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Effects of Adverse Pressure Gradient on the Incompressible Reattaching Flow over a Rearward-Facing Step

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Donald M. Kuehn*
NASA Ames Research Center, Moffett Field, Calif.

Introduction

THE turbulent, incompressible reattaching flow over a rearward-facing step has been studied by many researchers over the years (e.g., Refs. 1-3; see also, Table 1, Ref. 2). One of the principal quantities determined in these experiments has been the distance from the step to the point (or region) where the separated shear layer reattaches to the surface (x_r). The values for x_r/h, where h is the step height, have covered a wider range than can reasonably be attributed to experimental technique or inaccuracy. Often the reason for a largely different value of x_r/h can be attributed to an incompletely developed turbulent layer, or a transitional or laminar boundary layer. However, for the majority of experiments where the boundary layer is believed to be fully developed and turbulent, x_r/h still varies several step heights; generally, $5\frac{1}{2} \lesssim x_r/h \lesssim 7\frac{1}{2}$. This observed variation has usually been attributed to such variables as ℓ/h (step length to height, h/δ (step height to initial boundary-layer thickness), R_{e_θ}, or the experimental technique for determining reattachment location. However, there are so many different combinations of variables in the previous experiments that it was not possible to sort out the effects of particular conditions on the location of reattachment.

Possible Reasons for the Variation of x_r/h

Eaton et al.[3] have offered an explanation of the observed variation of x_r/h. They have shown in their experiments that x_r is a strong function of R_{e_θ} for $R_{e_\theta} \lesssim 1000$ (x_r/h varied between 7.0 and 8.2 for $R_{e_\theta} < 500$ and approached a constant value of 7.7 at $R_{e_\theta} \sim 1000$). At these low values of R_{e_θ}, it is not clear how much of the observed variation of x_r/h was a direct effect of R_{e_θ} and how much was an indirect effect through a change in type of boundary layer, i.e., a laminar, a transitional, or a less than fully developed turbulent boundary layer. It is obvious from their data, however, that in the region where we know the boundary layer to be fully developed turbulent ($R_{e_\theta} >> 1000$) there is no R_{e_θ} effect.

Many of the published experiments with rearward-facing steps have been examined to determine why x_r varies from one experiment to another. There was no consistent influence of the specified variables that was of the magnitude necessary to explain the observed variation of x_r. In Fig. 1, however, a sizable variation of x_r is shown as caused by a variable not discussed in any published experiments, specifically, y_1/y_0 (the ratio of the channel dimension downstream of the step to that upstream of the step). In subsonic flow, this step expansion in cross section causes an adverse pressure gradient. The inviscid pressure coefficient C_p that corresponds to y_1/y_0 is shown in Fig. 1 to indicate the magnitude of C_p that is associated with the channel expansion. These values of C_p are not useful in correlating the reattachment data, however, because the flow over the step is altered considerably by the

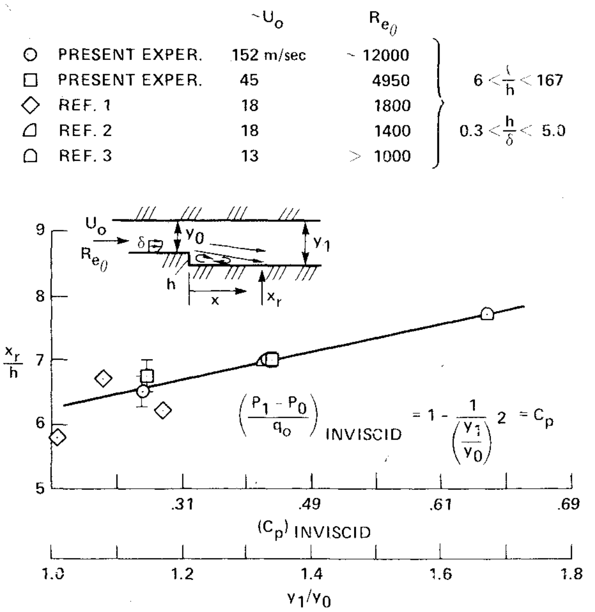

Fig. 1 Effect of adverse pressure gradient on reattachment distance for parallel-walled channels.

thick, turbulent boundary layer. The rapid growth of displacement thickness limits the adverse pressure gradient —the effective pressure gradient is much less than the inviscid one. The data in Fig. 1 are from experiments where the channel dimensions (y_1 and y_0) are given and where the values of R_{e_θ} are sufficiently large to be reasonably sure that the measurements were indeed with a fully developed turbulent boundary layer. These experiments show no systematic variation of x_r caused by the wide range of ℓ/h, h/δ, U_0, and R_{e_θ}. It appears, however, that the geometry of the specific test channel can have a significant influence on the location of reattachment.

In the present experiment velocity profiles have been measured in and around the region of separated flow. Velocity profiles downstream of reattachment are shown in Fig. 2 for two conditions: $y_1/y_0 = 1.14$ and 1.33 (the reattachment location for these data is included in Fig. 1). In both cases, the adverse pressure gradient through the reattachment zone has greatly altered the profiles by decreasing the velocities. Also, as the adverse pressure gradient relaxes downstream of reattachment, the profiles gradually approach the fully developed reference profile measured upstream of the step. Obviously, considerable length is required for full recovery of the profile. The stronger adverse pressure gradient ($y_1/y_0 = 1.33$) not only causes the reattachment to move downstream as shown in Fig. 1, but it also distorts these velocity profiles considerably more; velocities near the wall have been decreased more in magnitude and this velocity reduction extends further through the boundary layer.

The influence of adverse pressure gradient on boundary-layer reattachment has been investigated further in the present experiments. In the channel where these experiments were run, the wall opposite the step can be rotated about a pivot point located at the $x=0$ station; this is directly opposite the step location (Fig. 3). The value of y_0 was the same as previously used, $7h$ for $h=1.27$ cm and $3h$ for $h=2.54$ cm. This alteration to the channel geometry superimposed a pressure gradient on the self-imposed gradient from the channel expansion over the step.

The result of altering the adverse pressure gradient by rotating the channel wall (Fig. 3) is consistent with the result where adverse pressure gradient was altered by changing y_1/y_0 (Fig. 1). In both cases, an increasingly adverse pressure gradient caused x_r to move downstream. For the experiment with the wall deflected to the negative α_w position, the self-

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*Aerospace Engineer, Experimental Fluid Dynamics Branch, Thermo- & Gas-Dynamics Division.

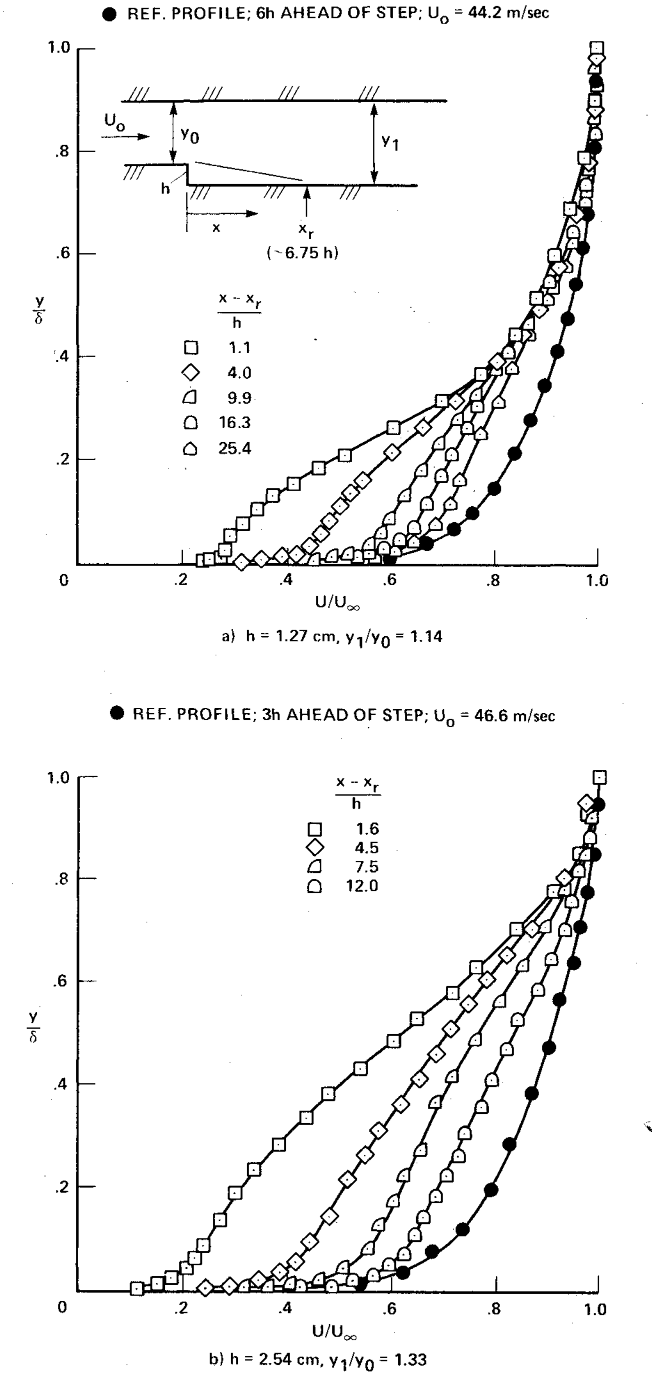

Fig. 2 Velocity profiles downstream of reattachment for two values of y_1/y_0: a) $h = 1.27$ cm, $y_1/y_0 = 1.14$; b) $h = 2.54$ cm, $y_1/y_0 = 1.33$.

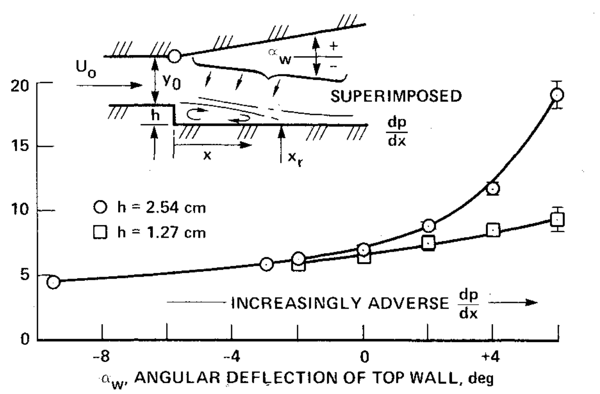

Fig. 3 Reattachment location where a pressure gradient is superimposed on the flow over a rearward-facing step; $U_0 \sim 45$ m/s.

imposed adverse pressure gradient was reduced by a superimposed favorable gradient. This caused the reattachment region to move closer to the step. When an adverse gradient was superimposed on the adverse gradient due to the step expansion, reattachment moved far downstream.

Conclusions

These data show a large influence of adverse pressure gradient on the reattaching flow over a rearward-facing step that has not been reported previously. Further, the many previous experiments for fully developed, turbulent flow in parallel-walled channels have shown a range of reattachment location that has not been explained by differences in initial flow conditions. Although these initial flow conditions might contribute to the observed variation of reattachment location, it appears that the pressure gradient effect can explain most of that variation.

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Use of Metallic Analog Materials in Low-Gravity Solidification Experiments

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John M. Papazian*

Grumman Aerospace Corporation, Bethpage, N.Y.

As part of the NASA space processing effort, several solidification experiments have been performed which used aqueous ammonium chloride solutions (NH_4Cl:H_2O) as a model material.[1,2] The transparency and ease of handling of this material make it attractive from an experimenter's point of view, and the dendritic nature of its solid-liquid interface provides a good analog for metallic systems.[3] Since convective effects can be very significant in solidification experiments and since differences exist between the thermophysical properties of aqueous and metallic liquids, some care must be taken in translating experimental conclusions from one class of materials to the other. Several authors have considered this problem,[4,5] and a convection analysis of one of the low-gravity experiments has been published.[6] This analysis concluded that, for the particular experimental geometry under consideration, aqueous and metallic convective velocities expected in the low-gravity rocket experiment are of insignificant magnitudes and that crystallization phenomena observed in such experiments using

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*Staff Scientist, Research Dept.