AIAA 80-1438R

A Review of Research on Subsonic Turbulent Flow Reattachment

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Nomenclature

h = step height
Re_θ = momentum thickness Reynolds number
u = streamwise velocity
U = mean streamwise velocity
u' = $u-U$
U_0 = freestream velocity at separation
v' = fluctuating component of cross-stream velocity
x = streamwise coordinate
x_R = reattachment point
$\hat{x}$ = $(x-x_R)/h$
y = cross-stream coordinate
δ_s = boundary-layer thickness at separation
θ = momentum thickness at separation

Introduction

THE reattachment of a turbulent shear layer is an important process in a large number of practical engineering configurations, including diffusers, airfoils with separation bubbles, buildings, and combustors. In order to predict these complicated flows, we must understand and be able to predict the behavior of reattaching shear layers. However, our current understanding of the reattachment process is poor, a fact demonstrated by our inability to predict simple reattaching flows over a wide range of parameters. In fact, a complete list of the parameters that affect reattachment has yet to be formulated.

Among two-dimensional flows, the backward-facing step is the simplest reattaching flow. The separation line is straight and fixed at the edge of the step, and there is only one separated zone instead of two, as seen in the flow over a fence or obstacle. In addition, the streamlines are nearly parallel to the wall at the separation point, so significant upstream influence occurs only downstream of separation. Although they are not always stated explicitly, these are the reasons why most of the research on reattachment has been done in backward-facing step flows. The backward-facing step is also used as a building block flow for workers developing turbulence models.[1] Therefore, it is important to supply data which can be used to test codes and information that may aid the development of future codes.

Bradshaw and Wong[2] reviewed the experimental data for reattaching flows in 1972. Since that time there has been a proliferation of new research in the area, particularly since the advent of the laser anemometer and the pulsed-wire anemometer. This research has been conducted by a number of independent groups, and therefore the net result is somewhat disorganized. Very little systematic study has been done on the effect of the governing parameters on reattachment. In addition, most of the experiments, when viewed separately, have failed to cast any new light on the underlying physics of the reattachment process.

The purpose of this paper is twofold. The primary purpose is to review the available data for turbulent flows over backward-facing steps, including some new data of our own and other previously unpublished data. Second, we suggest several areas of research that we feel could lead to improvements in our ability to predict flows with separation bubbles. Several physical mechanisms will be proposed to explain some of the phenomena that have been observed. It is our hope that these suggestions will provoke further thought, comment, and research.

The review covers subsonic flows over backward-facing steps in which the Reynolds number is high enough to insure that the separated shear layer is fully turbulent. Important work on laminar and transitional reattaching shear layers has been performed by Goldstein et al.[3] and Armaly et al.[4] but will not be referred to here. Primary emphasis is on planar flows, but some data from axisymmetric flows will be utilized. Double-sided, sudden expansion flows in which the flow is asymmetric are not considered here, because these flows are even more complicated than flows with a single separation bubble.

A companion paper[5] examines the uncertainty of the available data in more detail. It also assesses the usefulness of the various data sets as test cases for computational procedures.

General Features of the Backward-Facing Step Flow

Although the backward-facing step is the simplest reattaching flow, the flowfield is still very complex. Figure 1 illustrates some of the complexities. The upstream boundary layer separates at the sharp corner forming a free-shear layer. If the boundary layer is laminar, transition begins soon after separation, unless the Reynolds number is very low.

The separated shear layer appears to be much like an ordinary plane-mixing layer through the first half of the separated flow region. The dividing streamline is only slightly curved, and the shear layer is thin enough that it is not af-

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Presented as Paper 80-1438 at the AIAA 13th Fluid and Plasma Dynamics Conference, Snowmass, Colo., July 14-16, 1980; submitted Sept. 24, 1980; revision received March 2, 1981.

fected by the presence of the wall. However, the reattaching shear layer differs from the plane-mixing layer in one important aspect; the flow on the low-speed side of the shear layer is highly turbulent, as opposed to the low turbulence-level stream in a typical plane-mixing layer experiment. Some authors, including Chandrsuda[6] and Chandrsuda et al.[7] have suggested that the turbulent recirculating flow causes the reattaching shear layer to be substantially different from a plane-mixing layer. This question will be more fully discussed later.

The separated shear layer curves sharply downward in the reattachment zone and impinges on the wall. Part of the shear-layer fluid is deflected upstream into the recirculating flow by a strong adverse pressure gradient. The shear layer is subjected to the effects of stabilizing curvature, adverse pressure gradient, and strong interaction with the wall in the reattachment zone. One or more of these mechanisms cause(s) a rapid decay of Reynolds normal and shear stresses within the reattachment zone. The flow in this zone is very unsteady. Very large turbulence structures with length scales at least as large as the step height are passing through the reattachment region. In addition, flow visualization by Abbott and Kline[8] and Kim et al.[9] showed that the length of the separation region fluctuated so that the impingement point of the shear layer moved up and downstream. Quantitative measurements by Eaton and Johnston[10] confirmed this conclusion.

The recirculating flow region below the shear layer cannot be characterized as a dead air zone. The maximum measured backflow velocity is usually over 20% of the freestream velocity, and negative skin-friction coefficients as large as $C_f = -0.0012$ (based on the freestream velocity) have been measured.[6,10]

Downstream of reattachment, the Reynolds stresses continue to decay rapidly for a distance of several step heights. Simultaneously, a new sub-boundary layer begins to grow up through the reattached shear layer. The measurements of Bradshaw and Wong[2] and more recent measurements by Smyth[11] have shown that the outer part of the reattached shear layer still has most of the characteristics of a free-shear layer as much as 50 step heights downstream of reattachment. This observation demonstrates the remarkable persistence of the large-scale eddies that are developed in the separated free-shear layer.

Until recently, the measurement of turbulence data in the backward-facing step flow was very difficult. The flow is highly turbulent, and frequent flow reversals occur, particularly in the reattachment zone, one of the most important areas in the flow. Hot-wire anemometers are not suitable for use in reversing flows, a fact that has severely restricted the quality of available data. The current generation of turbulence models suffers from a lack of experimental input because of this problem. Since the introduction of the laser-Doppler anemometer and the pulsed-wire anemometer, the quality of available data has slowly begun to improve.

Summary of Experimental Results

At the time of Bradshaw and Wong's[2] review, very few reliable data for reattaching flows were available. Only a few sets of hot-wire turbulence data were available,[12-14] and measurements in the reattachment zone were lacking. Bradshaw and Wong[2] concluded that the ratio of the boundary-layer thickness at separation to the step height was an important parameter characterizing the downstream flow. On the basis of the available turbulence data, they concluded that the shear stress $(-\overline{u'v'})$ in the reattaching layer is much larger than the shear stress in an ordinary plane-mixing layer. They also pointed out that the shear stress decreases rapidly near reattachment, despite the fact that there is very little change in the mean-velocity gradient $(\partial U/\partial y)$.

Since the time of Bradshaw and Wong's[2] review, several data sets have been taken in the two-dimensional, backward-facing-step flow using hot-wire anemometers,[6,9,15,16] pulsed-wire anemometers,[10,17,18] laser anemometers,[11,19-24] and flow visualization.[25,26] These data sets are summarized in Table 1.

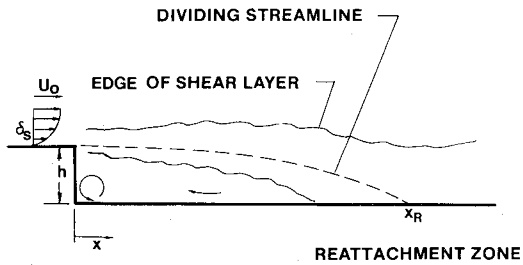

Fig. 1 Backward-facing step flowfield.

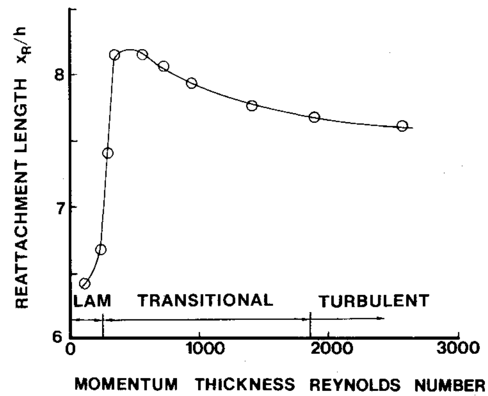

Fig. 2 Reattachment-length measurements showing dependence on the state of the separating boundary layer; note that the scaling of the abscissa is experiment-dependent.

Effect of System Parameters on Reattachment

The experiments just listed have covered a wide range of initial and boundary conditons, so some measure of the effect of various parameters on the flow can be seen by examining the data in Table 1. The most important dependent parameter characterizing the individual flowfield is the reattachment length which varies from 4.9 to 8.2 step heights for the experiments in Table 1. Comparison of the reattachment length from various experiments provides insight into the effects of varying the following five principal independent parameters: 1) initial boundary-layer state, 2) the initial boundary-layer thickness, 3) freestream turbulence, 4) pressure gradient, and 5) aspect ratio. We shall consider each effect separately below.

1) The effect of changing the *state (laminar/turbulent) of the separation boundary layer* has been systematically studied by Eaton et al.[17] and Eaton and Johnston.[10] This parameter was found to have a significant influence on the reattachment length (see Fig. 2). The flow apparently becomes independent of the Reynolds number when the boundary layer is fully turbulent. Furthermore, the results in Fig. 2 agree qualitatively with the results of Bradshaw,[27] who found that layers originating from laminar boundary layers initially grow more rapidly than those originating from turbulent boundary layers.

2) The data of Narayanan et al.[28] show a weak effect of the *boundary-layer thickness* on the reattachment length (Fig. 3). However, by using four data sets with different values of δ_s but similar values of other parameters, we see a somewhat stronger effect of δ_s on the reattachment length (Fig. 3). Further systematic study is needed to resolve this issue.

3) The effect of *freestream turbulence* on the reattachment length has never been studied systematically. However, three of the data sets in Table 1 (Etheridge and Kemp, Hsu, and

Table 1 Summary of backward-facing-step data sets

Author(s)	B.L. Thickness at Separation δ_s/h	R_θ Separation	B. L. State at Separation	Re_h	Free-Stream Turbulence u'/U_o	Aspect Ratio	Reattachment Length x_R/h	Turbulence Data	max $\overline{u'v'}/U_o^2$ x 100	max $\overline{u'^2}/U_o^2$ x 100	Configuration
Abbott & Kline [8]	.16-1.97	800-1600	Turb.	$2x10^4$-$5x10^4$		2-15	7±1	Hot-film dubious results	---	---	Sudden expansion; double-sided
Baker [18]	.71	3500	Turb.	$5x10^4$	.15%	18	5.7-6.0	u' PWA u'v' x-wire	1.1	4.2	Small step in large tunnel y_1/y_o = 1.10
Bradshaw & Wong [2]	0.13	730	Lam.	$4.2x10^4$		30.5	6	--	--	--	Sudden expansion, shaped upper wall
Chandrsuda [6]	0.04	570	Lam.	$1.1x10^5$	0.07%	15	5.9	$\overline{u'}$ u-wire v', u'v' x-wire	1.1	2.7 4.0 w/ u-wire	Sudden expansion; top wall sloped down at 1.7°
Denham [20]	0.5	~150	Lam./Turb.	$3x10^3$	--	20	6	u' laser	--	5	Sudden expansion 2:3
Eaton [10] & Johnston	0.23	890	Turb. trans.	$3.9x10^4$	0.3%	12	7.97	u' pulsed wire anem.	--	4.5	Sudden expansion 3:5
Eaton [10] & Johnston	0.23	510	Trans.	$2.3x10^4$	1.0%	12	8.2	u' pulsed wire anem.	--	3.4	Sudden expansion 3:5
Eaton [10] & Johnston	0.18	240	Lam.	$1.1x10^4$	0.3%	12	6.97	u' pulsed wire anem.	--	3.7	Sudden expansion 3:5
Etheridge & Kemp [19]	2.0	600	Trans.		2%		5.0	Frequency shifted LDV $\overline{u'}, \overline{v'}, \overline{u'v'}$	1.7	4.2	Free surface water channel; distance to surface ≈ 14.5 h.
Grant [21]	--	--	Turb.	$3.4x10^3$	--	23	--	Laser u'	--	4.5	Small step in large tunnel
Haminh & Chaissing [15]	.05	--	Turb.	$1x10^5$	.1%	6	~6	--	--	--	Sudden expansion 5.5-6.6
Hsu [13]	.13	3300	Turb.	$2.5x10^5$	3.5%	4.5	>6.0 (6.3)	Hotwire u', $\overline{u'v'}$	50	3.6	Sudden expanpansion 2:3
Kim et al. [9]	.45	1400	Turb.	$3.0x10^4$	~.6%	24	7±1	$\overline{u'}, \overline{v'}, \overline{u'v'}$ x-wire	.95	2.47	Sudden expansion 3:4
Kim et al. [9]	.30	1400	Turb.	$4.5x10^4$	.6%	16	7±1	$\overline{u'}, \overline{v'}, \overline{u'v'}$ x-wire	1.00	2.84	Sudden expansion 3:4.5
Kuehn [24]	--	4950/12,000	Turb.	--	--	6	7	--	--	--	Sudden expansion 3"-4"
Kuehn [24]	--	4950/12,000	Turb.	--	--	12	6.74/6.51	--	--	--	Sudden expansion 3.5"-4"
Narayanan et al. [28]	3.33-.2	1800	Turb.	--	.03%	166-10	5.6-6	--	--	--	Small step in lg. wind tunnel
Rashed et al. [41]	--	--	--	$3.9x10^4$	.3%	10	6	u' hotwire	--	--	Sudden expansion 2.4:2.8
Rothe [26] & Johnston	.5	<900	Trans. turb.	--	5.5%	15	7	--	--	--	--
Seki [16]	--	--	--	$3.3x10^4$	?	?	?	Hot-wire u'	.6	1.1	Sudden expansion, double sided
Smyth [11]	Fully devlpd.	--	Turb.	$7.0x10^3$	--	30	6	Laser $\overline{u'}$, $\overline{v'}$, $\overline{u'v'}$, $\overline{w'}$	1.1	2.8	Double-sided expansion 1:1.5
Tani [12]	.28	2100	Turb.	$6x10^4$	?	47.5	6.5-6.9	$\overline{u'}$ u-wire $\overline{u'v'}$ rotatable slant wire	1.3	3.5	Small step in large channel y_1/y_o = 1.07
Tropea & Durst [23]	2	1080	Trans. turb.	$5.5x10^3$	2%	--	15	Laser $\overline{u'}$, $\overline{v'}$, $\overline{u'v'}$	--	2.8	Free Surface water channel 7.5:1

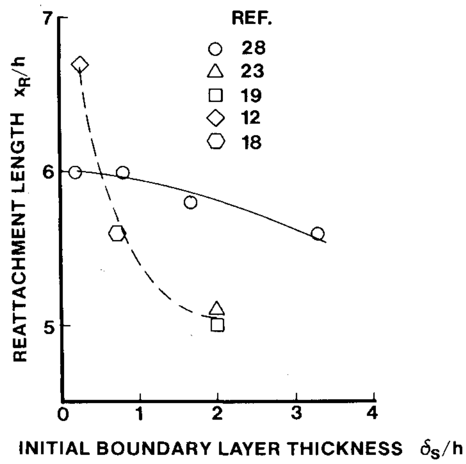

Fig. 3 Plot of reattachment length vs initial boundary-layer thickness, showing ambiguous results.

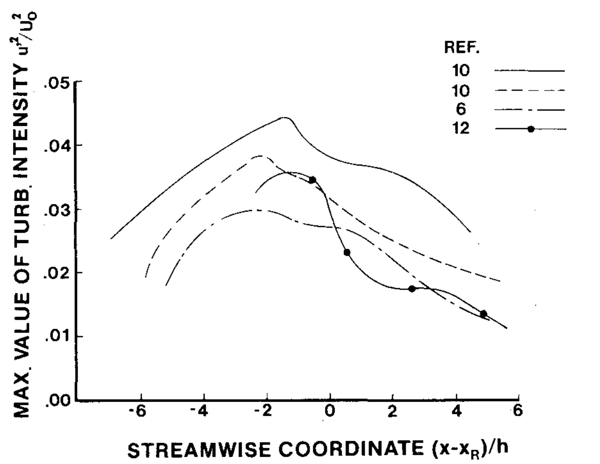

Fig. 5 Maximum values of the streamwise turbulence intensity $(\overline{u'^2}/U_0^2)$ for data sets which have a plateau in the reattachment zone.

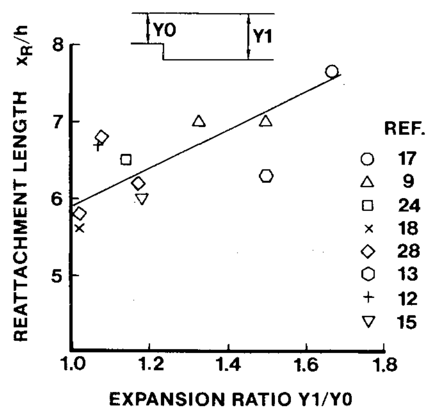

Fig. 4 Effect of pressure gradient on the reattachment length.

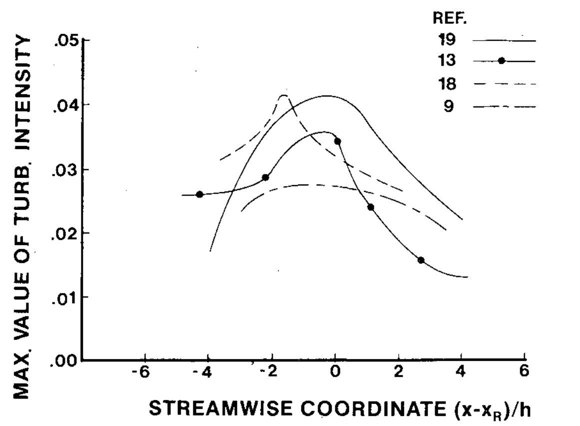

Fig. 6 Maximum values of the streamwise turbulence intensity for data sets which do not have a plateau in the reattachment zone.

Tropea and Durst) had fairly high levels (>1%) of the freestream turbulence. An examination of Figs. 3 and 4 suggests that high levels of the freestream turbulence decrease the reattachment length. This result is in qualitative agreement with the measurements of Patel[29] in a plane-mixing layer. He found that plane-mixing layer growth rates were increased by increasing the freestream turbulence level. The sensitivity to freestream turbulence is surprising since, according to most authors, the separated shear layer is already strongly affected by the turbulence in the recirculating flow. The magnitude of the effect of freestream turbulence is likely to be dependent on a) the initial conditions of the free-shear layer and b) the spectrum of the freestream turbulence. Further investigation into the effect of freestream turbulence on free-shear layers definitely is needed.

4) The effect of changing the *streamwise pressure gradient* in the reattachment zone has not been studied systematically. This pressure gradient is in part controlled by the overall system geometry. Kuehn[30] pointed out that a plot of reattachment length vs area expansion ratio for sudden expansion flows shows a very substantial effect of the pressure gradient on the reattachment length. In Fig. 4, reattachment lengths have been plotted vs expansion ratio for flows in which the boundary layer is fully turbulent at separation. There is a considerable amount of scatter, but a trend of increasing reattachment length with increasing expansion ratio is apparent. Kuehn and Seegmiller[24] are proceeding with further investigation of this question.

5) The *aspect ratio of the flow apparatus* (channel width/step height) can also have an effect on the reattachment length. This effect was systematically studied by de Brederode and Bradshaw,[31] who found that the effect was negligible for aspect ratios greater than ten. For aspect ratios less than ten, the reattachment length increases if the boundary layer at separation is laminar and decreases if it is turbulent. de Brederode and Bradshaw[31] attributed this difference to differences in details of the corner flow.

Turbulence Measurements

Turbulence quantities have been measured for most of the experiments in Table 1. There is a substantial variation between experiments in the peak values of the turbulence intensity and shear stress (see Table 1). The variation is probably caused as much by experimental uncertainty as by real differences in the flows. Many of the turbulence measurements were done with x-wire hot-wire probes, which are inadequate for use in highly turbulent flows (see Tutu and Chevray[32]). The local turbulence intensity near the center of the reattaching shear layer exceeds 30%, so the x-wires are expected to undermeasure turbulence quantities (particularly the shear stress) in this region. In addition, the turbulence-intensity measurements can be affected strongly by low-frequency motions of the shear layer that are certainly present in some of the experiments, but may not be present in all of them.

The turbulence-intensity measurements do show a consistent pattern when the maximum intensity in a given profile is plotted as a function of streamwise distance (Figs. 5 and 6). In almost all cases, the turbulence intensity reaches a peak value approximately one step height upstream of reattachment, then decays rapidly. Many of the data sets have a short plateau of constant turbulence intensity followed by

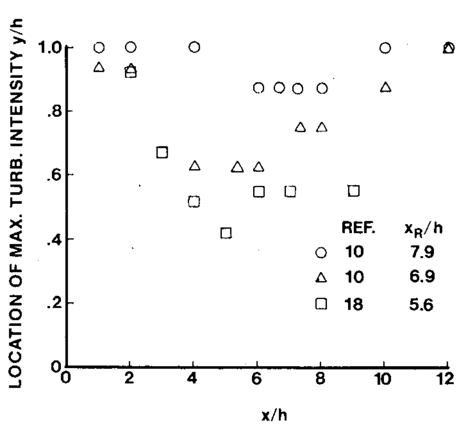

Fig. 7 Vertical location of maximum turbulence intensity as a function of streamwise distance from the step.

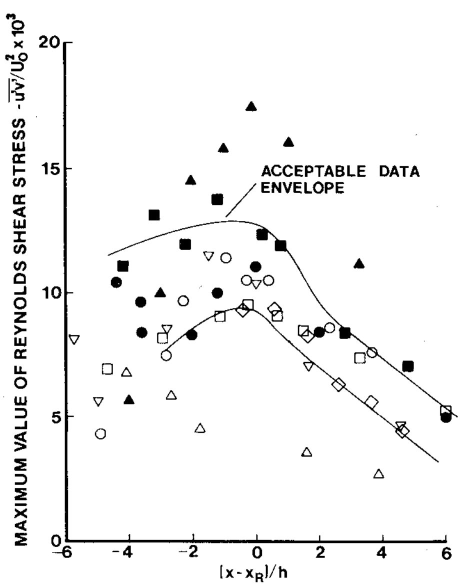

Fig. 8 Maximum values of the Reynolds shear stress for different experiments: Baker[18]; Chandrsuda[6]; Etheridge and Kemp[19]; Kim et al.[9]; Kuehn and Seegmiller[24]; Seki et al.[16]; Smyth[11]; and Tropea and Durst.[23]

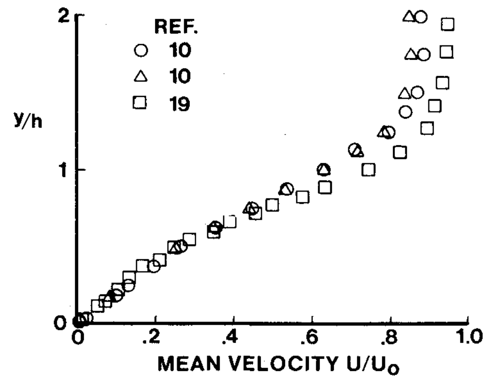

Fig. 9 Comparison of mean velocity profiles at $\hat{x}=0$ from three different experiments.

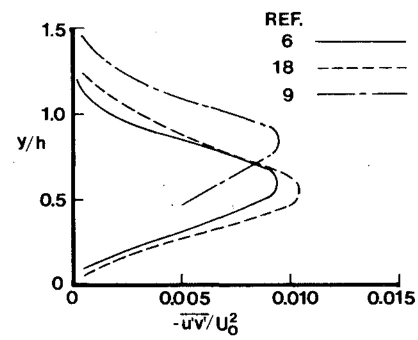

Fig. 10 Comparison of shear stress profiles from three different experiments.

another region of rapid decay (Fig. 6). The locus of points (normal to the wall) where turbulence intensity is a maximum dips toward the wall in the reattachment zone and then moves back out away from the wall downstream of reattachment. The point of maximum turbulence intensity dips closer to the wall the shorter the reattachment length, as shown in Fig. 7. Only three data sets are shown in Fig. 7 for clarity, but the pattern illustrated is almost universal for backward-facing-step experiments. Despite the rapid decay of the peak value of turbulence intensity which occurs away from the wall, the turbulence intensity decays very slowly near the wall.[9,10,23]

The shear stress $(-\overline{u'v'})$ measurements show the same general pattern observed in the turbulence-intensity measurements (Fig. 8). Some of these data sets[18,23] also have a plateau in the reattachment region. Lines of "acceptable data" are shown in Fig. 8. In the authors' estimation, the two experiments outside these bounds must have encountered some unrecognized measurement problem. The large difference between data sets far upstream of reattachment is caused by two factors: 1) the scaling of the x coordinate used here is not appropriate to this region, and 2) differences in initial conditons cause large differences in the early development of the shear layer. The collapse of the data is better in the reattachment region and much better downstream of reattachment. The variation within the reattachment zone is caused largely by instrumentation problems. The values measured with hot-wire arrays are consistently lower than those measured with laser anemometers. Based on the information in Fig. 7, the peak value of the shear stress for most experiments is estimated to be in the neighborhood of $-\overline{u'v'}/U_0^2 = 1.25\times 10^{-3}$.

Chandrsuda[6] has made the only measurements of higher-order turbulence quantities in the reattachment zone. Unfortunately, the measurements were made with hot wires, and the accuracy of the measurements is therefore questionable. However, Chandrsuda and Bradshaw[33] felt that the measurements at least could be used qualitatively. They concluded that the triple products in the outer part of the shear layer decrease at roughly the same rate as the Reynolds stresses, but decay much more rapidly than the Reynolds stresses near the wall. They felt that this was primarily due to the imposition in the reattachment region of the wall constraint on the normal velocity ($v=0$ at $y=0$). This result indicates the gradient diffusivity of the Reynolds stresses is not an adequate model for the triple products in the reattachment region. Further measurements of the triple products using laser-anemometer techniques are needed to verify these conclusions.

Comparison of Profiles Near Reattachment

It is difficult to compare mean velocity and Reynolds stress profiles from different experiments due to the effects of different initial and boundary conditions. Much of the apparent differences between profiles from different experiments is caused by differences in the reattachment length. One possible way to compare profiles from various experiments is to renormalize the streamwise coordinate as $\hat{x}=(x-x_R)/h$. In this way, features of the reattachment zone may be examined independent of experiment-to-experiment variation in the reattachment length. Mean-velocity profiles at $\hat{x}=0$ have been compared for the experiment of Etheridge and Kemp[19] and two experiments from Eaton and Johnston.[10] The initial conditions for these experiments ranged from a very thick ($\delta_s/h=2$) turbulent boundary layer to a thin

($\delta_s/h \simeq 0.2$) laminar boundary layer. The reattachment lengths ranged from 5 to 7.9 step heights. The velocity profiles are in excellent agreement in the inner layer (Fig. 9). The differences in the outer layer are caused by differences in the boundary geometry among the three experiments.

A similar comparison was made of shear stress ($-\overline{u'v'}$) profiles. In this case, the data are taken from the experiments of Kim et al.,[9] Chandrsuda,[6] and Baker.[18] All three of the profiles were measured with x-wire hot-wire probes. The profiles (Fig. 10) are again quite similar despite large differences in the initial conditions (see Table 1). The profile of Kim et al. is shifted up because the reattachment length is substantially longer than in the other two experiments.

The agreement of the profiles in Figs. 9 and 10 shows that the effect of initial conditions has been overwhelmed by the time the shear layer reattaches. Therefore, it appears that the criterion for an overwhelming perturbation of the shear layer can be extended out to a value of $\delta_s/h \leq 2$, a considerable increase compared to $\delta_s/h \ll 1$, as suggested by Bradshaw and Wong.[2] In fact, this criterion may be further extended to even higher δ_s/h with more research.

Large-Eddy Structure in the Reattaching Shear Layer

The large-eddy structure in the reattaching shear layer is an area of much current interest. Brown and Roshko[34] and Winant and Browand[35] observed two-dimensional, spanwise vortices in plane-mixing layers. They suggested that the spanwise vortices are the dominant structure in plane-mixing layers and are responsible for most of the growth and entrainment of the shear layer. They showed that plane-mixing layers grow by successive amalgamations (pairings) of the spanwise vortices. In more recent years this has been an area of much interest and controversy. However, very little work has been done on structure in reattaching shear layers. Chandrsuda et al.[7] claim that the spanwise vortices would not form if the boundary layer at separation were turbulent. They also suggested that, if these structures were formed in a backward-facing-step flow, they would be broken down quickly by three-dimensional disturbances introduced by the fluctuations in the recirculating flow. They did not support this latter conclusion experimentally, and there remains considerable controversy on this question.

A few investigations of the large-eddy structure in reattaching shear layers have been done. Rothe and Johnston[26] observed spanwise vortices which grew by pairing in the reattaching shear layer. They found that three-dimensional turbulence could be suppressed by rotating the test section about a spanwise axis in the stabilizing direction. The spanwise vortices, however, were not affected by the rotation. When the test section was rotated at a sufficient rate to completely suppress all three-dimensional turbulence, the reattachment length increased by only 8% over the reattachment length with no rotation. In contrast, when the test section was rotated in the opposite direction, thus enhancing the three-dimensional turbulence, the reattachment length decreased by over 50%. This result indicates that the spanwise vortices are responsible for most of the entrainment from the recirculating flow in the zero-rotation case. Rothe and Johnston also concluded that the spanwise vortices are primarily responsible for the region of unsteady reversing flow centered around the mean reattachment point.

Kasagi et al.[36] used smoke-wire flow visualization to examine the structure in a reattaching shear layer. Their photos showed that the turbulence structure becomes fully three dimensional upstream of reattachment. The spanwise length scale of the large eddies was of the order of one step height. Their work did not confirm or deny the existence of spanwise vortices upstream of the reattachment region. McGuinness[37] studied the large-eddy structure in a reattaching shear layer behind an orifice at the entrance of a pipe. Spectra of streamwise velocity fluctuations and of the wall static pressure were used, along with flow visualization, to infer the large-eddy structure. In addition, experiments were conducted in which the lip of the orifice was vibrated slightly. This served to organize the large-eddy structure, allowing phase averages of velocity and pressure fluctuations. McGuinness concluded that the reattaching shear layer grew by a pairing mechanism until it approached the wall in the reattachment zone. He also tentatively concluded that some of the large eddies were swept upstream with the recirculating flow, while others proceeded downstream. He attributed the decay of turbulent stresses in the reattachment zone to this mechanism.

The latter conclusion is a matter of current controversy. Bradshaw and Wong[2] believe that the eddies are torn roughly in two in the neighborhood of the reattachment point. Other workers, including Chandrsuda[6] and Kim et al.,[9] agree with McGuinness. Measurements by both Kim et al.[9] and Chandrsuda[6] show that the intermittency is less than unity near the wall just downstream of reattachment. This result supports the hypothesis that the eddies move alternately up- and downstream. Recent crude flow visualization in our laboratory showed no evidence of large eddies being swept upstream. More careful flow visualization will, we hope, resolve this question in the near future.

Discussion: Comparison of the Reattaching Shear Layer to a Plane-Mixing Layer

Several authors have pointed out the similarity of the reattaching shear layer to a plane-mixing layer. Shear-layer growth rates have been calculated for the experiments of Baker,[18] Eaton and Johnston,[10] Kim et al.,[9] and McGuinness.[37] In all of these cases, the growth rate was comparable to the plane-mixing layer growth rate. Baker[18] and Eaton and Johnston[10] have compared their mean-velocity profiles upstream of reattachment to plane-mixing layer profiles in detail. The profiles are nearly identical in the outer three-fourths of the layer but differ near the low-speed edge, as one might expect.

It is somewhat more difficult to compare the Reynolds stress measurements between the two types of shear layers. Turbulence measurements in plane-mixing layers typically are scaled by the total velocity difference across the shear layer. However, the velocity difference is not constant for a reattaching shear layer; it changes from roughly 1.0 times the freestream velocity just downstream of separation to about 1.2 times the freestream velocity at a point roughly halfway to reattachment. Therefore, we can never expect a reattaching shear layer to reach a fully developed state, even if it starts from a very thin boundary layer. Nevertheless, approximate comparisons of the two types of free-shear layers can be made. The peak values of the turbulence intensity ($-\overline{u'^2}/U_0^2$) are typically around 0.04 for data sets measured with laser anemometers or pulsed-wire anemometers. Guessing that the appropriate normalizing velocity difference is about 1.1 U_0, we get $\overline{u'^2}/\Delta U^2 = 0.033$. This value is 10-20% higher than typical values measured in plane-mixing layers. We feel that this higher intensity level is due to a very low-frequency vertical motion of the reattaching shear layer (flapping), but there is not general agreement on this point.

The peak value of the shear stress in the reattaching layer was estimated to be about $-\overline{u'v'}/U_0^2 = 1.25 \times 10^{-3}$. Again choosing 1.1 U_0 as the appropriate normalizing velocity difference, we get a value of $-\overline{u'v'}/\Delta U^2 = 1.03 \times 10^{-3}$, very close to the typical plane-mixing-layer value of about 1.0×10^{-3}. The low frequency motions of the shear layer, while having a substantial effect on $\overline{u'^2}$, would not contribute significantly to the shear stress.

The conclusion that can then be reached is that the reattaching shear layer is indeed very similar to a plane-mixing layer upstream of the reattachment zone. This conclusion is supported by observations of the large-eddy structure described in the previous section. The implication is that the effects of many parameters (such as freestream turbulence, Mach number, or upstream boundary-layer state) could be predicted using plane-mixing-layer data. The data also indicate that turbulence models useful in plane-mixing layers should be adequate for the reattaching shear layer, at least upstream of the reattachment zone. Improved models may be required closer to and downstream of reattachment.

Decay of Turbulence Quantities in the Reattachment Zone

Perhaps the most poorly understood part of a reattaching flow is the rapid decrease of the Reynolds stresses in the reattachment zone. A correct understanding of this decrease is necessary in order to correctly predict the redevelopment of the downstream boundary layer. However, as was pointed out earlier, the shear layer is subjected to several different distorting "forces" in the reattaching zone. In addition, detailed and accurate measurements are lacking for the reattachment zone.

Bradshaw and Wong[2] first concluded that the imposition of the normal velocity constraint by the wall ($v=0$) and the strong streamwise pressure gradients cause the large eddies to be torn in two in the reattachment zone. The rapid reduction in length scale would therefore be responsible for the decrease in the turbulence levels. However, the majority of other workers have disagreed that eddies are torn in two, and measurements far downstream of reattachment indicate that the free-shear-layer structure persists in the outer part of the boundary layer.

In many of the data sets, the decay of turbulence occurs in two stages, as shown in Fig. 5. The initial decay usually begins about 1.5 step heights upstream of the mean-reattachment point. This first stage of decay may be caused by stabilizing curvature of the free-shear layer. Castro and Bradshaw[38] and Gillis and Johnston[39] have shown that convex streamwise curvature can cause rapid decay of shear-layer turbulence. The separated shear layer is only slightly curved until it begins to curve sharply toward the wall about two step heights upstream of reattachment. Just upstream of reattachment, the ratio of shear-layer thickness to radius of curvature exceeds 0.1. Such strong curvature would be expected to reduce rapidly the Reynolds stresses in the absence of other effects. However, the shear layer curvature cannot account for the continued decay of turbulence quantities downstream of reattachment.

Summary and Recommendations for Future Work

With this paper we have attempted to consolidate the available experimental data for the subsonic backward-facing-step flow. We have also expressed some of our own opinions about the nature of the flow. It is apparent that a lot has been learned about two-dimensional reattachment since the time of Bradshaw and Wong's[2] review in 1972. Several additional experiments are needed before we can claim a good understanding of the flowfield.

An accurate assessment of the effects of freestream turbulence and streamwise pressure gradient on the reattachment length is needed. This information may allow us to predict accurately flows of engineering importance.

One or two complete sets of mean-velocity and turbulence data are still needed for checking computer codes. Despite the large number of experiments on reattachment, none is fully suited as a test case for computer codes (see Eaton and Johnston[5]). The experiment should be conducted in a large-scale, high Reynolds number facility with a fully turbulent boundary layer at separation. Laser anemometers should be used for most of the velocity measurements, but the results should be checked with other instrumentation where possible. Measurements should include mean velocity, Reynolds stress components, triple products, and an accurate measurement of the reattachment length.

Further experimentation is needed in the reattachment zone. The vital phase of this experimentation should be flow visualization to clarify our understanding of the large-eddy structure.

Finally, work is needed to understand the low-frequency motions of the shear layer. Eaton and Johnston[10] have observed very large-scale, low-frequency motions of their reattaching shear layer, using a variety of techniques. On the other hand, Chandrsuda[6] and Tani et al.[12] found no evidence of low-frequency motions in their experiments. These low-frequency motions could be very important in engineering applications. Therefore, it is important to understand the physical circumstances under which they occur and develop criteria for prediction of their occurrence.

Acknowledgments

We gratefully acknowledge the support of the National Science Foundation (Grant NSF-CME-78-02248), which supports our own reattachment research. We also thank the Organizing Committee of the 1980/81 Stanford Conferences on Complex Turbulent Flows, who helped support the data-review work. The willing cooperation of the entire community of researchers interested in the backward-facing step especially was appreciated.

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