EFFECT OF FREE-STREAM TURBULENCE ON SEPARATED- REATTACHING FLOWS FOR DIFFERENT ANGLES OF SEPARATION*

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Effects of a free-stream turbulence on a series of two-dimensional separation-reattaching flows (separation bubbles) were investigated experimentally in a low-speed wind tunnel. Models tested were two-dimensional triangular cylinders with a tail plate. Some important properties of the separation bubbles were measured with a split-film sensor driven by constant-temperature hot-wire anemometers. The effect of the turbulence on the reattachment length X_R was found not to be uniform with respect to the separation angle. Large-scale vortices were formed by coalescence in the reattaching zone of the shear layer and were shed downstream with a non-dimensional frequency $0.65 \times (\text{free-stream velocity})/X_R$, which was the same for all the combinations of the separation angle and the free-stream turbulence employed in this study. Geometry of the separated shear layer suggested that the large-scale vortices in the reattaching zone became flatter as X_R increased.

Key Words: Turbulence, Flow Measurement, Separation, Reattachment, Free-Stream Turbulence, Bluff-Body, Tail-Plate

1. Introduction

Flows encountered in practice are usually accompanied by turbulences of various intensities and length scales. For example, buildings and bridges are immersed in the atmospheric turbulent boundary layer; in multi-stage turbomachines turbulent wakes generated by upstream wing cascades hit downstream wing cascades. The aerodynamic characteristics of such bodies are different from those of the bodies in smooth flows; for example, the drag force acting on a circular cylinder immersed in turbulent free streams decreases with increasing intensity of the free-stream turbulence in the subcritical regime⁽¹⁾.

The present paper describes experimentally the effect of the free-stream turbulence on separated-reattaching flows (hereafter referred to as separation bubbles) behind triangular cylinders (with a tail plate) with various angles of separation. The separation of flow is fixed at both edges of the body. Ota et al.⁽²⁾ present the reattachment length as a function of the separation angle and Reynolds number in a low-Reynolds number regime. The free-stream turbulence hastens the transition of the separated shear layer to increase the entrainment rate and thus the growth rate of the shear layer; that is, the reattachment length decreases with increasing intensity of the free-stream turbulence. The purpose of this paper is to determine

experimentally the reattachment length, the growth of the shear layer and the unsteady flow in the reattaching region in terms of the free-stream turbulence and the separation angle of the triangular cylinders.

2. Experimental Apparatus and Procedure

The experiment was carried out in an open-return, low-speed wind tunnel with a square working section (35 cm x 35 cm) of 150 cm length. The free-stream turbulence was generated by monoplane square-meshed grids installed at the entrance of the working section. The grid produced nearly uniform and isotropic turbulent flows. The test cylinders were separately mounted at a location 50 cm downstream of the entrance, spanning the whole width of the tunnel. Thus the aspect ratio is 8.8. The turbulence properties at the position of the model are summarized in Table 1. The models tested were isosceles triangular cylinders of 4 cm base height with a 0.5 cm thick and 50 cm long tail plate; the angle 2θ of the vertex facing the main flow was set at $30^\circ, 60^\circ, 90^\circ$ and 180° (i.e. a normal

Table 1. Properties of grid-generated turbulence.

	u'/U_0	L_x mm
Case 1	0.0055	—
Case 2	0.055	20
Case 3	0.11	30

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plate)(see Fig.1). The length of the tail-plate was much longer than the time-mean length of the separation bubbles, so that the interaction between the shear layers separated from both edges of the model was prevented. The base pressure was measured by several pressure taps of 0.8 mm diameter symmetrically drilled onto the base of the model. The pressures from these taps were also employed to find out the proper alignment of the model in the working section.

The time-mean velocity profile in the shear layer was measured by a split-film sensor of 153 μm diameter⁽³⁾ (hereafter referred to as SFS) driven by two sets of constant-temperature hot-wire anemometers; the split of the sensor was set normal to the main-flow direction. The intermittency of the forward and reverse flows in the separation bubbles was also detected by SFS. The pressure fluctuation on the tail-plate was measured by a static-pressure tube of 1.3 mm outer diameter with a built-in pressure transducer (ENDEVCO-8507); the diameter of the pressure taps was 0.4 mm. Further details and calibration of the static-pressure tube are given in Ref.(4).

The r.m.s. value and power spectra of the fluctuations were obtained by a digital signal processor (SANEI 7T08).

The experiment was made at constant Reynolds number $U_o H/\nu = 3.3 \times 10^4$, U_o being the main-flow velocity and H the base height of the model. The blockage of the working section by the model had some effect on the base pressure and the behaviour of the shear layer because the blockage ratio was 11 %. It is also possible that the effect depends on the individual shape of the model and the free-stream turbulence. Unfortunately there is no reliable method for correction of the blockage effect when the main stream contains a turbulence of high intensity. Therefore, the results will be presented uncorrected.

3. Results and Discussion

3.1 Relation between free-stream turbulence and reattachment length

The flow near the tail-plate is parallel to its surface even in the separation bubble. If the splits of SFS were set normal both to the wall and to the local flow, output of the upstream film of SFS is larger than that of the downstream film. This property of SFS gives us the instantaneous local-flow direction. An example of

Fig. 1 Definition sketch and main symbols.

calibration of SFS is shown in Fig. 2; the outputs of the two films were linearized to match. The time-mean longitudinal velocity U near the wall can be determined by

$$U = \gamma_p (\alpha E_p) + (1 - \gamma_p) (\alpha E_N) \quad (1)$$

where α is a constant of proportionality (i.e. the velocity divided by the output (voltage) of SFS, see Fig. 2); E_p and E_N are respectively the output of the SFS film on the upstream and downstream sides of the main flow; γ_p is the forward-flow intermittency. The outputs of SFS were processed according to the block diagram shown in Fig.3. The outputs A and B of the films were discriminated by a comparator to generate a trigger pulse only when the output of the upstream film was larger than that of the downstream film of SFS. In this way, the fraction of time during which the flow was in the downstream direction was measured; this is the forward-flow intermittency γ_p . Moreover, using an analogue switch operated by the trigger pulse, $\gamma_p (\alpha E_p)$ and $(1 - \gamma_p) (\alpha E_N)$ in Eq.(1) were separately obtained.

Figure 4 shows the longitudinal variation of the forward-flow intermittency γ_p near the surface of the tail plate (measured at a height $y/h = 0.028$). The time-mean reattachment point was defined as the position where $\gamma_p = 0.5$. This position was close to the reattachment position obtained by a surface-flow visualization (an oil-

Fig. 2 An example of calibration curve of split-film sensor.

Fig. 3 Block diagram for measuring γ_p and U .

film technique). The reattachment position or the length of the separation bubble is hereafter denoted by X_R .

Figure 5(a) shows the length X_R plotted against the free-stream turbulence intensity u'/U_0 , where u' is the r.m.s. value of the streamwise velocity fluctuation. X_R is seen to decrease with increasing free-stream turbulence. It is noteworthy that the decrease of X_R depends on the vertical angle 2θ ; that is, the length decreases to a greater extent for a larger vertical angle than for a smaller one at the same intensity of the free-stream turbulence. This feature becomes more evident if X_R is normalized by the length (say X_{R1}) for the lowest intensity u'/U_0 of this study, see Fig. 5(b).

A decrease of X_R with an increasing turbulence intensity can be interpreted by an earlier transition (from laminar to turbulent flow) of the separated shear layer, which yields a greater entrainment rate of the shear layer owing to the increased scale of rolled-up vortices.

As mentioned above, an interesting feature of Fig. 5 is that the reduction of the free-stream turbulence is strongly dependent on the vertical angle of the triangular cylinder. An attempt will be made in what follows to relate this feature to changes in the property of the shear layer associated with the free-stream turbulence.

3.2 Time-mean properties of separated shear layer

The time-mean velocity in the separation bubble where the local-flow direction changes at random was obtained from Eq.(1) by using the intermittency γ_p measured beforehand. The constant α in Eq.(1) is generally a function of the angle of splits of SFS with respect to the local incident flow. Since the dependence of α on the angle was approximately represented by a cosine function, the error in estimating the velocity U by Eq.(1) is expected to become significant for large incident angles. It should be noted, however, that the locus of $\gamma_p = 0.5$ was in good agreement with that of $U = 0$ (which is shown in Fig. 9). Since positions of $\gamma_p = 0.5$ and $U = 0$ should coincide, this suggests that the local-flow direction at these positions was not far from the main-flow direction.

Fig. 4 Variation of γ_p in streamwise direction.

Hence, in this paper, the velocity U computed from Eq.(1) was regarded as the longitudinal component of the velocity vector. Figure 6 shows an example of the time-mean velocity profile in the separation bubble.

The thickness Δ of the shear layer is shown in Fig. 7 plotted against the longitudinal distance for angles $2\theta = 30^\circ$ and 90° . The thickness Δ has been defined as

$$\Delta = y_{3/4} - y_{1/4},$$

where $y_{1/4}$ and $y_{3/4}$ denote respectively the vertical position y at which the velocity U amounts to $1/4$ and $3/4$ of the maximum difference of U across the shear layer. Δ is probably proportional to the vertical scale of the rolled-up vortices in the shear layer. It is seen in Fig. 7 that the thickness Δ a little downstream of the separation point is larger for high turbulence than for low turbulence. Moreover, the growth rate $d\Delta/dx$ of the shear layer seems to be greater for the angle $2\theta = 90^\circ$ than for a smaller angle $2\theta = 30^\circ$. This feature well corresponds to the larger reduction of for a larger angle 2θ because the entrainment rate of the shear layer increases with $d\Delta/dx$. Figure 7 is replotted in Fig. 8 where the streamwise distance is normalized by the reattachment length X_R . The normalized thickness Δ/h now seems to fall on a single curve independently of the intensity of the free-stream turbulence. Since the base height h is common to all the models, this indicates that the thickness Δ is the same at the same normalized distance x/X_R for all turbulence intensities tested in this experiment. Moreover, Fig. 8 clearly shows that, the larger the vertical angle, the larger is the growth rate of the shear layer.

Fig. 5 (a) Relation between reattachment length and intensity of free-stream turbulence. (b) Normalized reattachment length.

Several previous studies⁽⁵⁾⁻⁽⁷⁾ on the plane turbulent mixing layer affected by the free-stream turbulence indicate the following features: (i) the growth rate of the mixing layer is increased by the free-stream turbulence⁽⁵⁾; (ii) the free-stream turbulence promotes the three-dimensionalization of the mixing layer⁽⁶⁾; (iii) a small scale turbulence effectively contributes to the enhanced growth of the mixing layer⁽⁷⁾. In these studies, however, the boundary layer developing along the splitter plate is certainly affected by the free-stream turbulence and this has an influence on the development of the mixing layer. The point is that we cannot discriminate the direct influence of the free-stream turbulence on the mixing layer. On the other hand, the laminar boundary layer along the upstream side of the model is expected to be only insignificantly affected by the free-stream turbulence because the model Reynolds number is so low, i.e., 3.3×10^4 that the transition is absent and because the boundary layer is accelerated up to the separation point. Accordingly changes in the properties of the separated shear layer associated with the free-stream turbulence can be regarded as the effect of the turbulence itself.

Figure 9 shows the position $y_{U=0}$ where the mean velocity U is zero as a function of the normalized longitudinal distance x/X_R . In this plot, the position $y_{U=0}$ appears to be independent of the turbulence

Fig. 6 Time-mean velocity profile in separation bubble (Case 1, $2\theta = 30^\circ$).

Fig. 7 Variation of thickness of separated shear layer.

intensity.

The streamwise length scale of vortices in the reattaching zone can be estimated as the streamwise distance where the forward-flow intermittency γ_p increases from 0 to unity. The profile of $\gamma_p(x)$ in the reattaching zone can be approximated by Gaussian error function. The standard deviation of the error function σ is thus a measure of the streamwise length scale of the vortices. Figure 10 shows the relation between σ and X_R . σ is seen to be approximately proportional to the bubble length X_R .

3.3 Unsteadiness in the separated shear layer

The separated shear layer rolls up into concentrated vortices owing to the Kelvin-Helmholtz instability. The vortices grow to a large scale by successive merging⁽⁸⁾.

Figure 11 shows the variation of peak frequency f of the streamwise velocity spectra measured near the outer edge of the shear layer. The decrease of the frequency f in inverse proportion to x is a manifestation of successive merging of the vortices. This also corresponds to a linear growth of the mixing layer in the streamwise direction. The peak frequency remains almost constant downstream of the

Fig. 8 Normalized thickness of shear layer.

Fig. 9 Locus of $yU=0$ in separation bubble.

reattaching zone. This shows that the merging of vortices is inhibited in this region.

Figure 12 shows the power spectra of pressure fluctuations near the surface in the reattachment region. A clear spectral peak appears at the frequency $0.65U_o/X_R$ even when the free-stream turbulence is added. The spectrum peak of the pressure fluctuations also appears at the same frequency for various vertical angles of the model(see Fig.13). This frequency $0.65U_o/X_R$ is a frequency at which large-scale vortices pass the reattaching zone⁽⁹⁾⁻⁽¹¹⁾. Accordingly it appears that the formation of the large-scale vortices and their shedding from the reattaching zone are a universal property of the separation bubbles; this property is independent both of the detailed geometry of the bodies and of the free-stream turbulence.

3.4 Base pressure and r.m.s. value of pressure fluctuation

Figure 14 presents the relation between the base pressure and the vertical angle of

Fig. 10 Relation between reattachment length X_R and spanwise extent σ of reattaching zone.

Fig. 11 Frequency at spectrum peak of velocity fluctuation in shear layer ($2\theta = 180^\circ$, case 1).

the model. The solid line in the figure indicates the result of Tanner⁽¹²⁾ at the Mach number 0.1 and it is in fairly good agreement with the present results. The case of $2\theta = 0^\circ$ corresponds to a downward facing step. The base pressure is seen to decrease as the vertical angle increases.

Figure 15 shows the r.m.s. value of the pressure fluctuations near the surface of the tail plate. The r.m.s. pressure attains a maximum somewhat upstream of the reattachment point. The maximum pressure is higher for larger vertical angle 2θ . (This tendency remains the same even when the free-stream turbulence is added.) This can be explained as follows. If the main-flow velocity U_o remains constant, a longer X_R yields a lower frequency $0.65U_o/X_R$ of the vortex shedding. The lower frequency

Fig. 12 Power spectra of pressure fluctuation near surface at $x/X_R \approx 0.95$ ($2\theta = 90^\circ$).

Fig. 13 Power spectra of pressure fluctuation near surface at $x/X_R \approx 0.95$.

Fig. 14 Base pressure versus vertical angle 2θ .

implies that more vorticity is accumulated in the shed vortices and that the strength of the vortices thus increases. It is reasonable to assume that stronger vortices produce greater pressure fluctuations. Since the bubble length X_R increases with an increasing angle 2θ , the above consideration is consistent with the result of Fig. 15.

4. Conclusions

The separation bubble formed behind a triangular cylinder with a tail plate has been studied in grid-generated turbulent flows. Reynolds number based on the base height and the main-stream velocity was 3.3×10^4 . Main results may be summarized as follows:

- (1) The length of the separation bubble decreases with an increase of free-stream turbulence. The rate of decrease is larger for a larger vertical angle of the cylinder.
- (2) The difference in degree of decrease in the bubble length is associated with the fact that the growth of the separated shear layer is larger for a larger vertical angle.
- (3) The streamwise length scale of vortices in the reattaching zone is proportional to the length of the separation bubble, whereas the vertical length scale is mainly determined by the base height of the cylinder.
- (4) The frequency of large-scale vortices shed from the reattaching zone remains almost constant at $0.65U_0/X_R$ independently both of the vertical angle of the cylinder and of the free-stream turbulence.

Fig. 15 Distribution of r.m.s. pressure fluctuation near surface of tail plate ($u'/U_0 = 0.005$).

- (5) The r.m.s. pressure fluctuation near the surface attains a maximum in the reattaching zone. The maximum value is larger for a larger vertical angle of the cylinder.

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