Acknowledgments

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Experimental Study of Roughness Effects on the Separated Flow over a Backward-Facing Step

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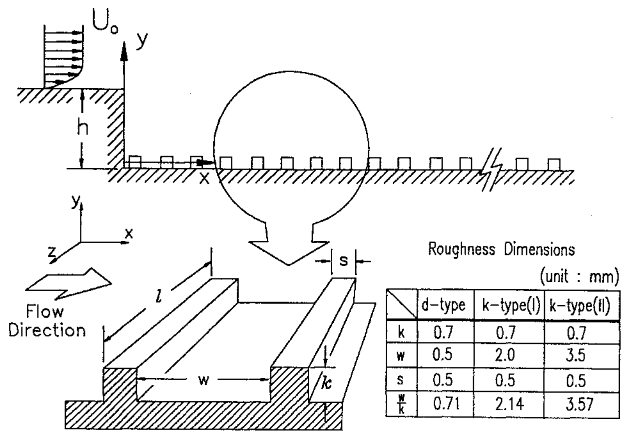
Introduction

THE flow over a two-dimensional backward-facing step is one of the simplest reattaching turbulent shear flows, where the separation point is fixed at the step corner and the separation line is straight. There have been a large number of experimental investigations on the flow structure over a two-dimensional backward-facing step. They reveal that the turbulent flow structure and integral properties depend on 1) the initial boundary-layer state before separation, laminar or turbulent, 2) the initial boundary-layer thickness, 3) the freestream turbulence, 4) the pressure gradient, and 5) the aspect ratio (see Eaton and Johnston[1] for a review).

In addition to these factors, since the surface roughness exerts appreciable resistance to the flow near the wall, we suspect that the surface roughness of the bottom plate may play a non-negligible role in controlling the separated recirculating and redeveloping flows. The purpose of the present study is to experimentally investigate the effects of surface roughness on the turbulent flowfield behind the step. Reattachment length, mean flowfield, fluctuating turbulent quantities, and forward flow fraction are measured by using a split film sensor.



Roughness Dimensions (unit : mm)

	d-type	k-type(I)	k-type(II)
k	0.7	0.7	0.7
w	0.5	2.0	3.5
s	0.5	0.5	0.5
$\frac{w}{k}$	0.71	2.14	3.57

Fig. 1 Surface roughness geometries.

Experimental Conditions

The experimental work was conducted in a low-turbulence level wind tunnel with a 250 × 150 mm cross section which provides a uniform flow condition at the inlet of a sudden expansion with the step height h of 20 mm. The test section and the roughness elements, which were specially designed and manufactured for the experiment, are shown schematically in Fig. 1. Conventionally when the ratio of the roughness width w to its height $k(w/k)$ is less than unity, the surface roughness is called d-type, whereas k-type roughness signifies that $w/k > 1$. In the present study, four different surface roughnesses are employed, as shown in the legend of Fig. 1. The mean velocity profile at 30 mm upstream of the step using a boundary layer pitot tube was measured. The upstream boundary-layer thickness $\delta_{0.995}$ before separation is 10.8 mm, the displacement thickness δ_* is 1.39 mm, the momentum thickness θ is 1.06 mm and the step-height Reynolds number Re_h is 26,500. Consequently, the boundary-layer shape factor H turns out to be 1.31 which is a little larger than the shape factor of 1.28 on a smooth wall.

A modified split film calibration technique of Ra et al.[2] was used to guarantee reliable calibration in a wide range of velocity magnitude and pitch angle. The experiment showed that the error in the maximum pitch angle at ±70 deg is less than 5%, and the error in the mean velocity measurement by the split film sensor is about ±2% at the maximum calibration velocity of 30 m/s. An uncertainty estimate by the Kline and McClintock method[3] showed that the error in the turbulent intensity is about 10% for its maximum value.

Experimental Results and Discussions

The velocity reversal characteristic in reattaching flows can be quantified by the forward-flow fraction. The forward-flow fraction γ_p is defined as the fraction of time for which the flow directs in the downstream direction. The reattachment point can also be determined from the distribution of the forward-flow fraction near the wall γ_{pw}. Eaton and Johnston[4] have shown that the point at which γ_{pw} is 50% coincides with the time mean reattachment point of the unsteady reattaching flow where the mean skin friction coefficient vanishes. In the present experiment, the same method reveals that the reattachment length X_R on the smooth surface is 5.86 times the step

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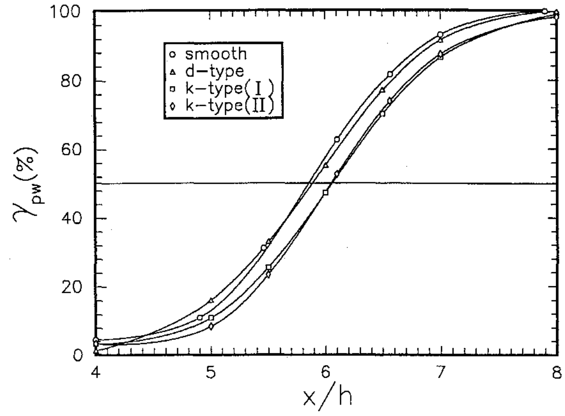
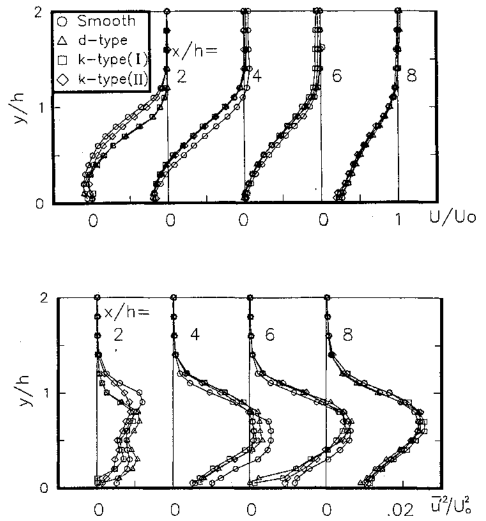


Fig. 2 Profiles of γ_{pw} vs the streamwise distance normalized by the step height; uncertainties in γ_{pw} and X_R/h are less than ±3.0% and ±0.02%, respectively, at 20:1 odds.

a)



b)

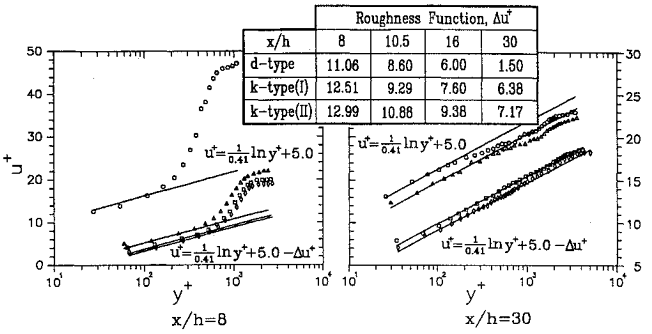
Fig. 3 a) Streamwise mean velocity profiles; uncertainty in U/U_0 is less than ±0.015 at 20:1 odds and b) Streamwise turbulent normal stress profiles; uncertainty in $\overline{u'^2}/U_0^2$ is less than ±0.001 at 20:1 odds.

height. Figure 2 shows that the reattachment lengths on the k-type rough surface are longer than those on the smooth and the d-type surface by about 0.2 step height (or +3.4%). This point lies in the reattachment zone visualized by using the ink-liquid-film method. According to the experiments of Kuehn[5] and Ra and Chang,[6] the reattachment length decreases with increasing favorable pressure gradient. Therefore, such an increase of the reattachment length in the present experiment where the pressure gradient is mildly favorable is evidently caused by the surface roughness.

The streamwise mean velocity profiles in the separation bubbles are shown in Fig. 3a. Upstream of the reattachment point, the velocity profile near the wall strongly depends on the surface roughness. The reverse flow near the bottom surface is less resisted by the wall shear stress on the smooth surface than on the rough ones. Consequently, the maximum reverse velocity is the largest on the smooth surface at $x/h = 2$, which results in slower forward flow in the mixing layer region above.

Streamwise turbulent fluctuations are shown in Fig. 3b. The mixing layer exhibits the highest turbulence level there.[7,8] The turbulence level at $x/h = 4$ is significantly higher over the smooth surface. Therefore, it may be concluded that the surface roughness suppresses the turbulent fluctuations in the recirculation region.

Regarding the redeveloping boundary-layer region after the reattachment, Bradshaw and Wong[9] found that the mean velocity distribution slowly recovers the form of an equilibrium boundary layer. In this process, they showed that the flow in the inner region near the wall rapidly reaches equilibrium, whereas the flow in the outer



Roughness Function, Δu^+				
x/h	8	10.5	16	30
d-type	11.06	8.60	6.00	1.50
k-type(I)	12.51	9.29	7.60	6.38
k-type(II)	12.99	10.88	9.38	7.17

a) b)

Fig. 4 Mean velocity profiles in the redeveloping boundary layer.

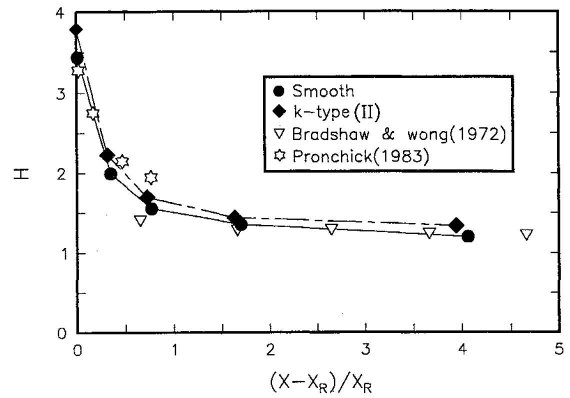


Fig. 5 Variation of the boundary-layer shape factor.

region goes through a much slower change. Here, to study the effect of surface roughness on the recovery process of the redeveloping boundary layer, the mean velocity profiles in the redeveloping boundary-layer region are presented in terms of the inner variables in Figs. 4a and 4b. The mean velocity profiles on the rough wall more quickly recover those of the wall-attached boundary layer than those on the smooth wall. But the velocity profile in the outer region far from the wall does not recover that of a turbulent equilibrium boundary layer even at the last test point ($x/h = 30$). At $x/h = 30$ the mean velocity profiles on the smooth surface slightly dip down below the logarithmic overlap and the wake region of the redeveloping boundary layer.[7,8] These phenomena were also observed in the experiments of Kim et al.[7] and Bradshaw and Wong.[9]

The distribution of the boundary-layer shape factor H in the redeveloping region is compared in Fig. 5 with the experiments of Pronchick[8] and Bradshaw and Wong,[9] both on the smooth surface. The comparison shows that H decreases a little more slowly on the k-type rough surface to an asymptotic value of about 1.34, which is larger than that on the smooth and d-type surface by about 10%.

Conclusions

The effect of surface roughness on the recirculating and redeveloping flow over a backward-facing step has been experimentally investigated in a specially designed wind tunnel with four different surface roughness conditions. It was found that the surface roughness on the bottom plate retards the reattachment process by about 3.4% in comparison with that on the smooth surface. Because of the stronger resistance to the back flow in the recirculating bubble zone by the rough bottom surface, the maximum negative velocity is smaller than that over the smooth surface. The streamwise turbulent fluctuations are also decreased in the recirculating bubble zone by the surface roughness. Finally, in the redeveloping boundary layer the mean velocity profiles on the rough wall more quickly recover those of the wall-attached boundary layer than those on the smooth wall. But the velocity profile in the outer region far from the wall does not recover the wake profile in the turbulent equilibrium boundary layer for all test cases in the measured streamwise distance.

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Comparison of Linear Stability Results with Flight Transition Data

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Introduction

A NEED exists to predict the location of transition on aerodynamic surfaces both efficiently and with reasonable accuracy. Currently, the most common approach for predicting transition in two- and three-dimensional flows is the empirical e^N method,[1,2] which utilizes linear stability theory. The e^N method assumes that transition takes place when the integrated growth rate computed from linear stability theory reaches a certain value N. As a result, this method is most successful in predicting transition when most of the disturbance growth that leads to transition is linear. Quiet wind tunnels and actual flight conditions are typical environments that allow such linear growth of disturbances over long distances before transition onset. Under these conditions, transition onset can be correlated with an N factor on the order of 9–11.[3] On the other hand, noisy tunnels introduce disturbances with large initial amplitudes, and the associated transition process is such that its prediction is outside the scope of the e^N method.

In this work, we compare the results of the e^N method with the experimental flight data of Fisher and Dougherty[4] for compressible flow past a sharp cone. The comparisons demonstrate the effect of mild heat transfer at subsonic freestream Mach numbers and the effect of compressibility for freestream Mach numbers up to 2.

Masad and Malik[5] developed a transition correlation based on the e^9 method for subsonic flow over a flat plate. The correlation accounts for the effects of uniform wall suction, heat transfer, and Mach number. The correlation is given by

$$(Re_x)_{N=9} = a^2\Lambda^2 \tag{1a}$$

$$\Lambda = \Lambda_1\Lambda_2\Lambda_3 \tag{1b}$$

where

$$\Lambda_1 = a_1 + M_\infty^{a_2} + a_3 M_\infty^{a_4} \tag{2}$$

$$\Lambda_2 = b_1 + 10^8|v_w|^{b_2} + b_3 10^8 |v_w|^{b_4} \tag{3}$$

$$\Lambda_3 = c_1 + (T_{\text{ad}}/T_w)^{c_2} + c_3(T_{\text{ad}}/T_w)^{c_4} \tag{4}$$

and

$$a = 0.0183, \quad a_1 = 4.1, \quad a_2 = 3.5$$

$$a_3 = 1.41, \quad a_4 = 1.83$$

$$b_1 = 1310, \quad b_2 = 1.28, \quad b_3 = 0.082, \quad b_4 = 1.0$$

$$c_1 = 7.9, \quad c_2 = 5.8, \quad c_3 = 9.1, \quad c_4 = 5.9$$

In Eqs. (1–4), Re_x is the x Reynolds number given by $Re_x = U_\infty^* x^*/\nu_\infty^*$, where U_∞^* is the freestream velocity, x^* is the distance measured from the leading edge of the flat plate, and ν_∞^* is the freestream kinematic viscosity. The continuous uniform nondimensional suction velocity is denoted by v_w such that $v_w = v_w^*/U_\infty^*$, where v_w^* is the dimensional suction velocity. The actual nondimensional wall temperature is denoted by T_w, whereas the adiabatic nondimensional wall temperature is denoted by T_{ad}. Both T_w and T_{ad} are made nondimensional with respect to the dimensional freestream temperature T_∞^*, such that $T_w = T_w^*/T_\infty^*$ and $T_{\text{ad}} = T_{\text{ad}}^*/T_\infty^*$. The ratio T_w/T_{ad} is used to specify the level of heat transfer. For a value of T_w/T_{ad} that is less than unity, the plate is cooled; when the value is larger than unity the plate is heated. In Eq. (2), M_∞ is the freestream Mach number. In the calculations used to develop the previous correlation and throughout this work, the specific heat at constant pressure is assumed to be a constant. The Prandtl number Pr is also assumed to be fixed at 0.72. The variation of dynamic viscosity with temperature is given by the Sutherland formula, and the freestream temperature is 300 K. The effect of variation in the freestream temperature on transition location is insignificant for subsonic flow. For example, at Mach 0.8, the predicted transition Reynolds number changed from 5.57×10^6 to 5.48×10^6 when T_∞^* decreased from 300 K to 150 K.

Equations (1–4) determine that the ratio r of $(Re_x)_{N=9}$ with heat transfer to $(Re_x)_{N=9,\text{ad}}$ for the adiabatic plate is given by

$$r = \frac{(Re_x)_{N=9}}{(Re_x)_{N=9,\text{ad}}} = \frac{\Lambda_3^2}{\Lambda_3^2\big|_{\text{ad}}}$$

or

$$r = \frac{\Lambda_3^2}{324} \tag{5}$$

A comparison of the results of Eq. (5) with the experimental flight data of Fisher and Dougherty[4] is shown in Fig. 1. In the figures the predicted transition Reynolds number $(Re_x)_{N=9}$ is denoted by Re_t. Fisher and Dougherty's curvefit of the experimental data is shown for the variation of r with T_w/T_{ad}; the agreement between our correlation and the curvefit is remarkably good over most of the range. The experimental data in Fig. 1 are for freestream Mach numbers in the range from 0.55 to 0.86. Fisher and Dougherty[4] noted no significant dependence of r on M_∞. Our correlation for r [Eq. (5)] has no dependence on M_∞ either. The correlation results are for flow over a flat plate, and the experimental data are for flow past a cone. It is assumed that the cone transition Reynolds number

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