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Laminar Separating Flow over Backsteps and Cavities
Part I: Backsteps

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Although significant data on flow over backward facing steps and cavities in turbulent flow are available, the corresponding data for the laminar flow are rather scant. The present work reports the results of an experimental investigation carried out at a wind speed of 1.8 m/s over three backward facing steps 0.625, 1.25, and 2.5 cm high; the separating boundary layer in all cases was laminar and was 1.4 cm thick. Data obtained through smoke flow visualization and static pressure and hot wire measurements are divided into two categories: category A—variation of the reattachment length with Reynolds number in the range 100-12,500, and category B—general pattern of flow between the point of separation and that of reattachment. The data in the latter category include 1) pressure profiles on the step surfaces, 2) typical development of streamwise mean velocity profile and intensity of fluctuations, 3) variation of momentum thickness of the laminar separating shear layer downstream of the steps.

Nomenclature

C_p = pressure coefficient $= (p - p_\infty) / \frac{1}{2}\rho U_\infty^2$
C_{pm} = reattachment pressure rise coefficient $= (C_{p\max} - C_{p\min})/(1 - C_{p\min})$
E = dc voltage output from hot wire anemometer
h = height of the step
p = static pressure
Re_h $= U_\infty h/\nu$
u' = fluctuating x component of velocity
U = x component of mean velocity
x = coordinate along the floor of the step with origin at the separation edge
x_r = reattachment length
y = coordinate normal to the floor of the step with origin at the separation edge
δ = boundary-layer thickness
δ^* = displacement thickness
θ = momentum thickness $= \int_0^\infty (U/U_m)(1 - U/U_m)\,\mathrm{d}y$
ν = kinematic viscosity of air $= 1.7 \times 10^{-5}$ m²/s

Subscripts

∞ = freestream condition at reference point
h = at separation edge
m = local maximum value

I. Introduction

INCOMPRESSIBLE parallel separating flow over two-dimensional backward facing steps is probably the simplest class of separated flows because the separation point is fixed and the flow leaves the boundary at zero angle of separation. Some experimental and numerical investigations for the laminar separating flow over backsteps have been reported; e.g., the experiments and numerical analysis of Mueller and O'Leary[1] in the Re_h range 25-200, the measurements of Goldstein et al.[2] up to $Re_h = 500$, the starting flow studies of Honji,[3] the laser Doppler anemometry measurements of Denham and Patrick,[4] the base bleed effect studies of Leal and Acrivos,[5] the experiments on sudden expansion by Durst et al.,[6] the experiments of Roshko and Lau[7] on different forebody shape models, the investigations of Macagano and Hung,[8] and the theoretical analysis of Batchelor[9] and Childress.[10]

The experimental results indicate that x_r/h increases linearly with Re_h as long as the reattachment is laminar. The characteristics of the recirculating region for a laminar separating shear layer is controlled by δ_h/h and Re_h. The present experimental investigation was undertaken to study in greater detail a parallel laminar separated shear layer 1.4 cm thick moving over three different backsteps of $h = 0.625$, 1.25, and 2.5 cm. The values of parameters δ_h/h and Re_h were 2.24, 1.12, 0.56 and 662, 1324, 2648, respectively. Smoke flow visualization, surface static pressure, and hot wire anemometry measurements were carried out to obtain the details of the flowfields.

II. Experiments

The backsteps were formed on the floor of an open-circuit suction-type wind tunnel of floor width 40.5 cm; test section height and length were 30.5 and 100 cm, respectively. The tunnel turbulence level was about 0.15% at a wind speed of 1.8 m/s. The blockage ratios for the three models were 2.05%, 4.1%, and 8.2%, respectively. The characteristics of the laminar boundary-layer velocity profile at a station 0.15 cm upstream of the separation line were $\delta = 1.4$ cm, $\delta^* = 0.406$ cm, $\theta = 0.177$ cm, $H = \delta^*/\theta = 2.29$.

Static pressures were measured by providing a row of pressure orifices 1 mm in diameter located along the midspan of the model and using an electronic manometer (Barocel 1014) with a pressure cell of 0.7 kg/cm² range. The reference pressure and velocity used for computing C_p was taken at a point 7 cm upstream of the separation line and 15 cm above the floor of the test section.

A DISA 55A01 constant temperature hot wire anemometer in conjunction with a Fluke 830 DA digital dc voltmeter was used for measuring the mean velocity and the intensity of fluctuations. The problem of the shape of the calibration curve in the low-speed region was tackled in the following manner. The speed U was calculated by measuring the frequency f of vortex shedding past a thin wire and using the empirical relation between f and U given by Tritton.[11] The values of U so calculated were plotted against the voltage E and a fourth degree curve was fitted, using the least-square technique. However, as a single wire probe was used, there was no way to rectify the error due to inclination of the

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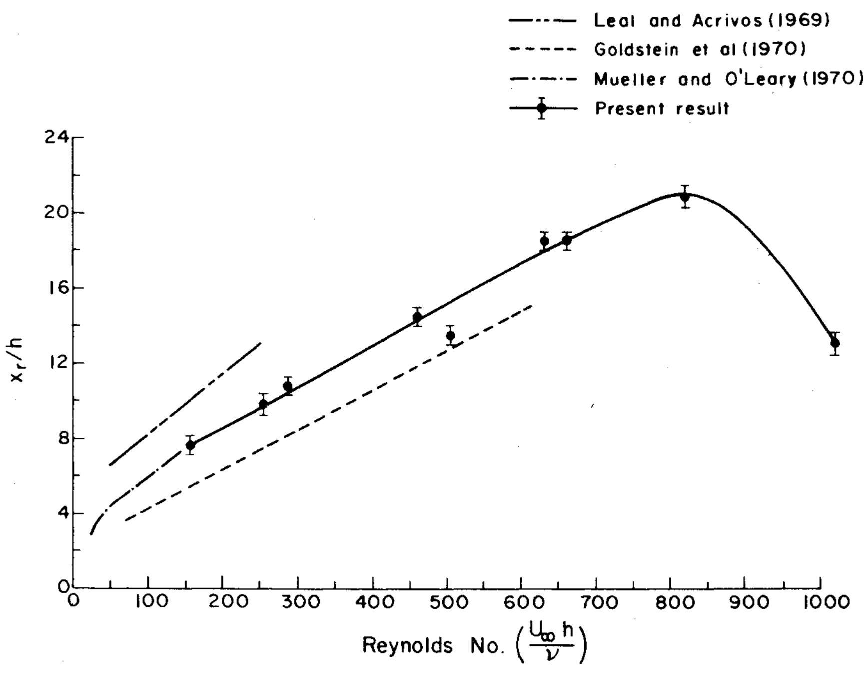

Fig. 1 Variation of reattachment length with Reynolds number for backsteps in the range $100 < Re_h \leq 1000$.

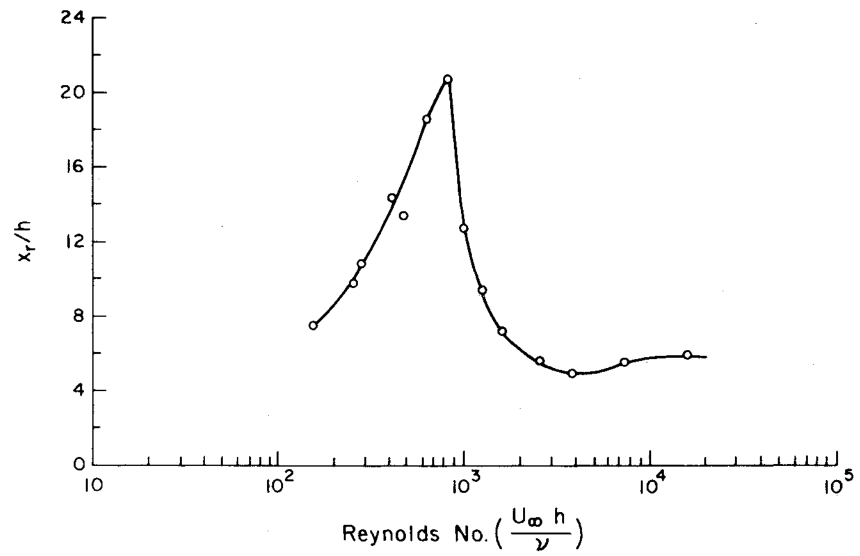

Fig. 2 Variation of reattachment length with Reynolds number for backsteps in the range $100 < Re_h < 2 \times 10^4$.

streamlines, though we are aware that such an error becomes significant in the corner regions; this was a limitation of the present investigation and the corresponding results have been included to show the qualitative trends only.

The location of reattachment was determined by allowing the smoke to be sucked into the test section through pressure taps located in the base of the models and observing the fore and aft motion of the smoke. In the case of laminar attachment, the location was further confirmed by projecting the 35-mm negative smoke patterns, using an optical projector. Details of the experimental setup and techniques as well as the discussion on limitations imposed by instrumentation at our disposal are given by Sinha.[12]

III. Results and Discussion

A. Reattachment Length

Smoke flow visualization showed that the reattachment was laminar in the case of the 0.625-cm step, and was turbulent in the other two cases; the transition occurred approximately at $x = 4.5$ and 2 h for the 1.25- and 2.5-cm steps, respectively.

The reattachment length is nearly a linearly increasing function of the Reynolds number for fully laminar flow (laminar separation, laminar reattachment), as shown in Fig. 1. This is in agreement with the trend exhibited by the data of Leal and Acrivos,[5] Goldstein et al.,[2] and Mueller and O'Leary,[1] indicated by different types of broken lines in Fig. 1.

The maximum value of x_r/h observed in the present experiments was about 21 at $Re_h \simeq 820$. It should be mentioned that for collecting data for Fig. 1, the wind speed was varied in the range 0.4-10 m/s.

The reattachment length starts decreasing once the separating shear layer undergoes transition prior to reattachment. This is observed in Fig. 2, where x_r/h vs Re_h is plotted in the range $100 < Re_h < 1.5 \times 10^4$. For $Re_h > 10^4$, the value of x_r/h is constant at about 6, the value reported by investigators experimenting with turbulent flows.

B. General Flow Pattern

The surface pressure distributions on the floor of the three steps are shown in Fig. 3. The data points in the range $-1 < x/h < 0$ correspond to pressure tap locations on the vertical base of the step at $x/h = 0$. The static pressure profiles are characterized by a negative pressure immediately downstream of the step, followed by a pressure recovery in

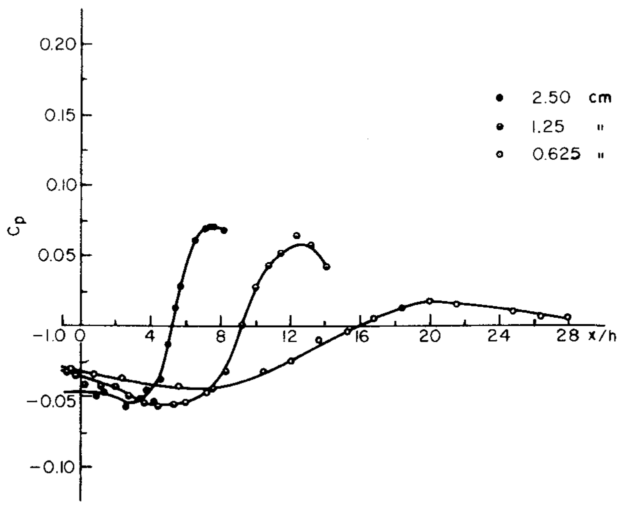

Fig. 3 Pressure distribution along the walls of the backsteps; $\delta_h = 1.40$ cm, $U_\infty = 1.8$ m/s.

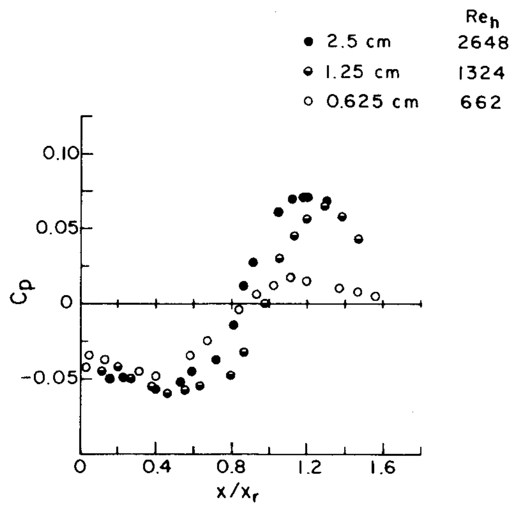

Fig. 4 Pressure distribution on backsteps in terms of similarity variable C_p vs x/x_r.

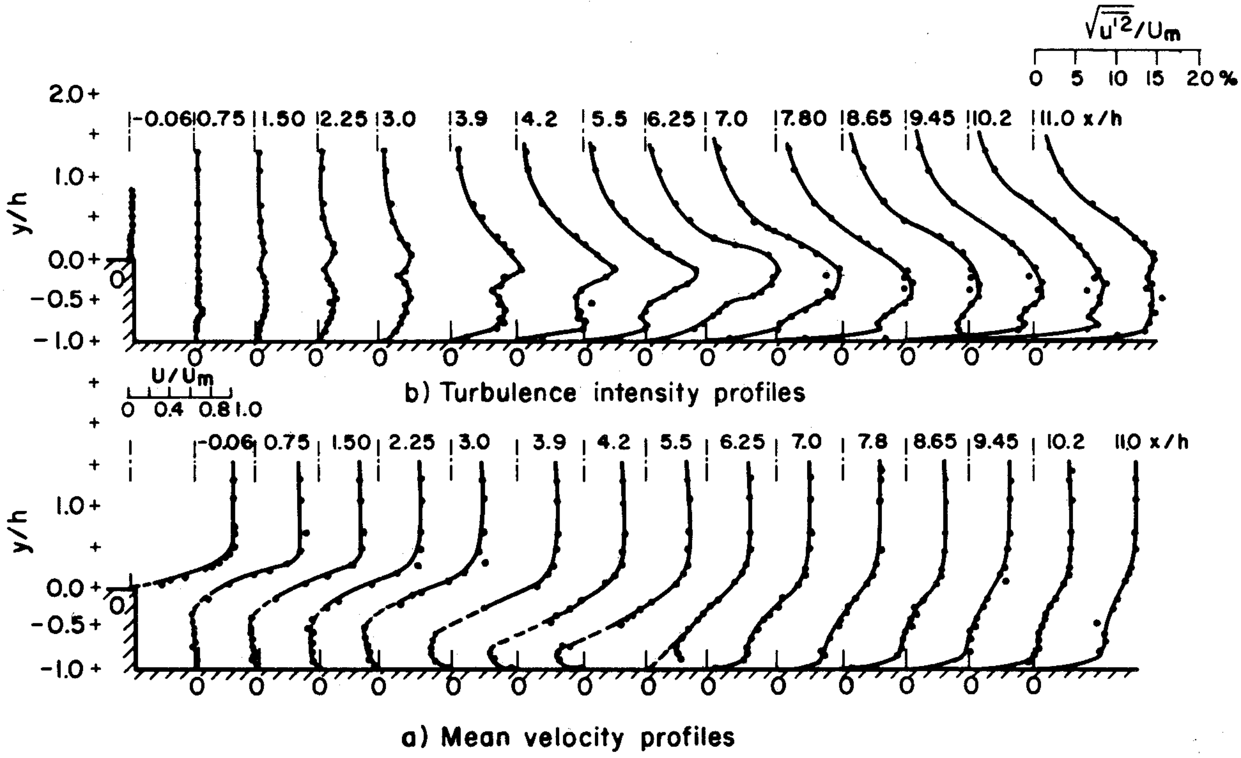

Fig. 5 Mean velocity and fluctuation intensity profiles for the backstep; $h = 2.5$ cm, $\delta_h = 1.4$ cm, $U_\infty \simeq 2.01$ m/s, $Re_h = 2956$.

the reattachment region. These features are in agreement with the data of Tani et al.[13] and Moore.[14] The values of C_{pm} are 0.06, 0.12, and 0.13 for the 0.625-, 1.25-, and 2.5-cm-high steps, respectively. Noting the similarity in the shape of the $C_p - x/h$ curves for the 1.25- and 2.5-cm steps (Fig. 3) the data were replotted in terms of C_p vs x/x_r (Fig. 4) to verify if such scaling would make the two curves overlap.§ Although Fig. 4 does indicate such a trend, the scatter is too significant to make a conclusive statement.

A typical set of streamwise mean velocity profiles and intensity of fluctuations for the 2.5-cm-high step measured at 14 stations covering the range $0 \leq x/h \leq 11.0$ is presented in Fig. 5. Salient features of these plots follow:

1) Mean velocity profiles shown in Fig. 5a have features similar to those observed by Tani et al.[13] The reattachment point is at $x_r/h \simeq 6.25$. The maximum reverse velocity of 0.28 U_m appears at $x/h \simeq 4$. Velocity profiles for $x/h > 6.25$ appear to be typical of a redeveloping turbulent boundary layer.

2) In Fig. 5b, $\sqrt{u'^2}$ intensity profiles at each x station show two maxima from $x/h \simeq 2.0$ to $x/h = 6.25$. The upper maximum near $y \simeq 0.0$ corresponds to the separating shear layer undergoing transition, the magnitude of u' increasing from about 2% at $x/h \simeq 2.0$ to 14% at $x/h = 6.25$. The lower maximum in the recirculation region, on the other hand, decreases in magnitude as the reverse flow moves towards the step base, indicating the possibility of reverse transition near the floor of the step.

Similar features were observed for the 1.25- and 0.625-cm steps and are reported by Sinha.[12] For 0.625-cm step the flow was laminar everywhere and the u' intensity was less than 1%.

§This was suggested by one of the referees; the authors are grateful for the suggestion.

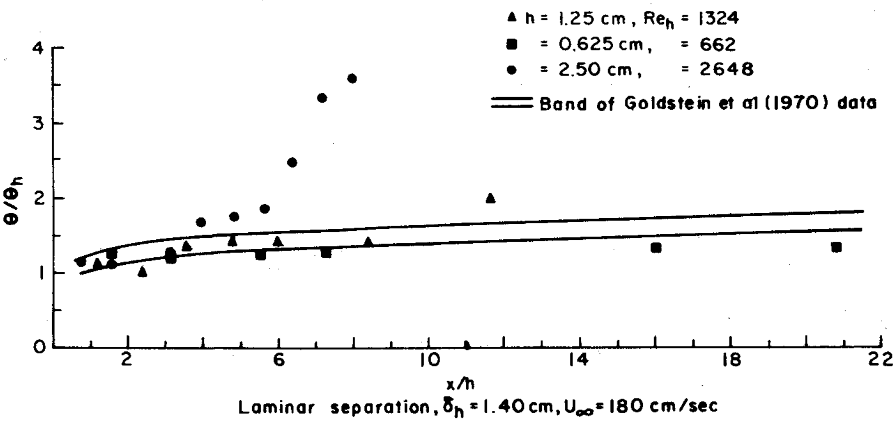

Fig. 6 Variation of laminar separated shear layer θ with distance downstream for backsteps; $\delta_h = 1.4$ cm, $U_\infty = 1.8$ m/s.

The streamwise growth of θ/θ_h for the three backsteps is shown in Fig. 6. The value of θ/θ_h near laminar reattachment is 1.3. Present results for the 0.625- and 1.25-cm steps show fair to good agreement with the data band of Goldstein et al.[2] The departure of 2.5-cm data for $x/h \gtrsim 3$ can be attributed to the separating shear layer undergoing transition to turbulence, resulting in a faster rate of increase of θ.

IV. Conclusion

The most significant contributions of the present investigation are the data on 1) reattachment length x_r for Re_h in the range 100-12,500, 2) momentum thickness in the transition region, and 3) the intensity of fluctuations along with the mean velocity profile, for a laminar shear layer undergoing transition over a backward step.

One of the referees pointed out that it would be interesting to indicate the variation of δ with the wind speed. Unfortunately δ was measured only for two values of U_∞—180 and 1000 cm/s. The corresponding values of δ (at $x = -0.15$ cm) are 1.4 and 1.6 cm, respectively.

Acknowledgments

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