Effects of Pressure Gradient on Reattaching Flow Downstream of a Rearward-Facing Step

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Nomenclature

Æ	= aspect ratio, W/h
C_p	= static pressure coefficient, $(P - P_o)/\frac{1}{2}\rho U_o^2$
C_{p_ℓ}, C_{p_u}	= static pressure coefficient of the lower and upper wall surface of the test section, respectively
ER	= expansion ratio, Y_1/Y_0
h	= step height
P_ℓ, P_u	= wall static pressure at the lower and upper wall surface of the test section, respectively
P_o	= static pressure at the reference point
Re_h	= Reynolds number based on the step height, $U_o h/\nu$
Re_θ	= Reynolds number based on the momentum thickness, $U_o\theta/\nu$
U_o	= streamwise mean velocity at the reference point
W	= test section width
x,y	= streamwise and cross-stream direction coordinates with origin at the step bottom edge, respectively
x_o, y_o	= streamwise and cross-streamwise positions of the reference point
$x_{p/2}$ axis	= distance between the step and the point on the x where the pressure rise is $(C_{p_{\ell,\max}} - C_{p_{\ell,\min}})/2$
x_R	= reattachment length
Y_0	= test section height upstream of the step
Y_1	= test section height downstream of the step, $h + Y_0$
α	= deflection angle of the upper wall surface at the pivoted point
θ	= momentum thickness of the boundary layer at the reference point
ρ	= density of the air
ν	= kinematic viscosity of the air

Introduction

REATTACHMENT problems of separated flow on a solid surface such as an airfoil, diffuser, cavity wall, etc., are of interest because a rapid rise of pressure and heat transfer takes place at the reattachment zone. Among the solid surface models for the study of the separated flow reattachment, the rearward-facing step is one of the simplest since the separation point is readily known. A number of investigations[1-4] for the rearward-facing step flow showed that the reattachment length is strongly affected by the pressure gradient. This Note presents the experimental results of reattachment length and wall static pressure distribution affected by the constant streamwise pressure gradients.

Test Section Configuration and Experimental Conditions

The test cross section of the rearward-facing step is shown in Fig. 1. By applying the convenient and simple ink-dot-liquid-film method,[5] the surface streamlines of spanwise secondary flow were visualized on the lower wall at Æ = W/h = 5.56 with h = 45 mm. This indicates that separated flow is three dimensional. However, at Æ = 12.5 with h = 20 mm, no such spanwise flow surface streamlines were found. This result is in agreement with the following findings of de Brederode and Bradshaw.[6] The two-dimensional flow upstream of separation, if Æ > 10, remains two dimensional downstream of separation, whereas if Æ < 10, separated flow becomes three dimensional. By providing Y_0 = 150 mm, the expansion ratios of the test section are ER = 1.13 with h = 20 mm and ER = 1.3 with h = 45 mm.

The streamwise pressure gradient can be produced by deflecting the straight upper wall, which is pivoted at P[2-4] (Fig. 1), but the resulting streamwise pressure gradient $dC_p/d(x/h)$ is not constant. Therefore, the constancy of the upper wall streamwise static pressure gradient $dC_{p_u}/d(x/h)$ is produced by properly curving the upper wall surface, as shown in Fig. 2, except for straight wall conditions (20S, 45S) and 20P cases. The eight different values of $dC_{p_u}/d(x/h)$ obtained are listed in Table 1. Each value of $dC_{p_u}/d(x/h)$ is evaluated with two freestream velocities U_o, high and low. The upstream boundary-layer profiles at the reference point are maintained as those of the fully developed turbulent boundary layer.

At 20 pressure holes on such curved upper wall surface, correct static pressure distributions were measured by multimanometers confirming the accurate curving. Measured static pressures of the streamwise main core flow between the upper wall and outer edge of shear layer and the streamwise static pressure on the upper wall surface were close to each other. Thus, it is assumed that the main core streamwise static pressure is equal to the upper wall surface pressure. Figure 3 shows the pressure distributions over the upper wall surface. It is

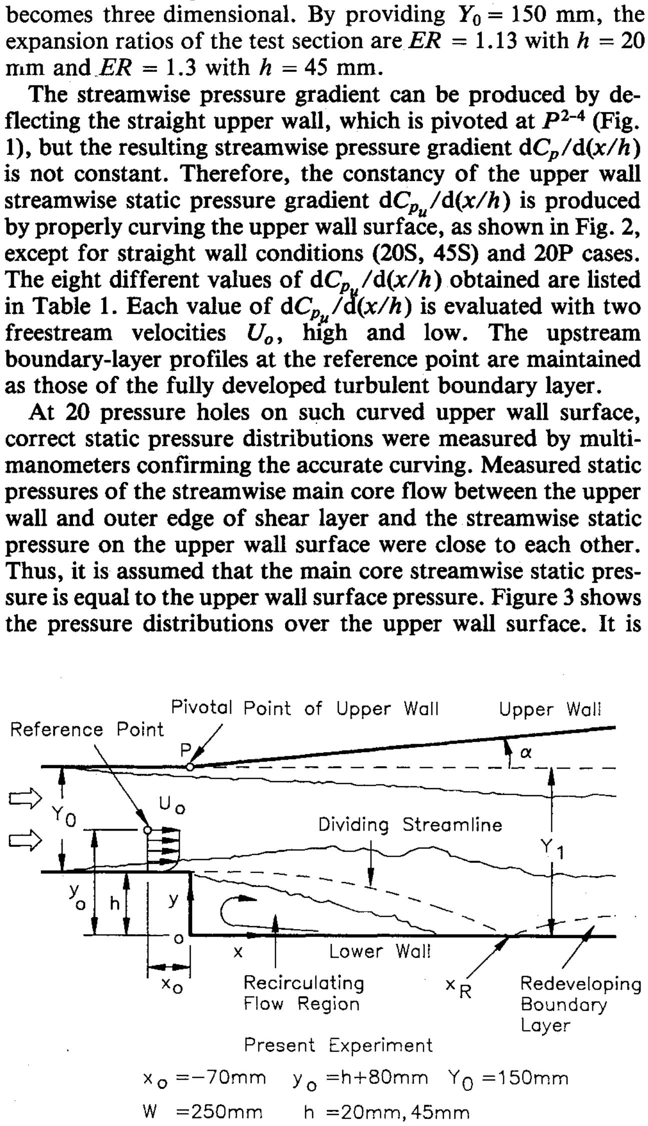

Fig. 1 Sketch of the rearward-facing step configuration.

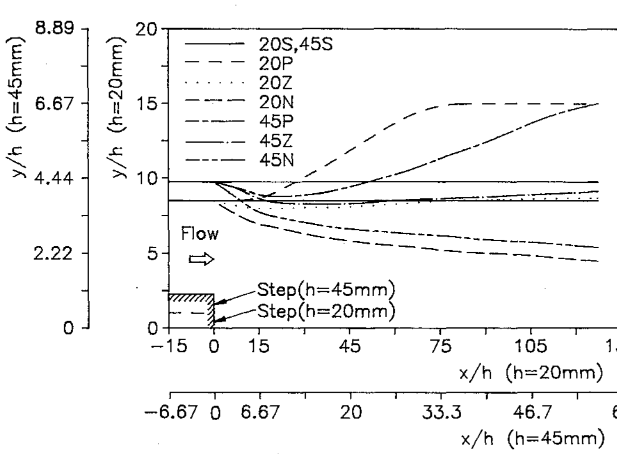

Fig. 2 Geometries of the upper wall surface for each pressure gradient.

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Table 1 Experimental condition

$\frac{dC_{p_u}}{d(x/h)}$	Step height h, mm	Re_θ^a	$Re_h \times 10^{-4}$	Freestream velocity U_o, m/sec	Flow condition designation
0.012[b]	20	1100	2.9	22.5	20S29
0.013[b]	20	709	1.9	14.9	20S19
0	20	1100	3.0	22.6	20Z30
0	20	730	2.0	15.1	20Z20
−0.016	20	780	2.3	17.5	20N23
−0.016	20	530	1.7	13.1	20N17
0.01[c]	20	1300	3.2	25.0	20P32
0.01[c]	20	830	2.0	15.7	20P20
0.027[b]	45	1000	6.7	23.0	45S67
0.026[b]	45	690	4.3	14.9	45S43
0	45	990	6.6	22.6	45Z66
0	45	690	4.3	14.8	45Z43
−0.021	45	740	5.5	18.8	45N55
−0.022	45	560	3.9	13.5	45N39
0.01	45	1300	7.2	24.5	45P72
0.01	45	840	4.5	15.2	45P45

[a]Momentum thickness θ was evaluated at the surface of reference point. [b]Mean pressure gradient between $\theta < x/h < 15$ with straight upper wall. [c]Mean pressure gradient between $\theta < x/h < 75$.

found that the pressure distributions for each step height are nearly the same and are not affected by the magnitude of freestream velocity.

Effect of Pressure Gradient on the Reattachment Length

The reattachment length is determined also by the ink-dot-liquid-film method visualizing the surface streamline orientation. Reattachment length increases with the increase of the streamwise pressure gradient due to the increments of the pressure-gradient-driven backflows,[7] as shown in Fig. 4. Test results indicate that the measured values of x_R/h vary nearly linearly with respect to $dC_{p_u}/d(x/h)$, and for $h = 20$ mm magnitudes of x_R/h are larger than those of $h = 45$ mm at the same $dC_{p_u}/(x/h)$ affected by the three-dimensional flow.[6] Note that the reattachment length is not affected by the freestream velocity with $h = 45$ mm, whereas with $h = 20$ mm reattachment lengths are slightly shorter at lower freestream velocities. For the comparative study of reattachment lengths of nonconstant streamwise pressure gradients with those of constant streamwise pressure gradients, the two cases of x_R/h of Kuhen[2] and Driver and Seegmiller[4] affected by nonconstant pressure gradients are shown in Fig. 4. The values of $dC_{p_u}/d(x/h)$ are averaged in the x region extending beyond the reattachment region up to $x = 1.5x_R$. Assuming the flow is inviscid, its C_{p_u} is computed approximately by

$$C_{p_u} = 1 - 1/(1 + x/Y_0 \tan\alpha)^2 \tag{1}$$

From Fig. 4, it is evident that for the nonconstant pressure gradient, the reattachment length is larger and its growth becomes more rapid with the increase of $dC_{p_u}/d(x/h)$ compared with that of the constant pressure gradient. The reason for such a rapid increase of reattachment length is probably due to the initial flow condition of the nonconstant pressure gradient, i.e., about twice as large as the freestream velocity and five times larger than Re_θ compared to this experimental condition.

Effect of Pressure Gradient on Lower Wall Static Pressure Distribution

The lower wall static pressure distribution of a separated flowfield is affected by the streamwise pressure gradient. After reviewing several investigations on the similarity of lower wall static pressure distributions of the rearward-facing step flow,[8-10] in this Note the measured streamwise static pressure distribution of the separated and reattaching flowfield is expressed by $(C_{p_\ell} - C_{p_{\ell,min}})/(C_{p_{\ell,max}} - C_{p_{\ell,min}})$ vs $(x - x_{p/2})/h$. This approach was successfully applied by Narayanan et al.[9] for separated flow with a straight upper wall. As shown in Fig. 5, a single curve similarity occurs only in the recirculating region independent of step height, pressure gradient, and freestream

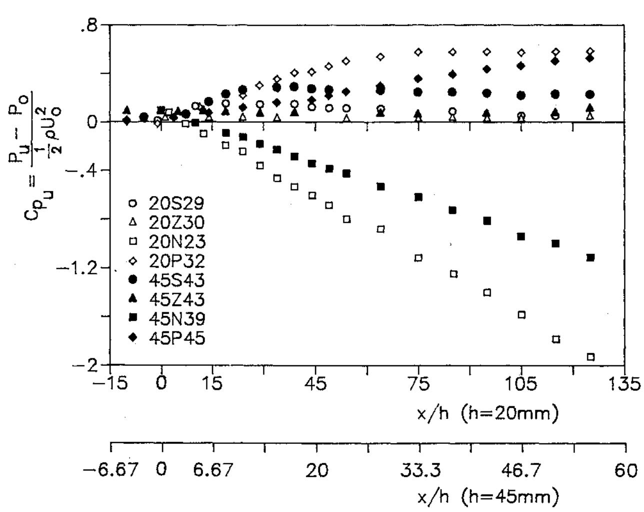

Fig. 3 Upper wall static pressure distribution of the test section.

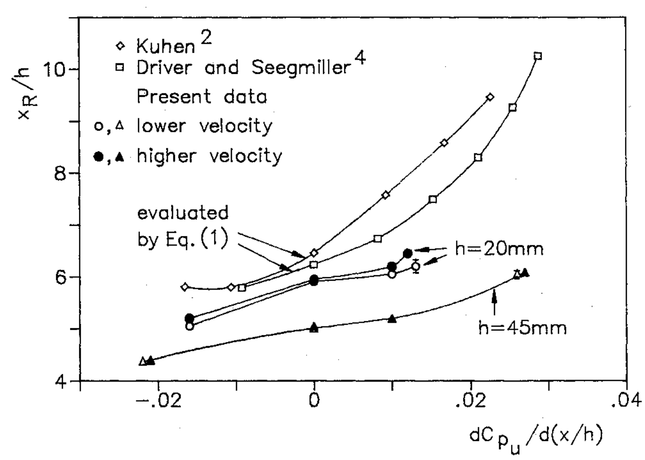

Fig. 4 Effect of pressure gradient on reattachment lengths.

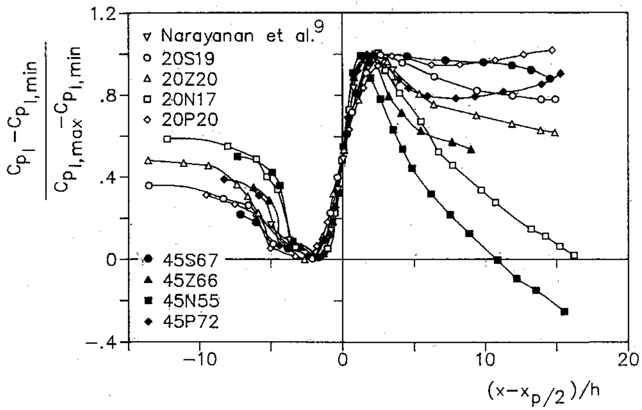

Fig. 5 Similarity curves for the lower wall static pressure distribution.

velocity. This fact confirms Westphal and Johnston's finding[10] that the recirculating flow region is not affected by the initial flow conditions involving streamwise pressure gradient, apparently due to universal flow structure in this region. However, in the upstream flat-plate boundary-layer region and redeveloping boundary-layer region downstream of reattachment, no similarity prevails as evidenced by a scattering of curves dependent upon pressure gradient and step heights. In the redeveloping boundary layer, the scattering affected by the step height and aspect ratio is more pronounced.

Conclusions

The experimental investigation of the effects of a constant streamwise static pressure gradient to the incompressible turbulent reattaching flow behind a rearward-facing step leads to the following conclusions.

The reattachment length increases in a function of streamwise static pressure gradient, i.e., smaller increase within its negative region and larger increase within its positive region. For the three-dimensional flow, the reattachment length is not appreciably affected by the magnitude of the freestream velocity in contrast to the two-dimensional flow. Furthermore, the three-dimensional flow reattachment length per step height is smaller than that of the two-dimensional flow. The reattachment length of a nonconstant streamwise pressure gradient is larger, and its growth becomes more rapid with increase of the pressure gradient compared with that of the constant pressure gradient. The static pressure distribution of the recirculating region is governed by a single similarity curve independent of the streamwise pressure gradient, magnitude of the freestream velocity, height, and aspect ratio of the step. However, the pressure distribution upstream of the step and the redeveloping boundary layer downstream of reattachment are affected by the streamwise pressure gradient and aspect ratio of the step.

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