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STREAMWISE VORTICES INDUCED BY SEMI-CIRCULAR RODS SUBMERGED IN TURBULENT BOUNDARY LAYER

Two semi-circular rods set up in V-shape form were used to generate streamwise vortices in a turbulent boundary layer. The vortices, due to induced helical flow, supplement the streamwise momentum of retarded air particles at the body surface with the momentum of the external flow. In this experimental study it was found that vortices are at their most intensity if the Reynolds number of the flow over generator, based on the diameter of rods is within the range 10^4–$1.5 \cdot 10^4$. Several semi-circular rods set up in a tooth line were examined in delaying the separation of the turbulent boundary layer at a convex cylindrical surface. It has been noted that delay of separation is at its most efficient when the height of the generator is equal to at least half of the boundary layer thickness.

1. Introduction

Flows in the boundary layer are retarded due to skin friction at the body surface. This, in case of an adverse pressure gradient being present in the flow, leads to boundary layer separation (airplane wings, engine diffusers, axial compressors). To prevent or at least delay this phenomenon, the streamwise momentum of air particles in the boundary layer should be continuously supplemented with the momentum of external flow. Numerous investigations conducted hitherto show that the streamwise vortices generated at the surface appear to be a favorable means of transverse streamwise momentum

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exchange. Due to such vortices fluid particles with high momentum are swept toward the surface to mix with the retarded air at the surface, which in turn is swept away from the surface. The mean streamwise momentum of the fluid particles in the boundary layer is thereby increased. Various vortex generators were employed to induce partially helical flow at the boundary layer. Fixed solid vortex generators of both the vane and wing types were used over a long period because of their simplicity and low cost [1], [2], [3], [4], [5], [6], [7]. They form an array of small plates or wings projected normally (in the former case) or parallel to the surface (in the latter case) at an angle of incidence to the flow.

Low-profile vortex generators in the form of triangular ramps (Wheeler generators, [8], [9]) and the like have been developed in recent years to reduce parasitic drag. Low-profile generators have been observed to possess drag about twice as low as conventional vane-type generator of the same relative height. ($h/\delta = 0.4$, where δ is boundary layer thickness).

In the present experimental study a fixed solid generator in the form of semi-circular rods settled on the surface at an oblique angle to the main stream is considered. It is expected that a generator of this type demonstrate high efficiency. This supposition results from following observations: (i) Air particles which pass over the top of the rod (like over a bump) accelerate and reach velocity larger then the external flow velocity. (ii) The streamwise momentum of air locally enhanced in this way, is transferred with a streamwise vortex to the near wall flow region.

The considered generator was examined in delaying the boundary layer separation at a convex cylindrical surface [10].

2. Apparatus and measuring technique

Experiments were carried out with two semi-circular rods joined together in the form of a V-shape element with its point directed downstream (Fig. 1). The generator was lodged on a glass plate, which was placed in the trailing section of an open circuit wind tunnel (Fig. 2a). The generator was submerged in the boundary layer; the height of the generator ($h = R = 20$mm) was approximately equal to the boundary layer thickness, which arise along a distance 800 mm downstream of the leading edge of the glass plate. The flow velocity over the plate (beyond the boundary layer) was controlled in the range of up to 19 m/s.

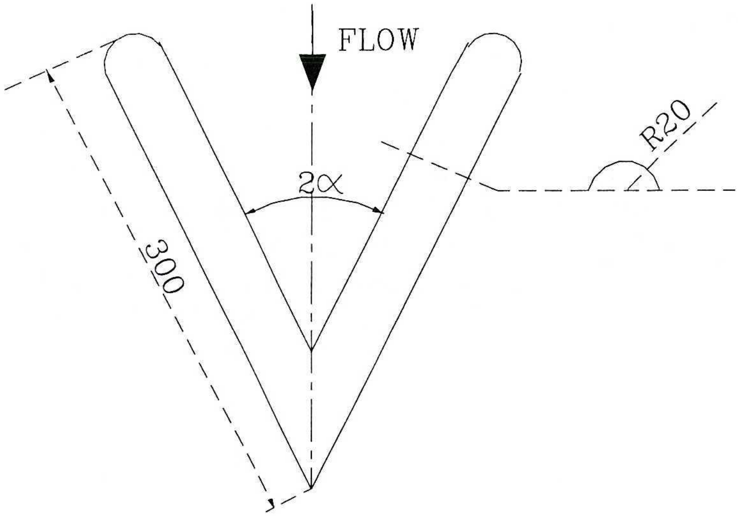

Fig. 1. V-generator

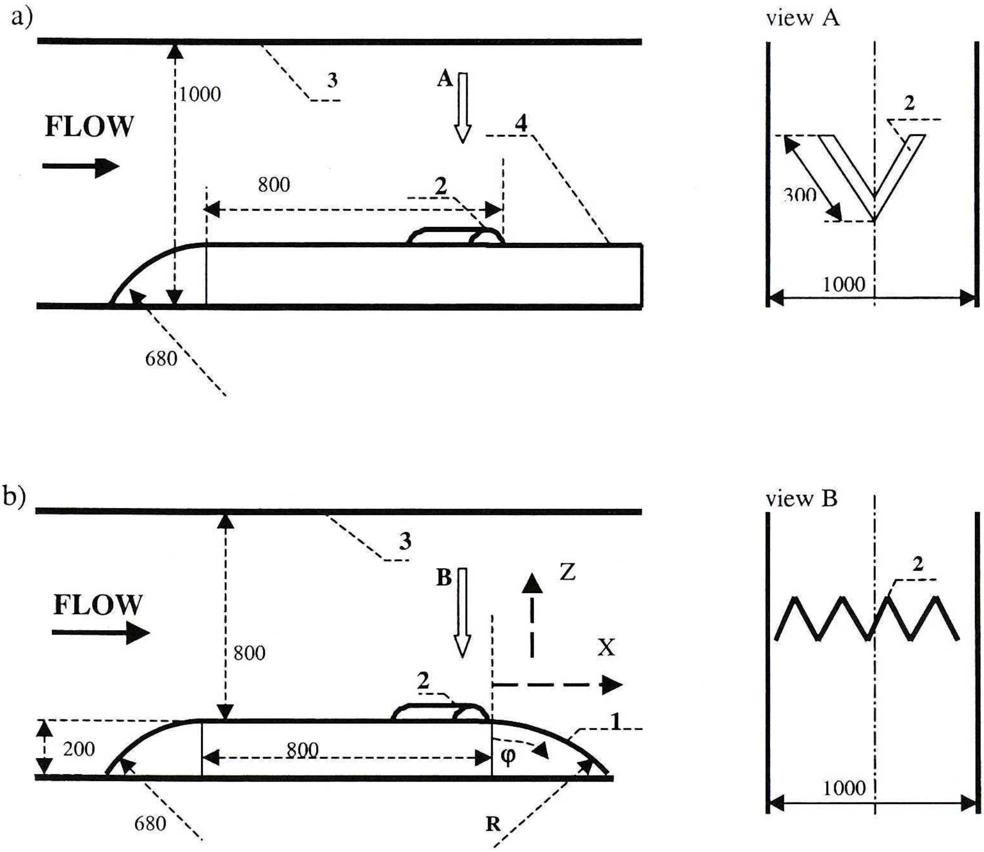

Fig. 2. Test section: a) with V-generator, b) with tooth generator. Dimensions in mm.
1 – test contour, 2 – vortex generator, 3 – roof of wind tunnel, 4 – glass plate

A simple probe (Fig. 3) was prepared to estimate the intensity of the streamwise vortices produced by the V-generator. The probe possessed a small rectangular plate, parallel to the direction of the mean flow that was able to rotate around its symmetry line. The frequency of rotation was measured by means of a miniature laser and photodiode. The probe was shifted along a line 11 mm over the glass plate and 20 mm downstream of the generator. The plate of the probe rotated when it passed by the vortex. Maximum rotation frequency occurred when the axis of the probe coincided with the axis of the streamwise vortex. In this way the locations of the two streamwise counter-rotating vortices were identified approximately (see section 3). The frequency of rotation observed in these locations was assumed to be the amount of intensity of the vortices. The experiment described above allowed the selection of the angle of the V-generator and the Reynolds number corresponding to the maximum intensity of the streamwise vortices.

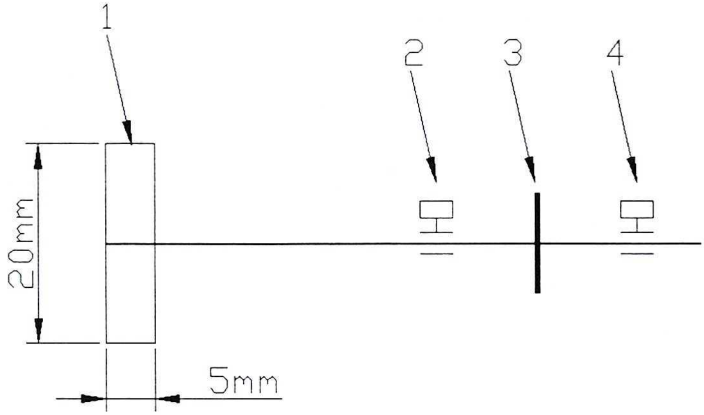

Fig. 3. Probe, 1 – plate, 2 – photodiode, 3 – rod, 4 – miniature laser

The ability of the semi-circular vortex generator to delay flow separation was examined for the flow at the cylindrical convex surface (this surface is appropriate to the present basic investigations because the flow over the cylindrical surface is separated for each Reynolds number, which is of practical significance). To this end, the trailing section of the glass plate was replaced by a cylindrical test contour (Fig. 2b). In this case, the semi-circular rods were set up in a continuous tooth line (tooth generator). They were settled on the trailing part of the plane section preceding the cylindrical surface.

3. Results

Figures 4a and 4b present two photographs of the oil layer on the glass plate (in case of Fig. 4b also on the V-generator) obtained at some delay after switching on the wind tunnel. Thin strips visible in the photograph in Fig. 4a indicate the flow directions at the glass plate whereas the thick strips in both photographs show the saddle lines. From these strips, the vortex pattern shown in Fig. 5 can be deduced. It consists of two primary stable counter-rotating vortices and secondary vortices in the corners of the half-cylinder and the glass plate. The secondary vortices occupy relatively small volumes, and have second order significance in the process of streamwise momentum transfer. Therefore, only the primary vortices were taken into account in subsequent investigations. Figure 6 shows the frequency of rotation of the probe in function of the flow velocity (V) for several angles (2α) between the arms of the V-generator. As can be expected the intensity (frequency) of the primary vortex increases with the flow velocity. However, the Strouhal number $St = fD/V$, which expresses the proportion between these parameters, shows its maximum at $\mathrm{Re} = 1.25 \cdot 10^4$ (Fig. 7). Considering these results, one can assume a Reynolds number (based on the diameter of the rod) in the range $10^4 - 1.5 \cdot 10^4$ to be the most effective in producing streamwise vortices by means of the V-generator. Vortex intensity increases with angle α and reaches a maximum for $\alpha \approx 30°$. When α oversteps a certain critical value (about 40°) the vortex becomes unstable. For a larger α the vortices are shed from the generator.

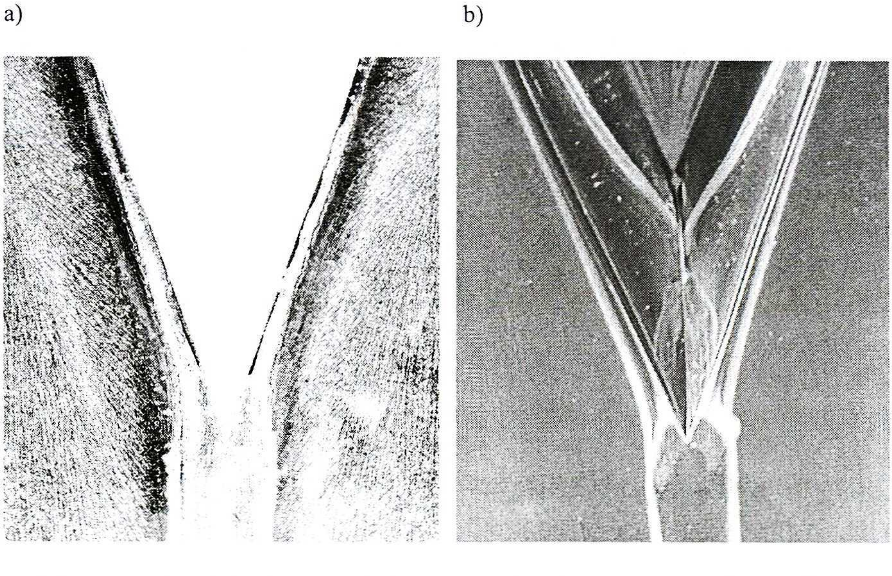

Fig. 4. Oil visualization of the flow around V-generator. Illumination source under the glass plate (a), over the plate (b)

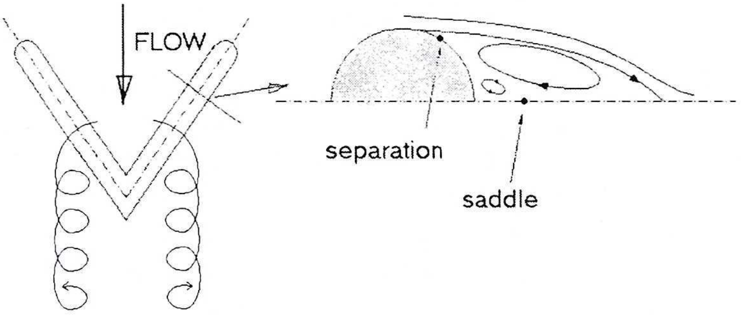

Fig. 5. Vortices downstream of V-generator

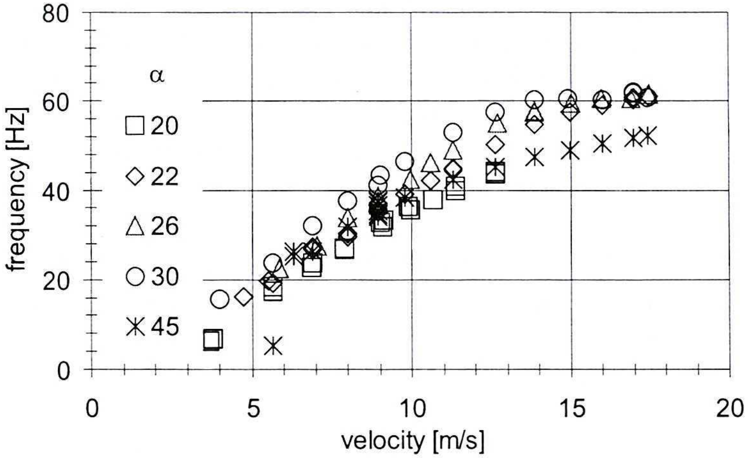

Fig. 6. Frequency of rotating plate in function of flow velocity, for different angles α of V-generator

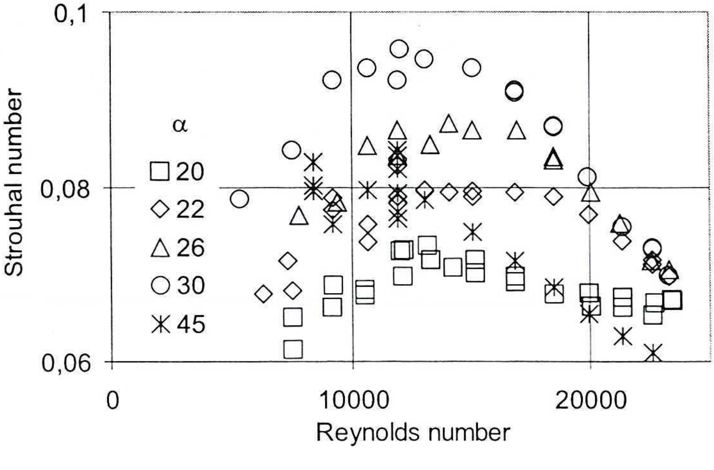

Fig. 7. Strouhal number versus Reynolds number for different angles α of V-generator

Fig. 8 displays the effect of vortex generators in delaying separation at a convex cylindrical surface. It shows the angular coordinate of the separation point (separation angle φ_s) obtained in this way as a function of the height of the tooth generator for two cylinders R = 500 mm and R = 680 mm. It is observed for both cylinders that the separation angle in the case when the vortex generator was absent does not show any distinguishable difference, and it is equal to 22°. In the case when the vortex generator is used, φ_s is slightly larger for R = 500 mm then φ_s for R = 680 mm. This occurs because the distance at which the vortex decays is, to some extent, independent of the cylinder radius. The same distance corresponds to the larger angle in the case of a lower R. In this consequence, φ_s for R = 500 mm is larger than φ_s for R = 680 mm.

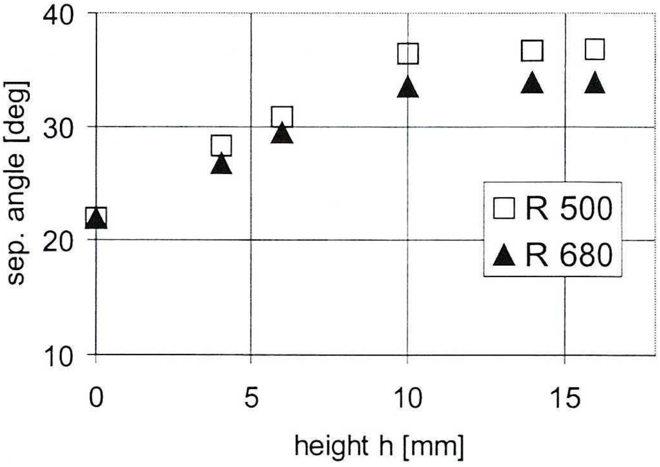

Fig. 8. Angular coordinate of separation point

4. Concluding remarks

Semi-circular rods positioned obliquely to the main flow direction appear to be an effective mean of streamwise momentum generation. These vortices have been used successfully to transfer the streamwise momentum of external flow to retarded air in the turbulent boundary layer. This occurs as a result of the high velocity of air particles, which accelerate when they pass over the top of the rod and are convected toward the surface. It was observed that a vortex generator consisting of semi-circular rods set up in a tooth line enables one to lengthen the distance of the attached flow at the cylindrical surface by nearly 50% in comparison with the case of a non-manipulated boundary layer [10]. To attain this, it is sufficient for the height of the vortex generator (radius of semi-circular rods) to be half of the boundary layer thickness. Owing to high efficiency, the generator need not be located close before the separation point of the non-manipulated boundary layer.

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Wiry wzdłużne generowane przez pręty półwalcowe w turbulentnej warstwie przyściennej

Streszczenie

Wiry, których oś wirowania pokrywa się z głównym kierunkiem przepływu (wiry wzdłużne) powodują ruch śrubowy elementów płynu. Tym samym, jeżeli wiry te generowane są w warstwie przyściennej, powodują intensyfikację transportu pędu w kierunku ścianki, a przez to uzupełnianie strat pędu warstwy przyściennej i opóźnianie jej oderwania. W pracy badano na drodze eksperymentalnej wiry wzdłużne generowane przez pręty półwalcowe zestawione w kształcie litery V, umieszczone na płaskiej ściance. Stwierdzono, że intensywność wirów jest największa dla liczb Reynoldsa w zakresie $10^4 - 1.5 \cdot 10^4$ i kąta rozwarcia między prętami ok. 60°. Efekt działania wytworzonych w ten sposób wirów na opóźnienie oderwania warstwy przyściennej badano przy opływie wypukłej powierzchni walcowej. Uzyskane wyniki świadczą, że skuteczność generatora wirów rośnie ze zwiększeniem promienia półwalca aż do wartości tego promienia równego w przybliżeniu połowie grubości warstwy. Dalsze zwiększenie promienia nie powoduje istotnego wzrostu opóźnienia oderwania.