various model shapes. Both are seen to be independent of object geometry inasmuch as four different shapes are represented - a compression corner, a step, a shock reflection, and a curved surface. Such independence would be required of a free interaction. Also, the variation in both cases follows closely the theoretical variation as the square root of skin friction, which, for laminar flow, is a variation as $Re^{-1/4}$. Mention is made that for the special case of pressure rise to a laminar separation point, a $Re^{-1/4}$ variation was first calculated by Lees (ref. 8), although various subsequent analyses, most of which neglect the interaction phenomenon, have obtained different variations. The present experiments cover a wide enough range in Reynolds number (a factor of 50 to 1) under sufficiently controlled conditions to settle finally this question of Reynolds number dependence in two-dimensional, supersonic, laminar separation.

Turning now to free-interactions in turbulent flow, it is clear that the square root of turbulent skin-friction coefficient will vary little with Reynolds number, so the pressure rise to turbulent separation also should vary little with Reynolds number. Experimental data confirm this, as shown in figure 7 which includes some data of Gadd obtained at the NPL in England (ref. 2). The trend of data is consistent with the dotted line representing a variation as the square root of turbulent skin friction, although it could be said with equal correctness that there is no significant effect of Reynolds number evident from the data.

In order to simulate in a wind tunnel any flow separation phenomenon of flight, it is necessary that the location of transition relative to reattachment be duplicated. This requirement is especially pertinent to hypersonic wind-tunnel investigations as a consequence of two results: (1) If a separated laminar mixing layer is relatively stable, transition will occur near reattachment, a condition under which Reynolds number effects are most pronounced, and (2) the stability of a separated mixing layer increases markedly with increasing Mach number. The first of these results can be deduced from the center portion of figure 2. The various curves are steepest at their left, where transition is near reattachment, rather than at their right, where transition is near separation. The second of these results is illustrated in figure 8. Plotted against Mach number in this figure are data points representing the maximum Reynolds number up to which pure laminar type separations were found under the present wind-tunnel conditions. The reference length for this Reynolds number is the distance Δx along the separated layer between the reattachment point and the separation point. Consequently, such Reynolds number measures the stability of a separated laminar mixing layer. According to figure 8, the separated laminar layer at subsonic Mach numbers is stable only to about 30,000 Reynolds number, whereas at Mach numbers near 5, it is stable to several million Reynolds number. Thus, an increase in Mach number has a pronounced stabilizing effect on the mixing layer. This trend is consistent with that calculated by Lin (ref. 9) for neutral stability to certain restricted types of disturbances.

For purposes of comparison, in figure 8 an analogous boundary is shown which represents the maximum Reynolds numbers of transition reported to date from wind tunnels under comparable conditions. The area under this top curve represents the domain of laminar boundary-layer flow under wind-tunnel conditions of essentially constant pressure and zero heat transfer. Inasmuch as flight conditions differ from these, and yield different Reynolds numbers of transition (as do experiments in different wind tunnels) the significant result is not the detailed position or shape of the two boundaries in figure 8. Instead, the important result is that under comparable conditions the stability of a separated mixing layer encroaches on that of the boundary layer as the hypersonic regime is entered.

Because of this trend, pure laminar separations - which have been primarily laboratory curiosities in the past - might become common practical phenomena in the future. There are several reasons why this trend looks significant and warrants much research effort. One reason, already mentioned, is that it means the Reynolds numbers of hypersonic wind tunnels must match those of flight more closely than has been done in the past. Another reason is that separated laminar regions have some unusual characteristics which are intriguing from the viewpoint of opening new possibilities: for example, the skin friction in such regions obviously is a small thrust due to the reversed flow; this is nice from the viewpoint of drag. Also, the heat-transfer characteristics would be quite different from those of a boundary layer. In fact, a recent theoretical calculation, as yet unpublished and untested by experiment, indicates the heat transfer in a laminar mixing layer to be roughly 0.6 of that in a comparable laminar boundary layer. Such considerations clearly outline what appears to be a profitable task for future research.

As a final topic for discussion, distinction is made between various types of pressure rise associated with separated flow, and an opinion is given as to their significance for design purposes. Only turbulent separations are considered. Three types of pressure rise are distinguished, as schematically illustrated in figure 9. Here two flow conditions are depicted for a simple compression corner which can be thought of as a deflected flap. One pressure distribution, represented by the dotted line, corresponds to a flap deflection which produces a separated flow. The other flow condition, represented by the solid line, corresponds to a somewhat smaller flap deflection for which there is no appreciable separated region, but for which the flow is just on the verge of separating. We distinguish between: (1) The pressure rise to the separation point S of a flow already separated, (2) the first peak pressure rise in a flow already separated, and (3) the over-all pressure rise for incipient separation in a flow for which the boundary layer is just on the verge of separation. The pressure rise to separation likely would not be of interest to a designer, but would be to a research worker concerned with the mechanism of turbulent separation. The first peak pressure rise, on the other hand, would be of interest to a designer concerned with loads, hinge moments, or flap effectiveness. The over-all pressure rise for incipient separation would be of interest to a designer who does not want a flow to separate, yet wants to achieve the maximum pressure rise possible, such as is the case for inlet design.

All three types of pressure rise are compared in figure 10, the smallest being the pressure rise to the separation point. This is indicated by a single dotted line inasmuch as it is independent of the mode of inducing separation. The peak pressure rise always is greater than the rise to the separation point, and is indicated by a region (shaded in fig. 10) since it depends on the geometry inducing separation. The over-all pressure rise for incipient separation of various configurations, represented by the curves through data points in figure 10, also depends on the particular configuration. In fact, this dependence is a strong one. The three sets of data represent shock reflections - taken directly from Bogdonoff's data in reference 10 - together with compression corners and curved surfaces from the present experiments. In the past it sometimes has been assumed, for lack of specific data, that the peak pressure rise is essentially the same as the over-all pressure rise for incipient separation. As figure 10 illustrates, and, as was initially pointed out by Bogdonoff, the over-all pressure rise for incipient separation can be considerably greater than the peak pressure rise. It is realized that these available data on over-all pressure rise for incipient separation are rather meager inasmuch as geometry is so important to incipient separation. Consequently, additional information along these lines currently is being obtained.

CONCLUSIONS

1. The variable most important to a separated flow is the location of transition relative to the reattachment and the separation positions. By classifying the various separated flows studied according to the relative location of transition, certain qualitative characteristics (Reynolds number effects and flow steadiness) were the same for all cases investigated.

2. Several predictions of a theoretical mechanism postulated as fundamental to separated flows have been satisfactorily tested by special experiments conducted for the case of pure laminar separation with zero thickness of boundary layer at the separation point.

3. The stability of a separated laminar mixing layer increases markedly as speed increases over the range investigated (from subsonic Mach numbers to Mach numbers just below the hypersonic regime).

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
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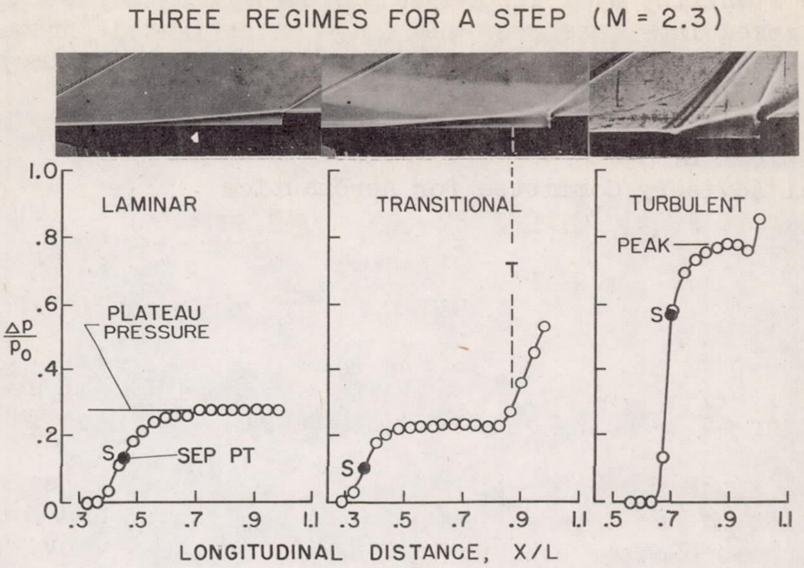

Figure 1

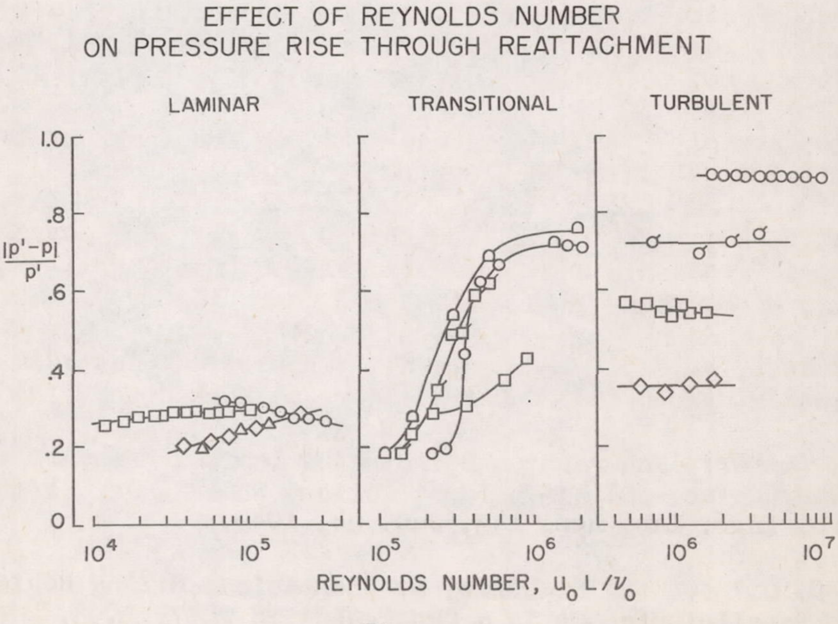

Figure 2

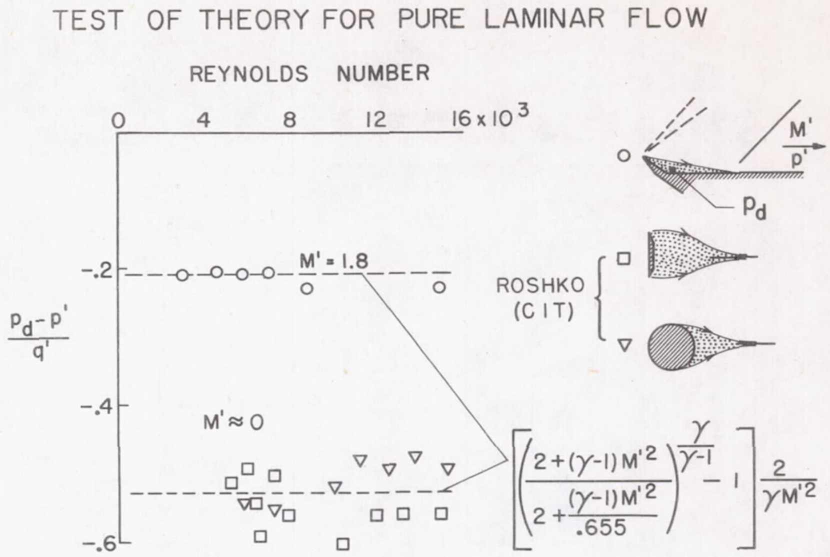

Figure 3

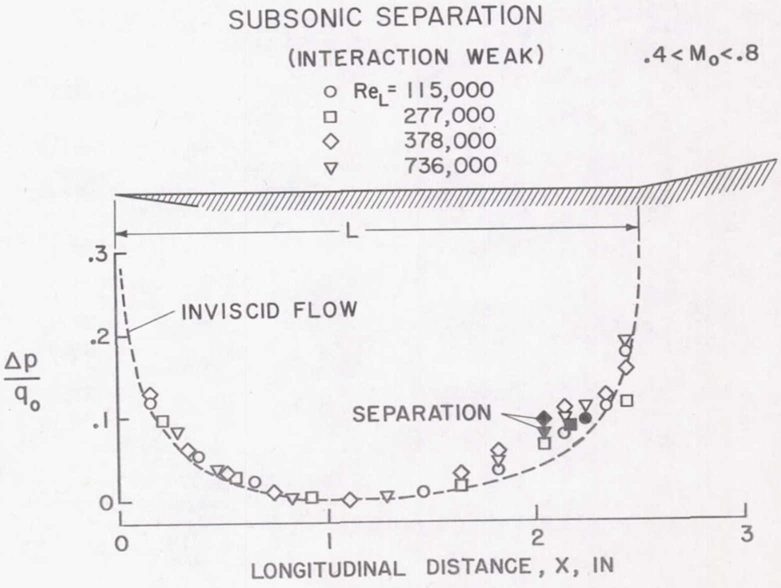

Figure 4

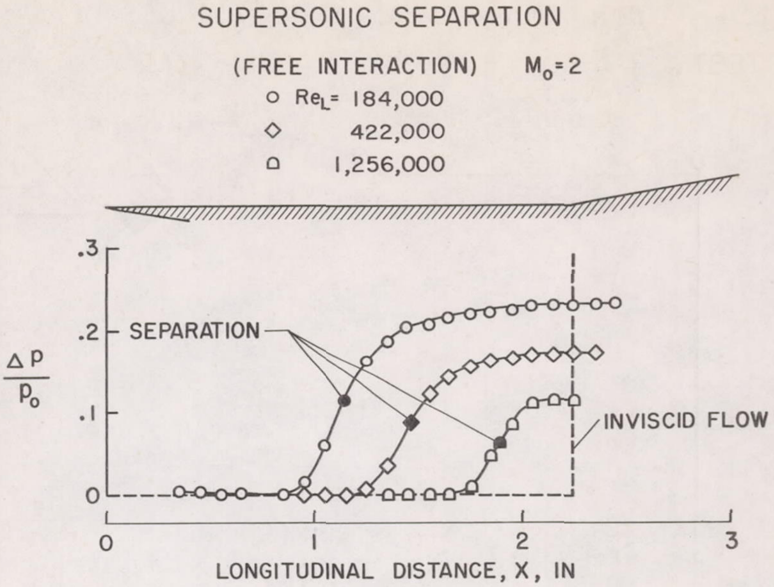

Figure 5

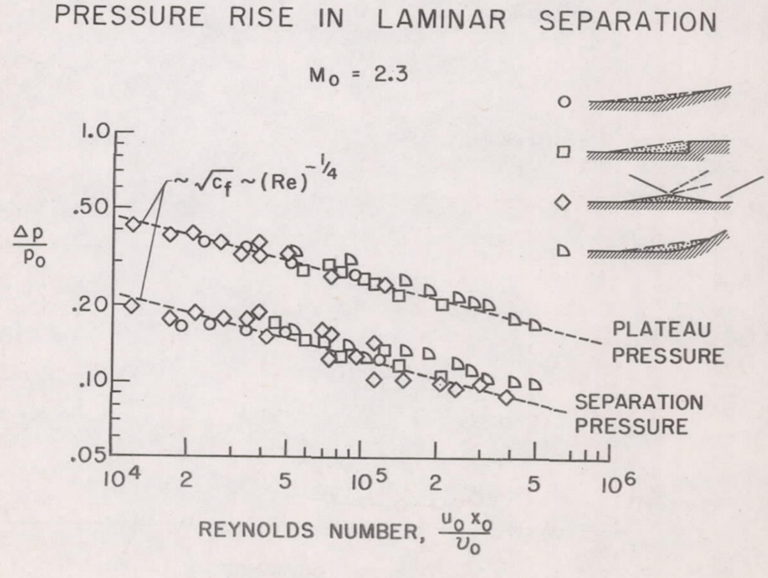

Figure 6

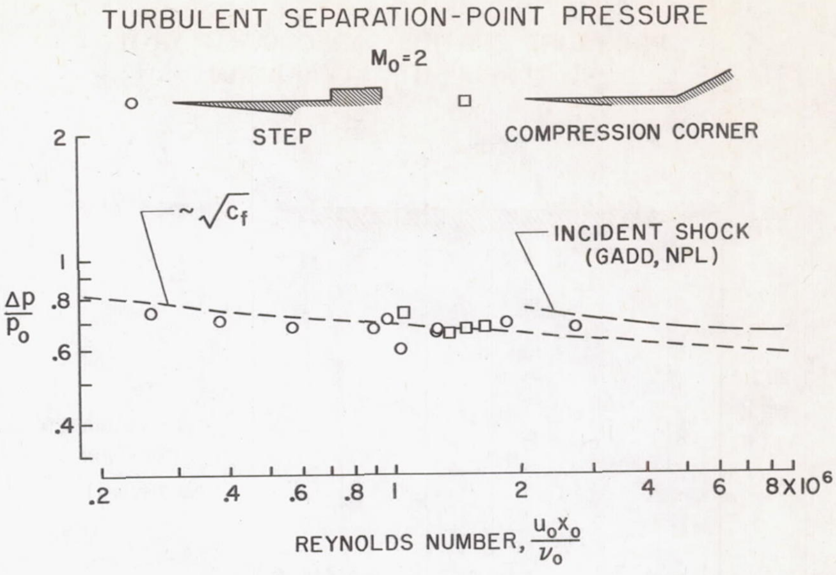

Figure 7

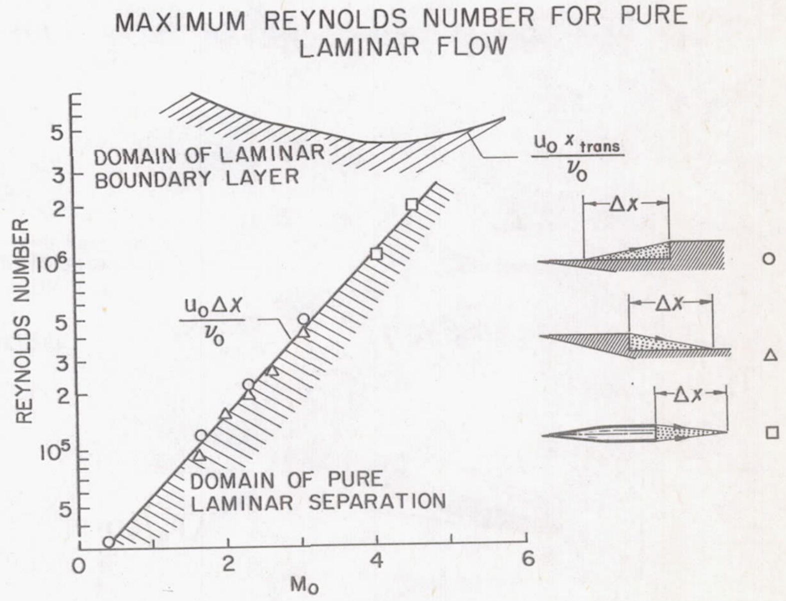

Figure 8

PRESSURE RATIOS ASSOCIATED WITH TURBULENT SEPARATION

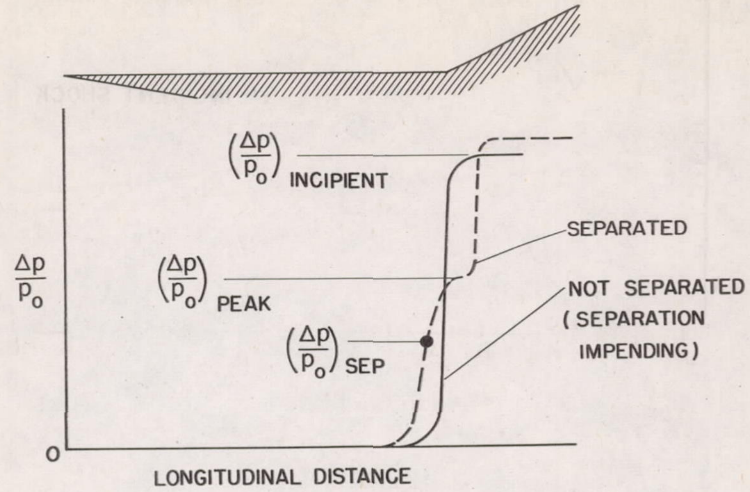

Figure 9

PRESSURE RATIOS FOR TURBULENT SEPARATION

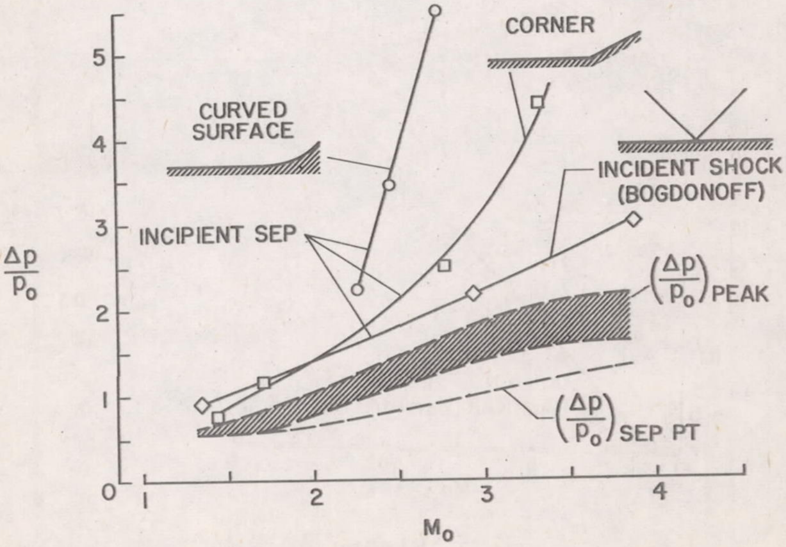

Figure 10

NACA - Langley Field, Va.