Effect of Initial Conditions on Turbulent Reattachment Downstream of a Backward-Facing Step

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The reattachment of a fully turbulent, two-dimensional shear layer downstream of a backward-facing step has been studied experimentally. The work examines the effect of variations in inlet conditions on the process of reattachment. A series of experiments were conducted in a low-speed wind tunnel using specialized instrumentation suited to the highly turbulent, reversing flow near reattachment. Accurate characterization of the time-mean features of the reattaching flows was possible. Assuming linear scaling normalized on distance from reattachment, distributions of C_p^*, γ, and C_f appear universal for two-dimensional reattachment, independent of initial conditions and step height, for given duct geometry (area ratio) and for high step height Reynolds numbers with thin, separating boundary layers. The results suggest universal flow structure in the reattachment zone.

Nomenclature

AR	= area ratio, W_2/W_1
C_p	= pressure coefficient, $(P-P_{\mathrm{ref}})\frac{1}{2}\rho U_{\mathrm{ref}}^2$
C_p^*	= normalized pressure coefficient, $(C_p - C_{p,\min})/(1-C_{p,\min})$
$\bar{C}_f$	= time-averaged skin friction coefficient, $\overline{\tau_w}/\frac{1}{2}\rho U_{\mathrm{ref}}^2$
H	= step height (= 5.08 cm for all cases reported)
P	= wall static pressure
P_{ref}	= wall static pressure at $X/H = -3$
Re_H	= Reynolds number based on step height, $U_{\mathrm{ref}}H/\nu$
u'	= rms intensity of streamwise velocity fluctuations
$\bar{U}$	= time-averaged streamwise velocity
U_{ref}	= streamwise velocity at $X/H = -3$, $Y/W_1 = 0.5$
W_1, W_2	= duct dimensions upstream and downstream of the step, respectively $(W_2 = W_1 + H)$
x	= streamwise distance measured along the surface with origin at the step base
x^*	= normalized streamwise distance, $(X - X_R)/X_R$
X_R	= reattachment length
Y	= distance normal to the surface
α	= angle between inlet and downstream duct
γ	= forward flow fraction
δ	= boundary-layer thickness at separation
ν	= air kinematic viscosity
ρ	= air density
$\bar{\tau}_w$	= time-averaged skin friction

Introduction

TWO-dimensional turbulent reattachment is defined as the process whereby a separated free shear layer becomes increasingly affected and, finally, dominated by the presence of an adjacent solid surface. Reattachment may be viewed as a zone of readjustment where the turbulence structure characteristic of a free mixing layer starts to recover to flat-wall boundary-layer structure. The broad objective of this study has been to describe the characteristics of the reattachment zone. Following a brief discussion of the problem to motivate specific objectives, the experimental apparatus and measurement techniques used will be described. Then the experiments will be described, and results will be presented and discussed.

For two-dimensional flow, the reattachment point is defined as the location of zero average local skin friction. Reattachment takes place in a zone which includes the reattachment point. In the reattachment zone, time-averaged streamwise velocities are very small, and instantaneous reversals in flow direction occur due to the turbulent fluctuations. Also, changes in mean streamwise momentum are negligible relative to pressure and shear forces, so that the streamwise pressure gradient must be approximately balanced by the gradient of total fluid shear stress normal to the surface. The average total shear at the surface in the reattachment zone is small (by definition of the reattachment point) but it is rather large in the shear layer above the surface. Consequently, a substantial pressure rise must occur in the reattachment zone. This brief description identifies two key observable characteristics of the reattachment zone: 1) instantaneous reversals in flow direction and 2) strong adverse pressure gradient.

Turbulent reattachment occurs in a variety of engineering systems. A few examples of such systems include diffusers, airfoils at angle of attack, sudden enlargements in pipes or ducts, and atmospheric flows over hills and structures. The single-sided sudden expansion (backward-facing step) is an appealing test configuration for studies of reattachment because of its simple geometry, which produces a single region of separated flow with a well-defined initial separation line at a fixed two-dimensional separation location.

Figure 1 depicts the important features of the backward-facing step flow with relevant nomenclature. Three nondimensional parameters may be defined which describe the test conditions for the simple backstep geometry: 1) the nondimensional boundary-layer thickness δ/H, 2) the Reynolds number based on step height Re_H, and 3) the area ratio AR. Attention will be confined here to the case of relatively thin separating boundary layers $[\delta/H < 0(1)]$ and high Reynolds number $(Re_H > 10^4)$ with one (fixed) value of area ratio.

Even for the restricted conditions just denoted, the flow pattern for the backstep (generally characterized by the reattachment length X_R) is known to be affected by changes in geometry and initial conditions. Eaton and Johnston[1] reviewed previous experiments and report reattachment lengths in the range of five to nine step heights. Considerable uncertainty remains as to the effect of, say, increasing the thickness of the separating boundary layer or changing the

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area ratio, as evidenced by the aforementioned review article. Recent work[2] seems to indicate that X_R increases with AR, and a preliminary report by Cheun et al.[3] (confirmed by our results reported herein) shows that X_R increases as boundary-layer thickness increases for thin separating boundary layers. Little attention has been devoted to the question of what effect, if any, changes in overall flow pattern which are evidenced by variation in X_R have on details of the reattachment process itself. The objective of the paper is to compare the reattachment process for a variety of backstep cases with perturbed initial conditions. The paper is based on the dissertation of Westphal.[4]

Experimental Apparatus

The experiments were performed in a small, open-return, blower-driven wind tunnel in the Heat Transfer and Turbulence Mechanics Laboratory at Stanford University. A closed-loop motor controller was used to maintain constant blower speed to within ¼%. The desired speed was set by the microcomputer used for data acquisition and experiment control (described subsequently). Filtered air (nominal filter size: 5m) was delivered through a constant-pressure diffuser to the settling chamber (61×61 cm cross section), where honeycomb and a series of three fine-mesh screens were located. A planar 8:1 smoothly faired contraction preceded the test section.

The test section was machined from 1.27-cm thick sheets of Plexiglas,‡ then fitted with instrument ports and static pressure taps. The spanwise dimension of the test section was 61.0 cm, and the length of the test section from the step edge to the exit was about 160 cm. The length of constant-area duct upstream of the step could be varied by adding or removing sections of duct to give several different effective lengths of development for the boundary layer prior to separation. Three different lengths of upstream duct were used (30.5, 61.0, and 106.7 cm); with the two longest development lengths, a small rectangular trip was employed so that the separating boundary layer was turbulent and of constant thickness across the span.

Spanwise uniformity of the flow entering the test section was characterized using a continuous spanwise transverse with a total pressure probe at five y locations out from the wall. These profiles were taken in a plane 2.5 cm upstream of the step. At all locations examined, the mean velocity was uniform to within 1% across the center half-span. The measured freestream turbulence intensity was about ¼% at this location. These preliminary tests were done with the step wall removed at a core flow speed of $U_{\text{ref}} = 12$ m/s, the speed of all tests except series 3 (see Table 1).

A step height of 5.08 cm was used for all cases, giving an area ratio of 5/3. The step aspect ratio (tunnel span/step height) was 12—large enough to prevent the presence of the sidewalls from influencing the overall flow pattern.[5] The two dimensionality of the mean flow downstream of the step could be characterized more completely than is usually possible for several of the cases, because all terms of the two-dimensional continuity and momentum conservation equations could be evaluated at successive streamwise locations through the reattachment zone. The cases checked satisfied the conservation laws to a few percent of the inlet mass and momentum fluxes (see Ref. 4 for details).

Measurements of pressure, velocity, wall flow direction, and skin friction will be reported subsequently. The total pressure and wall static pressure tap data were acquired using a transducer (±700 N/m^2 full scale) whose calibration was checked daily against a micromanometer with a resolution of 0.25 N/m^2. Flow temperature and atmospheric pressure were monitored for accurate determination of air properties. In regions of low-turbulence levels, a single, normal hot wire (DISA type 55P14) was used to measure $\bar{U}$ and u' in conjunction with a TSI model 1050 constant-temperature anemometer. Where flow reversals were possible or high turbulence intensities ($u'/\bar{U}>0.3$) were encountered, a pulsed-wire anemometer[6] was used. Automatic probe calibration and computerized data acquisition were used for both anemometry systems, and probes were recalibrated every few hours of operation.

‡Registered trademark of Rohm & Haas Co., Philadelphia, Pa.

Wall flow direction and skin friction were measured using instruments developed in our laboratory which were especially designed for the low-speed, reversing, highly turbulent near-wall flow near reattachment or separation (detachment). The "thermal tuft"[7] measures instantaneous flow direction at about 1 mm from the surface. Then, by averaging its output, the fraction of time that the flow was in a given direction (denoted γ) could be determined. Skin friction was measured with the "pulsed wall probe."[4,8] This device, based on the same concept as the pulsed-wire anemometer, measures the velocity at a Y location very near the surface ($Y<0.2$ mm). The instantaneous skin friction is related to the measured velocity through a calibration function obtained in a steady, fully developed laminar channel flow.

Description of the Experiments

Four series of experiments were performed from which seven separate cases will be discussed. For each of the seven cases, two key observable parameters, 1) static pressure rise and 2) instantaneous wall flow direction, were measured in the reattachment region. Three cases from among these were selected for more detailed measurements which included velocity profiles and skin friction near reattachment. Parameters for all the experiments are summarized in Table 1, and a schematic of the test geometry is given in Fig. 2. The "baseline" configuration has been designated as case A; it employs a boundary-layer thickness of $\delta/H=0.4$, an area ratio of $AR=5/3$, and a Reynolds number of $Re_H=4\times10^4$.

Series 1 consists of three different perturbations of the thickness and state of the separating boundary layer. The thinnest boundary layer (series 1a) is laminar with a thickness of about $\delta/H=0.06$ at separation. By using a longer development length and a boundary-layer trip, a low Re_θ turbulent separating boundary layer ($\delta/H=0.2$) is obtained for series 1b. Series 1c is identical to the baseline case, designated as A. The thicker separating turbulent boundary layer for series 1c (case A) is obtained by a further increase in the upstream boundary-layer development length.

Bending the duct downstream of the expansion relative to the inlet (see Fig. 2) produces a slight curvature of the separated flow. The convex curvature of the detached free shear layer was expected to stabilize the shear layer turbulence and reduce its rate of spread.[9] Three duct angles (5, 10, and 15 deg) constitute series 2b, 2c, and 2d, respectively. With the duct set at an angle of 0 deg (2a), the conditions of case A are duplicated. Series 2c was the second case selected for detailed study and is designated case B.

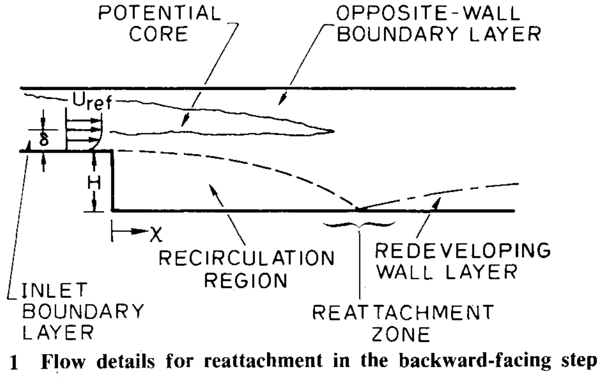

Fig. 1 Flow details for reattachment in the backward-facing step configuration.

Table 1 Test results

Series	Description[a]	$Re_H \times 10^{-4}$	δ/H	α, deg	X_R/H
1	Variable inlet boundary-layer thickness				
a	Thin laminar boundary layer	4.2	0.06	0	7.0
b	Turbulent boundary layer	4.2	0.2	0	8.0
c	Turbulent boundary layer (case A)	4.2	0.4	0	8.6
2	Angled downstream duct				
a	Straight case[b]	4.2	0.4	0	8.6
b	Small angle	4.2	0.4	5	9.1
c	Moderate angle (case B)	4.2	0.4	10	9.5
d	Large angle	4.2	0.4	15	9.7
3	Variable freestream velocity				
a	Thin boundary layer	2-8.8	0.06[c]	0	7.2-6.2
b	Angled duct	3-5.7	0.4	10	9.5-9.1
4	Imbedded inlet vorticity				
a	Large triangular generators	4.2	0.4[d]	0	6.8
b	Small triangular generators (case C)	4.2	0.4	0	7.2

[a] Area ratio $AR = 1.67$ and aspect ratio is 12 for all tests.
[b] Series 2a and 1c were performed using different test sections, but are nominally the same case otherwise.
[c] Boundary-layer thickness for all cases of variable freestream velocity is quoted at $Re_H = 4.2 \times 10^4$.
[d] Boundary-layer thickness for all cases with vortex generators is that which would occur if the generators were not present.

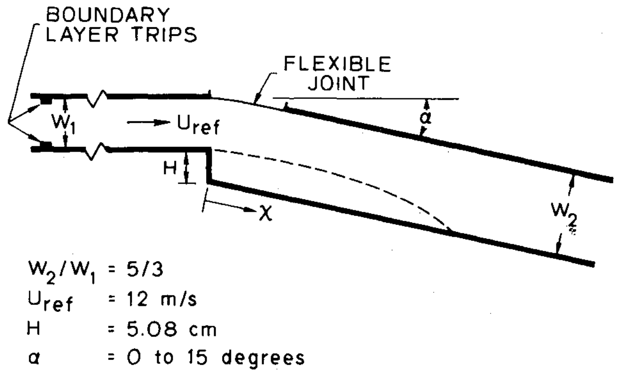

Fig. 2 Test section schematic.

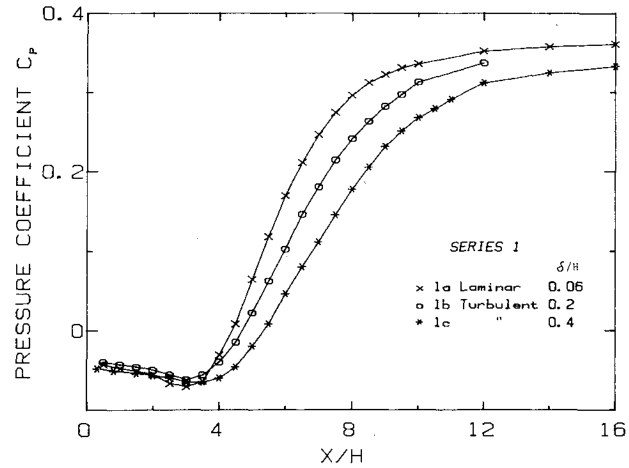

Fig. 3 Wall static pressure distributions for three cases.

The tests of series 3 were designed to check the sensitivity of the flow pattern to variations of the freestream velocity. Unfortunately, variations in U_{ref} produce changes in both Re_H and δ/H. More details of these tests can be found in Ref. 4. Reattachment length was measured for a number of values of U_{ref} for each of two basic configurations.

For series 4, vortex generators were installed along the surface, upstream of the separation location, for conditions otherwise the same as case A. The generators had a triangular planform, with a height of 1 cm and a chord of 2.5 cm. They were placed alternately at ±12 deg angle of attack and spaced evenly at the quarter-chord point in the spanwise direction (spacing equal to generator height) to generate an array of counterrotating vortices imbedded in the separating turbulent boundary layer.

Results and Discussion

Pressure rise and wall flow direction were measured for all seven cases described in Table 1. Figure 3 shows pressure coefficient vs distance (the latter normalized by step height) for a few selected cases. The base (minimum) pressures for the cases were found to be quite different—base pressures in the range of $-0.3 < C_{p,\min} < 0$ were measured for the seven cases. In spite of the difference in base pressures, the shape of the pressure rise through the reattachment region appears to be quite similar for all cases. Roshko and Lau[10] suggested some special nondimensional variables which they showed to correlate the pressure rise through turbulent reattachment onto a splitter plate affixed downstream of a bluff body. Specifically, they suggested that the reattachment length be used to nondimensionalize streamwise distance and that the pressure coefficient C_p^* would collapse the pressure distribution. To further investigate this similarity, accurate determination of the reattachment length for each case was necessary.

The reattachment length X_R was determined from the measured distributions of forward flow fraction γ by interpolating curves of γ vs X/H to find the location where $\gamma = 0.5$. We have shown[4] that the reattachment point (defined as the location where $\bar{C}_f = 0$) can be determined with an accuracy of $\pm 0.2H$ with the $\gamma = 0.5$ technique. Forward-flow fraction may be measured using any directionally sensitive anemometer or a device such as our thermal tuft very near the surface. Measurement of γ generally proved much easier than measurement of $\bar{C}_f$, because the latter required careful calibration of a delicate probe in a special facility and about ten times longer run times to acquire the data. For the seven cases discussed here, reattachment length was found to vary over a range of about 7-9.7 step heights; results are included in Table 1. Reattachment length varied substantially with the thickness of the separating boundary layer (series 1). A moderate increase in reattachment length was observed when the downstream duct angle was increased (series 2). When freestream velocity was increased (series 3), a small decrease in reattachment length was measured. Streamwise vortices added to the separating boundary layer caused reattachment length to be reduced by more than one step height (series 4).

The reattachment length determined from the forward flow fraction data for each case was used to rescale the wall pressure distributions in the reattachment region.[10] The renormalized plots are shown in Fig. 4. Also shown are two sample cases from previous studies.[10,11] The shapes of all of these curves appear to be nearly identical, especially in the region ahead of reattachment. The pressure rise at reattachment is in agreement with the relation proposed by Tanner,[12] which predicts $C_p^* = 0.27$ at reattachment for the range of minimum values of C_p of the present study. Downstream of $X^* = 0$ the similarity is not expected to be precise because the ultimate (far downstream) recovery is known to be influenced by test conditions such as AR and δ/H. For example, Tani et al.[13] found that the maximum pressure recovery was reduced when the separating boundary layer was quite thick compared to the step height, as did Narayanan et al.[14]

Since the pressure gradient near reattachment is quite large, it is important that reattachment length be accurately determined to assess the universality of the reattachment pressure distribution. In previous work (e.g., Ref. 11), uncertainty in X_R was typically at least $\pm 0.5H$, so that the reduced pressure coefficient could not be shown to collapse to a universal distribution in the reattachment region. The reattachment length reported by Kim was attributed an uncertainty of $\pm 14\%$, which correction would be enough to shift his data to agree with the results shown in Fig. 4.

Figure 5 shows the distributions of forward flow fraction plotted with streamwise distance normalized by the reattachment length. The data are found to collapse onto a nearly symmetrical S-shaped distribution (all the curves must intersect at $X^* = 0$, $\gamma = 0.5$ by definition). The universal forward flow fraction distribution demonstrated here provides a useful means of characterizing the extent of the reattachment zone. For example, the region extending $\pm 0.4\ X_R$ about $X^* = 0$ would encompass the entire region of flow direction reversal, and, in addition, includes most of the reattachment pressure recovery (refer to Fig. 4).

The collapse of the γ vs X^* curves suggests that the velocity fields, at least near the surface ($Y/H \lesssim 0.5$) of the various reattaching flows, are similar over the entire reattachment region when compared at equivalent values of X^*. Thus, the reattachment length is expected to be the appropriate scaling parameter for the spatial location of the velocity field as well as for the wall pressure. Representative velocity profiles, measured near reattachment, are compared at nearly the same values of X^* in Figs. 6-8. The comparison is complicated by the effects of the finite duct height, presence of the opposite-wall boundary layer, and the slight differences in the actual values of X^* at the profile stations where the data are compared. The presence and boundary-layer growth of the opposite wall give rise to changes in the velocity distributions far from the wall ($Y/H > 1$) which would probably not be observed if the area ratio were smaller. The effect of the opposite wall is even more noticeable around reattachment and beyond, due to the merger of the reattaching shear layer and the opposite-wall boundary layer. In spite of these problems, which preclude precise comparisons, the velocity distributions in the reattachment zone do seem to be similar at equal values of X^*, with the region of universal shape extending surprisingly far from the wall, to $Y/H > 1$.

Finally, measurements of time-averaged skin friction $\bar{C}_f$ for cases A and B are shown in Fig. 9. Also shown on this figure are results from the studies of Chandsuda and Brad-

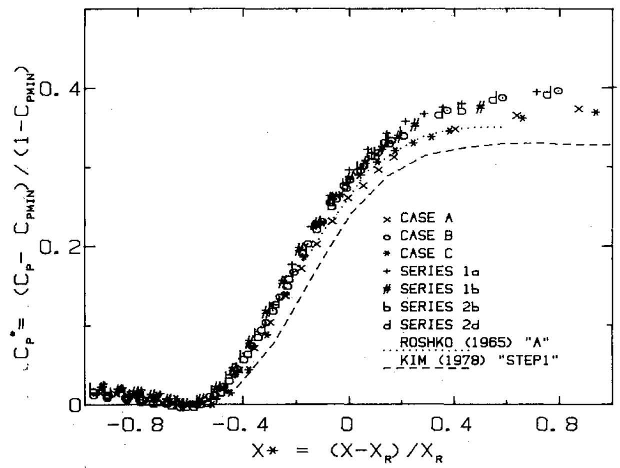

Fig. 4 Pressure distributions near reattachment, normalized as suggested by Roshko and Lau.

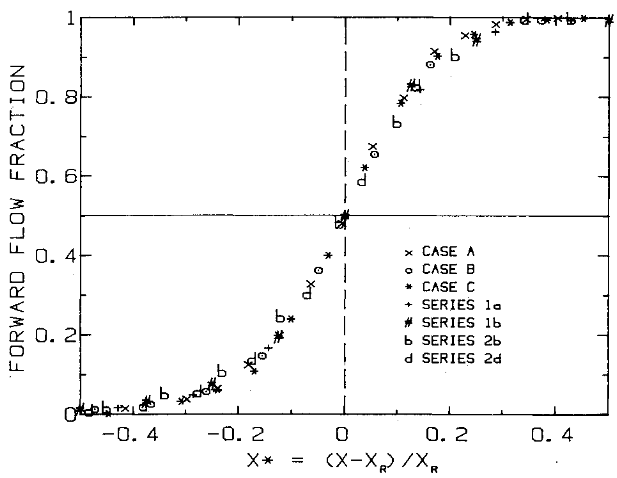

Fig. 5 Forward flow fraction near reattachment with streamwise distance normalized by the reattachment length.

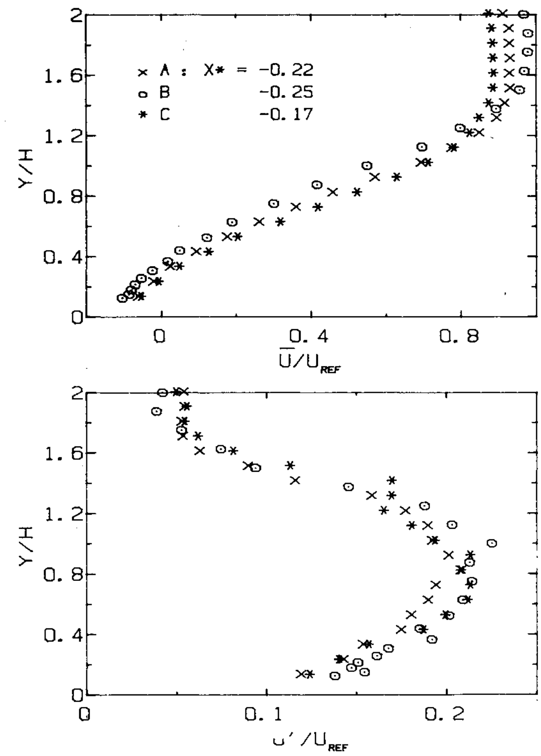

Fig. 6 Velocity distributions for cases A, B, and C compared near $X^* = -0.2$.

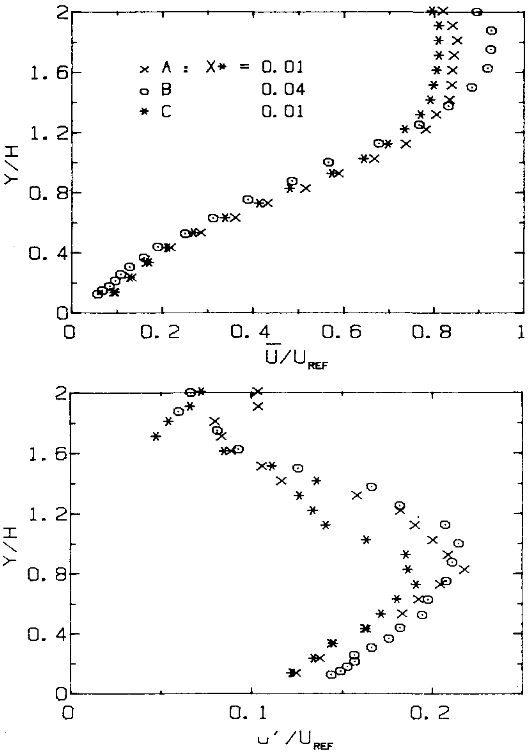

Fig. 7 Velocity distributions for cases A, B, and C compared near $X^* = 0$.

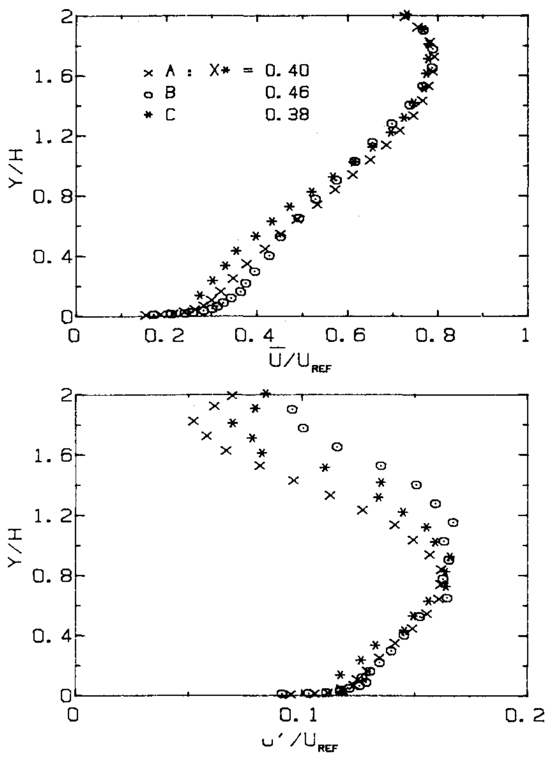

Fig. 8 Velocity distributions for cases A, B, and C compared near $X^* = 0.4$.

shaw[15] and those of Driver and Seegmiller.[16] The results from other studies have been plotted using the value of reattachment length given by the respective authors. Although these very recent results must be treated cautiously, skin friction also seems to depend only upon X^* in the reattachment zone. It must be noted that the downstream ($X^* > 1$) recovery of $\bar{C}_f$ in the reattached flow is not expected to be similar among the various cases shown in the figure.

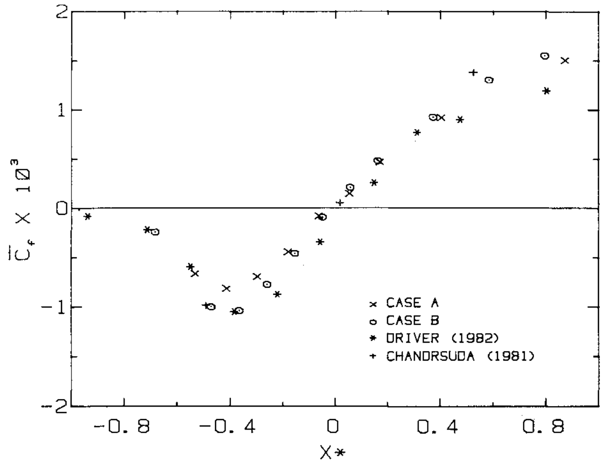

Fig. 9 Skin friction near reattachment plotted using normalized streamwise coordinate X^*

Concluding Remarks

It is shown that two wall layer parameters ($\bar{C}_f$ and γ) and three flowfield parameters (mean velocity, u', and C_p^*) obtain similar distributions when compared at equivalent locations relative to the reattachment location. These results were obtained in seven different tests with the backward-facing step configuration at fixed area ratio AR, thin separating boundary layers, and at fairly high Reynolds number Re_H. The coordinate X^* was found to be the appropriate measure of streamwise distance in the reattachment zone.

The location and extent of the reattachment zone is usefully defined by the distributions of forward flow fraction γ. The reattachment length X_R depends on initial conditions, as evidenced by the variation in X_R observed among the cases. However, the extent of the reattachment zone, when properly scaled on X_R, is seen to be independent of the variations in initial conditions examined here. A tentative conclusion is that the details of the interaction between the stress-carrying eddies and the surface in the reattachment zone are comparable when viewed in the properly scaled coordinates near the reattachment location. Accurate measurements of turbulent shear stress ($-\rho\overline{u'v'}$) over the reattachment of turwould be needed to test this hypothesis. It would also be desirable to test the proposed definition of the reattachment zone for other configurations with two-dimensional turbulent reattachment, using measurements of forward-flow fraction, skin friction, and velocity near the reattachment point.

Acknowledgments

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