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DISCRETE AIR JETS EMPLOYED TO CONTROL BOUNDARY LAYER SEPARATION

Turbulent boundary layer separation induced by positive pressure gradient at a plane surface is investigated experimentally. Separation is delayed by means of a jet vortex generator in a form of small jets injected to the boundary layer through orifices distributed across the main flow. The effect of jets intensity on delay of separation is examined. Swirled and non-swirled jets have been used. The energy of the air supplying the generator required to delay boundary layer separation is in the former case up to 40% lower than in the latter one.

1. Introduction

Streamwise vortices generated at a wall are known for several years as an effective means of control of the boundary layer separation. Due to helical flow induced by such a vortex the streamwise momentum of retarded air particles at the wall is partly supplemented by relatively high momentum of external flow (beyond the boundary layer).

Fixed solid elements in forms of rectangular or delta shaped winglets, oblique semi-circular rods, triangular ramps and the like [1], [2], [3], [4], [5], are commonly used to generate streamwise vortices, because of their simplicity and low cost. Their disadvantage is that they induce parasitic drag in situations where the flow separation is of minor significance or does not occur, e.g. during steady cruise conditions of an aeroplane. This disadvantage

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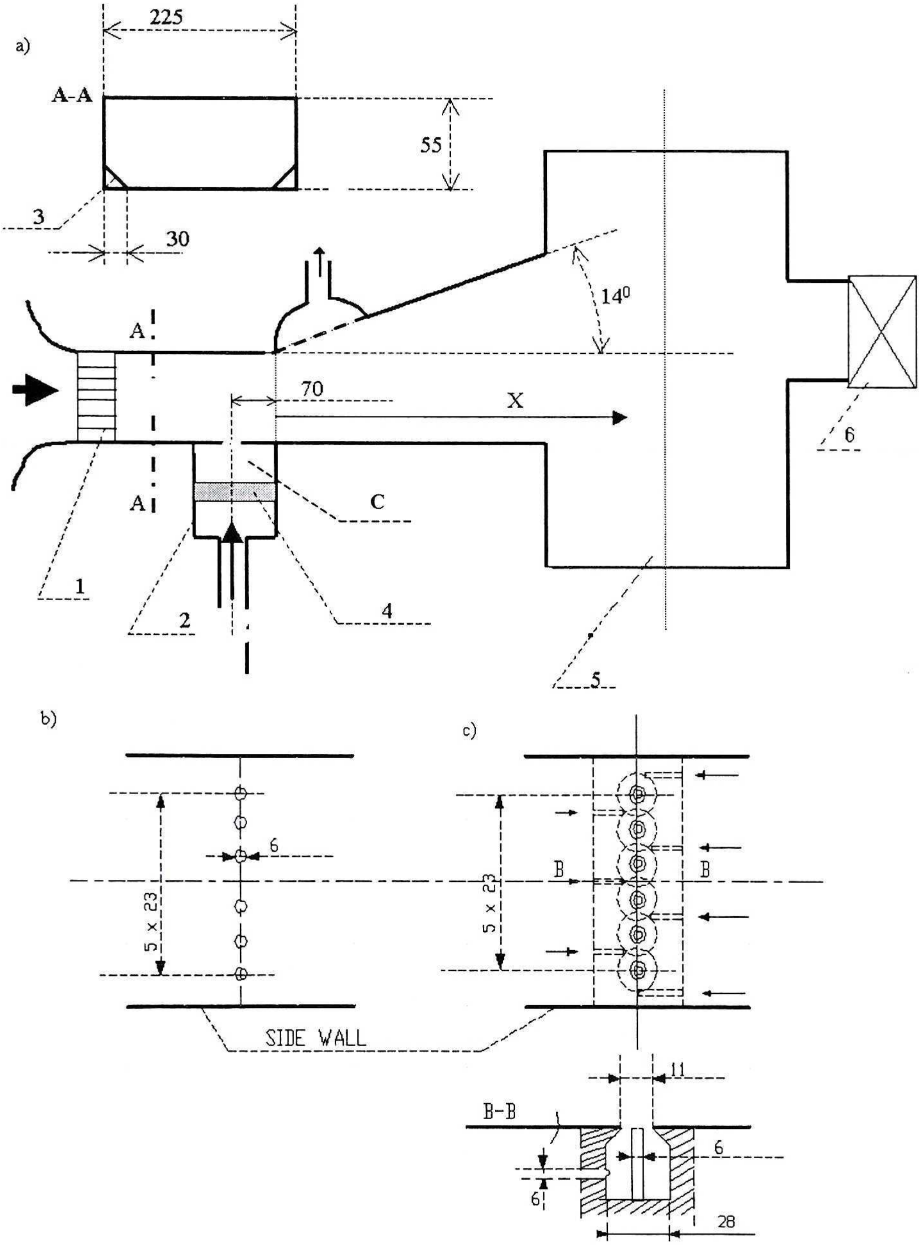

Fig. 1. Wind canal (a) with non-swirled (b) and swirled (c) vortex generators. 1 – honeycomb, 2 – vortex generator, 3 – batten, 4 – chocking filter, 5 – container, 6 – fan. Dimensions in mm

can be obviated by the use of generators, which could be switched on/off on command. This requirement can be realized using generators in a form of small jets injected into the boundary layer through an array of orifices in the wall, because the jet flow can be easy actuated or cut off. Moreover, in the former case the intensity of the jets, and thereby the intensity of generated vortices, can be changed. In this way, the boundary layer separation can be controlled. The jet vortex generator (JVG) was examined many years ago [6] to delay shock-induced separation of turbulent boundary layer at a semi-airfoil shape bump (6% thick). The experiments show that the JVG has potential. Substantial reduction of the separation region of turbulent boundary layer in diffuser flow of low velocity was noted by Johnson and Nishi [7]. They used jets issuing from orifices drilled in the wall at 45° to the wall surface, at various azimuthal angles in respect to the main flow. They observed that the generator was most effective when the azimuthal angle was about ±90° (perpendicular to the main flow direction).

The jet to the main flow velocity ratio in the experiments conducted by Johnson and Nishi, with which they obtained satisfactory results, was above 0.9. The jet of such velocity penetrates the flow in a distance usually much larger then the boundary layer thickness. In this effect, the main portion of the momentum of the jet is dispersed in the external flow, thereby, it is useless lost. This disadvantage does not occur when the jest is vigorously swirled to induce vortex breakdown phenomenon. In this case, the air particles of the jet spread out nearly parallel to the wall surface. In this way the jet influences the flow only in the near wall region.

In the present study the swirled and non-swirled jet generators are used to delay the turbulent boundary layer separation induced by positive pressure gradient on a plane surface.

The preliminary investigations presented in the paper are aimed to examine the influence of swirl on the effectiveness of the jet type vortex generator.

2. Apparatus and measuring technique

The experiments were conducted in a suction type wind canal shown in Fig. 1a. The air was sucked from the atmosphere through a rectangular test section to a container 6 m^3 in volume. The floor of the test section of the canal served as the boundary layer plate. The roof consisted of two sections: a leading section parallel to the floor and an aft section with adjustable angle of inclination. The triangular battens were installed in the corners between the floor and the sidewalls to diminish the corner flow effect. The boundary layer, which arises along the leading section of the roof, was evacuated by means of a separate suction system. The intensity of evacuation was adjusted to maintain the flow attached to the inclined section of the roof and separated from the opposite floor. As the boundary layer at the floor was manipulated, the separation point was shifted downstream.

The JVG was placed in the floor upstream of the inclined roof section. It possessed six orifices or six annular slits distributed uniformly across the channel in cases of non-swirled and swirled jest generator, respectively. The swirl was generated when the air passed through the actuator shown in Fig. 1c.

The ratio of the tangential and the normal (to the surface) flow velocity component V_t/V_n of the jet can be calculated considering the dimensions given in this figure; it reads about 6. The JVG was supplied with an external fan. The rate of air provided to the generator was measured by means of a diaphragm.

The flow velocity profile at the wall floor ahead the vortex generator is drawn in Fig. 2. It is very close to the standard exponential profile characteristic for a turbulent boundary layer $V/V_0 = (y/\delta)^{1/7}$, where V_0 is the flow velocity of the external flow in the leading section of the canal, and δ is the boundary layer thickness. The pressure distributions in the floor along symmetry plane of the test section were measured by means of a set of water manometers. Surface visualisation with suspension of titanium white in oil was applied to identify the separation at the floor.

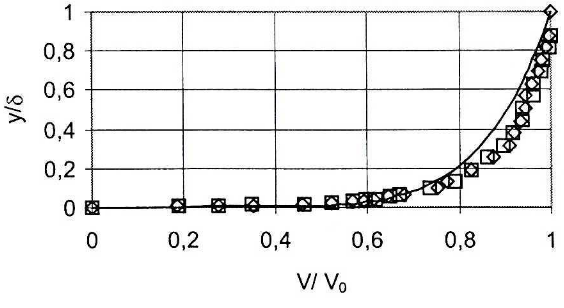

Fig. 2. Flow velocity profile at x = −7 cm, V_0 = 20 m/s, δ = 16 mm. Continuous line – standard exponential profile of turbulent boundary layer

3. Results

Figure 3 shows exemplary pressure distributions along the canal floor in case of manipulated, by swirled and non-swirled jets, boundary layer. The distributions are compared with that obtained in the case when the JVG was not actuated. One can note considerable difference between corresponding distributions (for actuated and not actuated JVG) in the case of non-swirled jets and small difference in the case of swirled jets. The difference in the former case finds its confirmation in experiments of Sugiyama [8], who investigated a flow over plane surface influenced by a cross jet. He observed substantial surface pressure decrease around the jet for azimuthal angles in the range 120°–150° (in respect to the main flow direction). Minimum pressure existing in the curve "c" in Fig. 3 corresponds to this observation. Non-uniform surface pressure distribution downstream of the jet that was observed in Sugiyama experiments induces a secondary cross flow (stream-wise vortex) [7]. In the case of swirled jet, the cross flow appears directly in effect of vortex breakdown phenomenon. In this case, the surface pressure field is only weakly influenced.

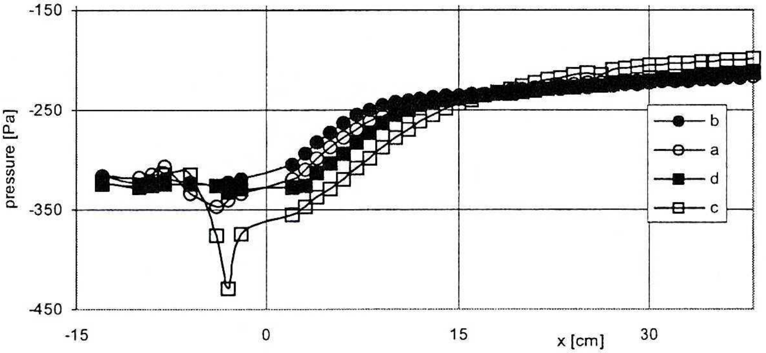

Fig. 3. Surface pressure distribution. Filled symbols – JVG non-actuated, open symbols – JVG actuated, overpressure in space **C** (Fig. 1) p_s = 1000 Pa (□) and p_s = 960 Pa (○)

Fig. 4 presents a photograph of oil layer covering the canal floor after 20 minutes duration of the flow. The strip remarkable in this photograph shows a saddle line, central section of which can be assumed as the separation line. The views similar to that presented in the photograph, allowed the authors to find the separation location (x_s) in function of jet intensity. The results are shown in Fig. 5 for both types of jet vortex generator under consideration. Separation point is more or less instable. Moreover, the influence of sidewalls increases along the channel. Due to those reasons, it is difficult to precisely identify the location of separation point. Dispersion of measuring points observed in Fig. 5 illustrates this difficulty. Considering the extrapolation lines presented in this figure, it can be noted that the delay of separation is proportional to the supply pressure (p_s) in the range of p_s under consideration. Factors of proportionality for the swirled and non-swirled jets are very close one to the other.

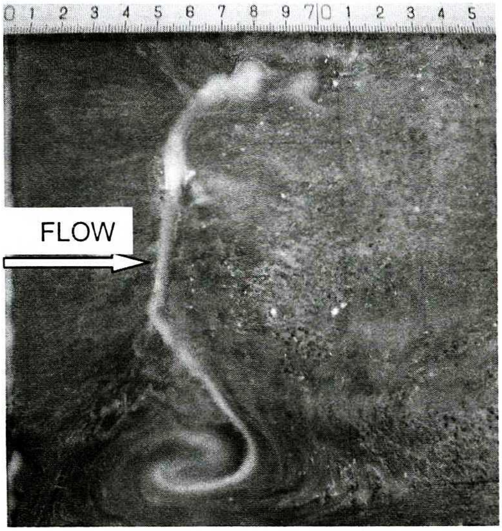

Fig. 4. Surface visualisation

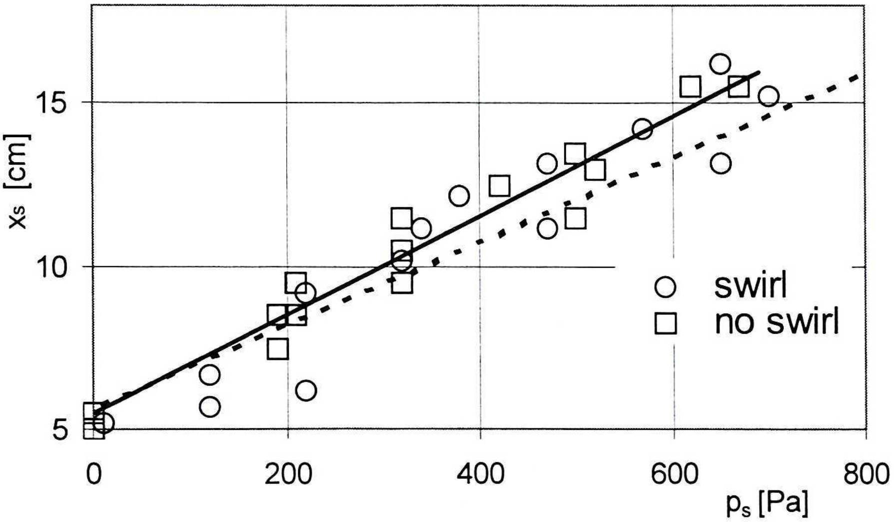

Fig. 5. Separation point location versus supply pressure, experimental points and corresponding extrapolation lines. Continuous line – non-swirled jet, dashed line – swirled jet

From practical point of view, it appears that the essential parameter of the generator is its efficiency. The efficiency can be expressed by the relationship between the displacement of separation point (delay of separations) caused by generator and the delivered energy (N).

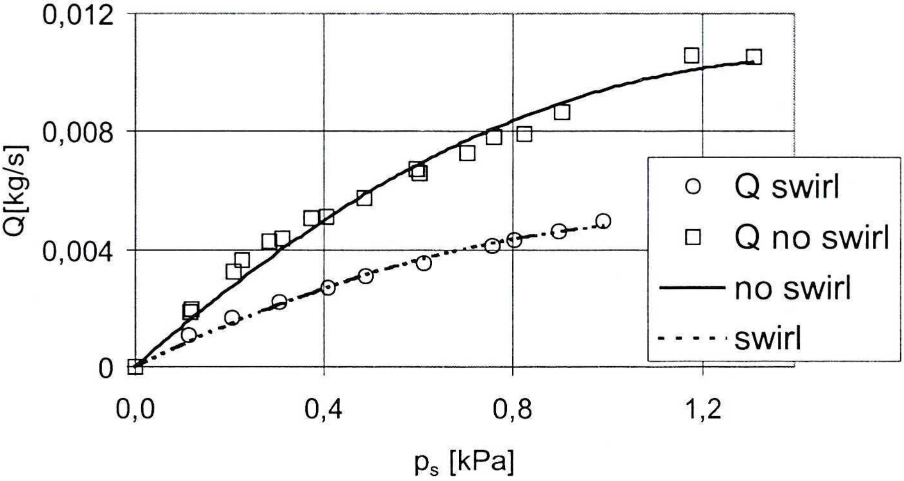

Fig. 6. Flow rate of air supplying generator versus supply pressure

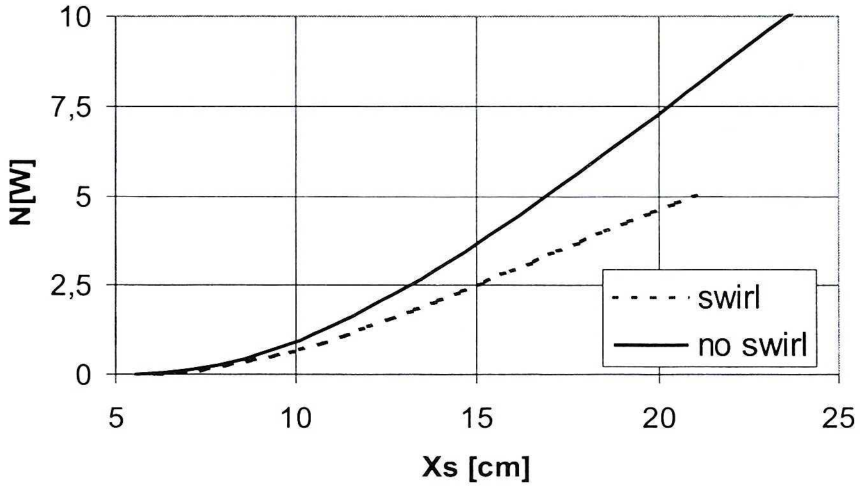

Fig. 7. Supply energy versus separation point location

The latter is defined here as a product of pressure (p_s) and the flow rate (Q) of the air supplying the generator. Fig. 6 shows the function Q (p_s) measured for both generators when the canal flow was present. As it can be expected, the flow rate in the case of swirled jets generator is lower due to larger chocking which exists in swirl actuator. Taking into account functions x_s (p_s) and Q (p_s) (the extrapolation lines in both cases) described above one can obtain the relationships x_s (N), shown in Fig. 7. It can be noted that the same delay of separation is reached with lower energy delivered to the generator in the case of swirled jet type. The relative difference of energy: $(N_{ns} - N_s)/N_{ns}$ which can be saved using swirled jets (index s) and non-swirled jet (index ns) in function of delay of separation, is displayed in Fig. 8. The saved energy increases with jet intensity, and reaches nearly 40% for the most intensive jet.

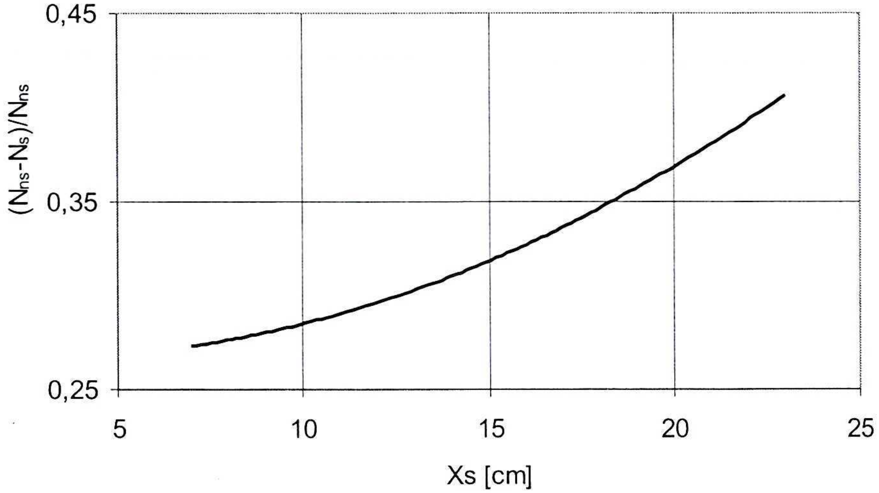

Fig. 8. Relative supply energy saved due to swirl versus separation point location

4. Concluding Remarks

Turbulent boundary layer separation can be actively controlled by means of jets injected through the wall. This is possible due to adjustable intensity of the jets.

The effectiveness of the jet type vortex generator can be considerably increased when the jets are swirled. The effectiveness is determined by energy of the air supplying the generators. In the case of the swirled jet type generator, the energy is up to 40% lower than the energy in case of the non-swirled one for the same separation delay equal in both cases.

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Zastosowanie dyskretnych strumieni powietrza do sterowania oderwania warstwy przyściennej

Streszczenie

Na drodze eksperymentalnej badane jest oderwanie turbulentnej warstwy przyściennej na płaskiej powierzchni powodowane dodatnim gradientem ciśnienia. Oderwanie jest opóźniane w wyniku oddziaływania wirów generowanych w warstwie przyściennej przez małe strumienie powietrza nadmuchiwane na ściankę. Rozpatrywane są strumienie proste (nie zawirowane) i zawirowane. W wyniku badań stwierdzono, że ten sam efekt opóźnienia oderwania można uzyskać przy około 40% mniejszym zużyciu energii w przypadku strumieni intensywnie zawirowanych w stosunku do strumieni prostych.