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Control of a channel-flow behind a backward-facing step by suction/blowing

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Abstract

Results of the experimental investigation on control of narrow channel flow behind a backward-facing step by blowing/suction near the step foot are presented. The slots differ in both the orifice shape (rectangle or serrated) and area ($50–375 \cdot 10^{-6}\ m^2$) of its cross-section. The intensity of flow control is characterized by the suction/blowing flow coefficient (mass flow through the slot over mass flow above the step, suction: negative values) that varies from −0.035 up to 0.035 at Reynolds number $5 \cdot 10^4$ (defined on the basis of the hydraulic diameter and volume velocity). Preliminary results indicate that both blowing and suction are able to reduce the length of the separation zone down to one third of its value without control. Control effectiveness is given by absolute value of the flow coefficient. The other parameters (slot area and shape) are important only for blowing, in this case small cross-section with serrated edge is the most effective. The existing three-dimensional vortex structures near the step (resulting from interaction of boundary layers near the step edge) are influenced by suction more then by blowing. The experiments are still in progress.

Keywords: Channel flow; Backward-facing step; Reattachment control; Blowing; Suction

1. Introduction

Active flow control concepts have become an increasingly attractive topic in fluid mechanics in the last few years. Flow separation results in negative effects such as drag increase, lift reduction and noise generation. The most common objective in the control of separated flows is the control of the size of the separation region. Thus the reattachment length x_r can be defined as a control variable, the control goal is in reducing this parameter.

Prandtl already in 1904 showed the modern way of flow control. In his famous paper he described several experiments in which the boundary layer was controlled. Prandtl used suction to delay boundary-layer separation from the surface of a cylinder.

The backward-facing step flow has been established as a benchmark configuration for separated flow studies in fluid mechanics first. The presented paper deals with possibilities of three-dimensional backward-facing step flow control at high Reynolds numbers (Re order of $5 \cdot 10^4$ based on hydraulic diameter d_h of the inlet channel and the bulk velocity U_e just upstream the step edge). A backward-facing step configuration of a channel occurs in many engineering applications ranging from various fluidic elements, cooling of turbine blades, air-conditioning pipelines to many other devices.

Flow separation on the step edge is a source of pressure loss, vibrations, and noise and affects heat transfer (reattachment region corresponds to maximum heat transfer however low-heat transfer appears in separation region). Turbulent shear flow in channels with sudden expansion of the cross-section could be met very often in many technical applications in mechanical and civil engineering. This flow belongs to the complex-flow family defined in the

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Nomenclature

a	effective slot gap (m)	H	channel height (m)
d_h	hydraulic diameter (m)	P_c	contact perimeter (m)
ei	voltage difference (V)	Re	Reynolds number (–)
f	frequency (Hz)	T	total observation period (s)
h	step height (m)	T_f	additive time of forward-flow (s)
p	wall pressure (Pa)	U_e	mean velocity in the inlet (m/s)
w	channel width (m)	γ_p	forward-flow-fraction coefficient (–)
x_d	position of maximum pressure derivative (m)	ρ	fluid (air) density (kg/m^3)
x_e	position of maximum pressure (m)		
x_r	reattachment position (m)	*Subscripts*	
C_p	static pressure coefficient (–)	e	at the inlet of the test section
C_Q	suction/blowing flow coefficient (–)	s	at the suction/blowing slot
C_U	suction/blowing velocity ratio coefficient (–)		
F	cross-section area (m^2)		

pioneering paper by Bradshaw (1971), specifically to the perturbed shear layer according to Bradshaw and Wong (1972). The flow over a backward-facing step is a very simple as to its geometry but the flow structure is extremely complex. A lot of experimental data sets have been collected using hot-wire and/or laser anemometry and flow visualisation from the simple case of the two-dimensional backward-facing step at low-values of Reynolds number, e.g., Biswas et al. (2004), and 3D case at high Reynolds number, e.g., Lee et al. (2004). Last two mentioned papers and paper by Ota (2000) and Nie and Armaly (2004) present literature surveys on channel flow over a backward-facing step. Some results on control the flow in the recirculation region were presented and quoted by Sakuraba et al. (2004).

The presented paper summarizes a recent stage of the work on the above mentioned subject in the Institute of Thermomechanics AS CR, some older achievements on this subject could be found in, e.g., Jonáš et al. (2005) and Jonáš et al. (2006).

The channel arrangement could be characterized by dimensions of the channel with rectangular cross-section, width w and height H upstream the step and step height h.

It has been shown, that the flow-field is well symmetrical with the plane of symmetry (identical with the geometric one). However, a three-dimensional vortex system could be observed in the flow behind the step. The mechanism of the vortices formation has not been fully explained yet, nonetheless their existence was confirmed also by mathematical modelling, e.g., Reinders et al. (2001) and Příhoda and Sedlář (2006). Initially, a couple of nearly stable contra-rotating corner vortices in the channel input near sidewalls are passing towards the plane of symmetry, they are pushed downwards in the same time. Then, they form a kidney-shaped common footprint on the bottom wall behind the step (see wall visualisation Fig. 3). Finally, the vortices rebound from the wall pointing up and turning downstream being pressed to the centre of the channel. Some experimental evidence of this scenario could be found, e.g., in Jaňour and Jonáš (1994) and Jonáš et al. (2004). For higher step ($h/w > 0.5$) only single oval footprint is observed on the bottom wall indicating strong interaction of the vortices. In all cases, the vortex structures are far from stable state showing apparent dynamical behaviour. Types of the footprints behind the backward-facing step in narrow channel are analysed in detail in the paper by Jonáš et al. (2005).

The aim of the presented investigation is to prove conclusions of the preliminary study by Jaňour and Jonáš (2004) on control strategy using more sophisticated experiments and examining the blowing/suction slot shape effect on the flow control effectiveness.

2. Experimental apparatus

The existing blow-down test rig was modified for experiments with the separated flow in a channel with a backward-facing step. The tunnel has rectangular cross-section with filled corners (to suppress corner vortices), honeycomb and a system of damping screens followed by contraction with contraction ratio 16. The area of the test section input is 0.25 m in height and 0.1 m in width. The time mean velocity departures from homogeneity in planes perpendicular to the tunnel axis are of order tenth of percent with the exception of corners, where corner vortex starters could be detected. Reynolds number based on the hydraulic diameter of the inlet channel and volume velocity was about $5 \cdot 10^4$, while that based on step height h was approximately $3.5 \cdot 10^4$. Conventional thickness of boundary layer at the step tip was approximately 0.003 m. The natural turbulence level was about 0.1% in the working section input. The channel downstream the backward-facing step was 1.4 m in length, and the ratio of the step height h to the input channel height H was 0.1 ($H = 0.25$ m, $h = 0.025$ m). A detailed description of the experimental arrangement could be found in Jonáš et al. (2004). The interchangeable step face allows varying slot for suction/blowing in the step foot. This allows modelling different area and/or shape of the slot cross-section. The layout is schematically shown in Fig. 1.

Various slots with rectangular and serrated cross-section shape were tested. The sketches of slots with fundamental dimensions and definitions are shown in Fig. 2, a is the effective width of the slot.

The reason for various shapes of the slot is to study influence of the slot perimeter, which forms the jet-like flow from the slot with different contact area with the controlled flow behind the step, if blowing from the slot is applied.

List of examined slots is given in Table 1 including some important characteristics: F_s is the area of the slot cross-section, d_s is slot hydraulic diameter and P_c is contact perimeter.

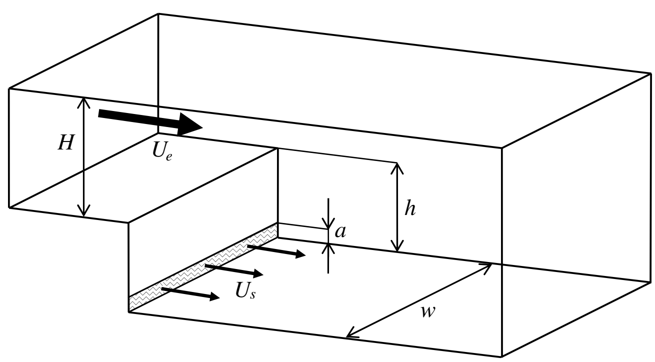

Fig. 1. Experimental setup (blowing, rectangular slot).

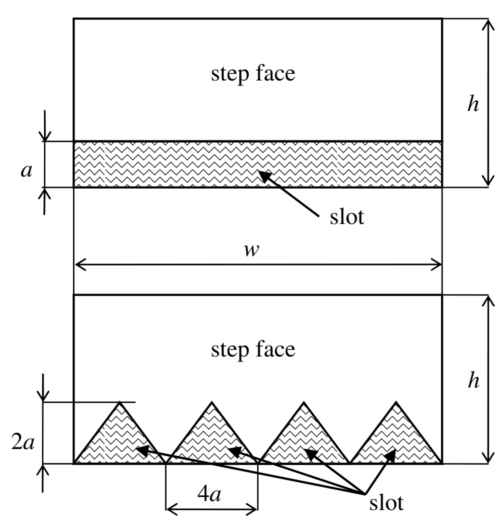

Fig. 2. Slots: rectangular (top), serrated (bottom).

Table 1
Slots parameters

Nos.	Type	a (10^{-3} m)	F_s (10^{-6} m^2)	d_s (10^{-3} m)	P_c (10^{-3} m)
1	Rect.	0.95	95	1.88	100.0
2	Rect.	2.25	225	4.40	100.0
3	Rect.	3.75	375	7.23	100.0
4	Serr.	1.00	50	0.83	141.4
5	Serr.	2.00	100	1.66	141.4
6	Serr.	4.00	200	3.31	141.4

The special exhauster/air pump serves for suction/blowing through the slot. It is connected with a metering nozzle and via a tube (inner diameter = 24.5 mm) with the slot chamber.

3. Experimental methods

The investigated flow-field is of very complex three-dimensional and non-stationary nature. Unfortunately, the study was limited by the methods available.

Short description of measurement techniques used in the presented study is to be given. Description covers used instrumentation, measuring and evaluation methods.

3.1. Reference quantities

The main flow parameters were measured by means of a Pitot-static tube (Prandtl type, dia 4 mm) and a RTD thermometer Pt100 inserted upstream the step. The bulk velocity U_e upstream the step was calculated from measured data. The mass flow through the slot was calculated from pressure differences measured on the metering nozzle (output section: dia = 13.7 mm, the contraction ratio is about 20) and temperature measured upstream from the inlet of metering nozzle. The velocity in the slot output was calculated with the respect to the static pressure value in the chamber upstream the slot.

The following differential pressure transducers were used at the mentioned measurements: two OMEGA PX653-05D5V 5, range 1.25 kPa, error $< \pm 0.2\%$ FS (OMEGA Technologies Ltd., England) and BHV 5355, range 10 kPa, error $< \pm 0.1\%$ FS and range 100 kPa, error $< \pm 0.1\%$ FS (BHV Sensors, Czech Republic). The pressure transducers were calibrated using the Betz type micromanometer (AVA Göttingen, Germany, range 4 kPa, direct reading 0.1 mm H_2O).

3.2. Wall pressure

Static pressure distribution on the bottom wall downstream from the step was measured with 0.4 mm diameter orifices (near the bottom wall centreline, spacing 0.01 m) successively connected to the sixteen-channel pressure transducer (Intelligent Pressure Scanner model 9010, Pressure Systems Int., range 2.5 kPa, accuracy $\pm 0.1\%$ FS).

The pressure distribution was originally analysed according to Chandrasuda and Bradshaw (1981). The length of the separated region x_r is evaluated from the position x_e of the maximum value of the pressure coefficient

$$C_p(x) = \frac{p(x) - p(0)}{0.5 \rho U_e^2}, \quad \max C_p = C_p(x_e). \tag{1}$$

Later on Příhoda (1991) found out (from the wall friction measurement) that the maximum C_p appears farther downstream from the reattachment x_r and proposed the empirical formula derived from measurements of numerous authors:

$$\frac{x_r}{h} \cong \frac{x_e}{h} - 0.238 \exp\left(0.25\frac{x_e}{h}\right). \tag{2}$$

Jaňour and Jonáš (2004) and Jonáš et al. (2005) noticed that the time mean position of reattachment lies between the locations x_e and x_d indicating positions of $\max C_p$ and $\max dC_p/dx$. In the paper Jonáš et al. (2006) a different empirical formula for the evaluation was derived:

$$\frac{x_r}{h} \cong 0.49\left(\frac{x_d}{h} + \frac{x_e}{h}\right)(1 \pm 0.04),$$

$$\max C_p = C_p(x_e), \quad \max\frac{dC_p}{dx} = \left[\frac{dC_p}{dx}\right]_{x=x_d}. \tag{3}$$

The accuracy of presented formulae is comparable and quite satisfactory. More details see the paper Jonáš et al. (2006).

3.3. Wall visualisations

The surface-streamline flow-visualisation technique is an old one (see, e.g., Rosenhead, 1963; Jaňour, 1972), but this method still gives a lot of information about the organisation of a complex flow near the wall. For this work a coating of magnesia (MgO) particles in a suspension in kerosene (70 g/l) is chosen. The coating is spread on the wall before starting the blower. When the fluid impinges the wall, the coating spreads over the surface showing the directions of the wall friction. After the coating has dried the wall is photographed and analysed.

The method works well for the suction control, for the blowing case there is a wall-jet along the wall behind the step with no back-flow near the wall. So the method fails to indicate the reattachment region is this case.

An example of the wall visualisation result is shown in Fig. 3 for the case without control, flow is coming from the right-hand side to the left. The forward- and back-flow regions as well as the reattachment could be easily identified.

The reattachment positions evaluated from the wall pressure distribution have been checked by visualisations.

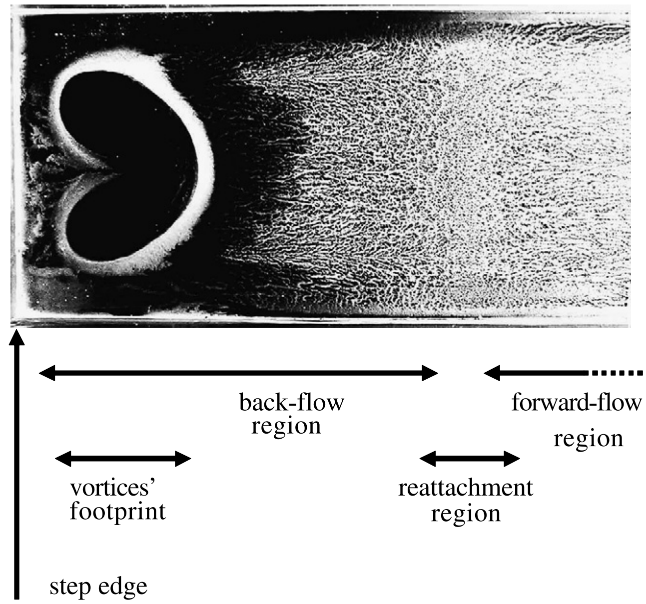

Fig. 3. Wall visualisation.

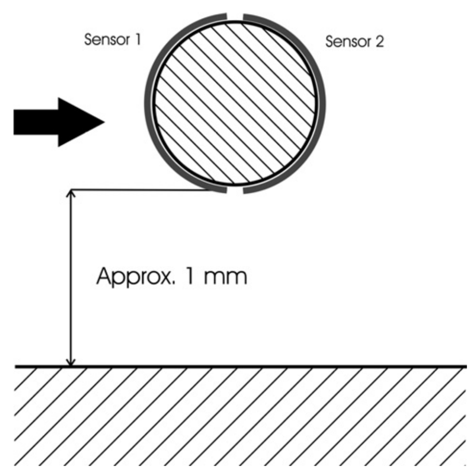

Fig. 4. The probe sensors.

3.4. Back-flow indication

The third approach to detection of the flow reattachment is based on measurement of the flow direction by means of a thermo-anemometer using a split-film probe. In a preliminary study of recirculation flow in separation region Uruba et al. (2005) applied a two-sensor split-film probe, which could detect direction of the velocity vector in plane perpendicular to the sensors' axis. The probe (DANTEC t. 55R58; both sensors heated to 200 °C, DANTEC StreamLine anemometer) was moving downstream from the step in the x direction with the sensor's axis perpendicular to the channel axis and parallel to the surface in the distance approximately 1 mm – see Fig. 4.

The probe calibration has been performed in a channel just on the exit of the contraction, air-flow velocity has been varied from −33 to 33 m/s, the sensor was located outside the boundary layer. To suppress influence of different voltage output levels the still air values were subtracted. The voltage differences with respect to still-air case were used for following analysis.

In Fig. 5 the voltage differences ei $(i = 1, 2)$ acquired from the split-film probe respective sensors are shown. From the graph it is clear that the windward sensor gives always higher output voltage difference then the downwind one.

The dynamical process of intermittent nature could be characterized by distribution of the local forward-flow-fraction coefficient γ_p, which is defined as follows:

$$\gamma_p = T_f/T, \tag{4}$$

where T_f is an additive time of forward-flow and T is total time of observation.

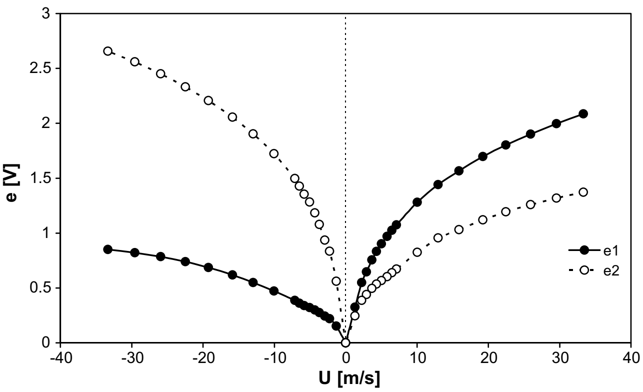

Fig. 5. Output voltage differences of the sensors.

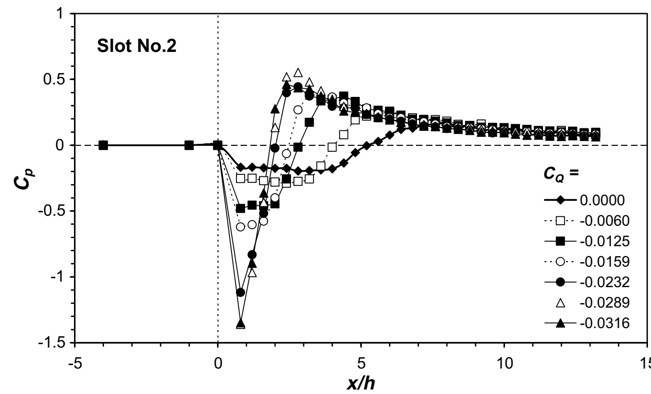

Fig. 6. Pressure distribution for suction.

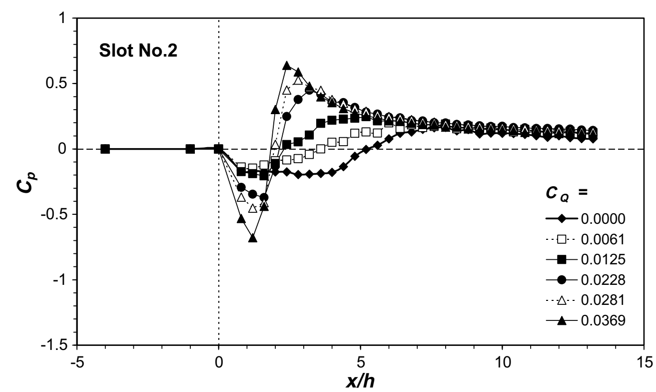

Fig. 7. Pressure distribution for blowing.

The forward-flow-fraction coefficient distribution $\gamma_p(x)$ was calculated from the anemometer output voltages ($\gamma_p = 0$ corresponds to the backward-flow – direction oriented to the step root; while $\gamma_p = 1$ corresponds to the same local flow direction as the outer stream). The "reattachment point" position x_r is defined as the point where the probabilities of the occurrence of the backward- and forward-flows are equal, that is, $\gamma_p(x_r) = 0.5$. In the reattachment region, the γ_p lays in open interval $(0, 1)$.

The 20 s records of voltage signals were acquired in 7.5 kHz acquisition frequency has been analyzed point-by-point.

4. Results

The intensity of blowing/suction is characterized by non-dimensional coefficients. The flow coefficient C_Q defined as the ratio of mass-flux through the slot over the amount of the incoming air-flow through the area of the step-head

$$C_Q = \frac{\rho_s U_s F_s}{\rho_e U_e F_e}, \quad F_s = w \cdot a, \quad F_e = w \cdot H. \tag{5}$$

The velocity ratio coefficient C_U is used alternatively:

$$C_U = \frac{U_s}{U_e}. \tag{6}$$

The coefficients are positive for blowing from the slot and negative for suction.

A systematic study of the wall pressure distributions has been carried out. An example of the blowing/suction effect on pressure coefficient (defined by (1)) is shown in Figs. 6 and 7 for the configuration with a canonical slot no. 2 (rectangular cross-section). The typical shape with pressure drop just behind the step followed by steep pressure increase could be seen in both graphs. The pressure drop is more pronounced for suction, as expected, however even for blowing significant negative values were obtained. The pressure maxima are rather flat.

The pressure distributions were examined for all defined combinations of slots and flow coefficients. The separated region length x_r has been evaluated using the formula (2), which is considered to give reliable results. The formula (3) has been tested as well, but no important difference in results was detected.

Reduction of the separated region length by blowing/suction as function of the flow coefficient is shown in Fig. 8. It is clear that both suction (negative C_Q) and blowing (positive C_Q) is effective in shortening the recirculation zone. While suction effectiveness is relatively insensitive to

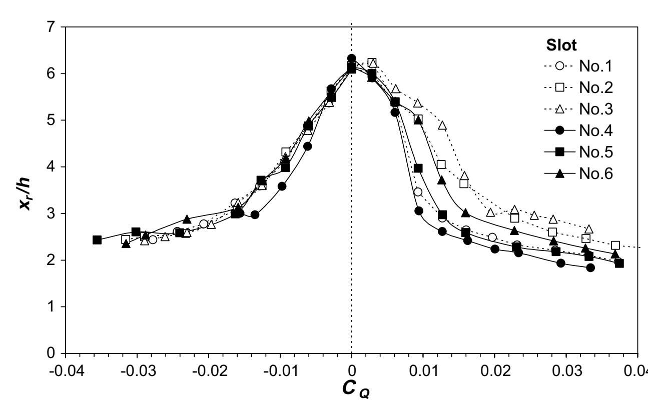

Fig. 8. Reattachment length from pressure distribution as function of flow rate.

the slot profile, that of blowing strongly depends on the slot geometrical parameters. Reduction of the recirculation zone length is more effective for smaller slot cross-section keeping the same C_Q value. Shape of the slot orifice is not very important, serrated shape gives slightly shorter recirculation zone than rectangular one for the same blowing rate and orifice cross-section. The most effective is the slot no. 4 producing the fastest jet flow for a given flow rate, while the longest recirculation zone produces slot no. 3 with the biggest cross-section.

The suction control mechanism is based on removing of low-velocity fluid from the recirculation zone. The slot works as a sink, only its capacity is important and not the orifice geometrical parameters, nor the suction velocity.

Blowing control, unlike suction, is influenced by the slot geometry. Higher velocity (that is smaller slot area) gives more intensive static pressure drop, which promotes the control mechanism. Thus entrainment mechanism in the wall-jet boundary plays an important role in the control process. This hypothesis is supported by effect of interface area on control effectiveness. (Compare results in blow-control for rectangular and serrated slot orifice). However, the role of the control flow velocity is not very clear – see Fig. 9 showing effect of blowing in reducing the separated zone length as function of the velocity ratio coefficient C_U.

Apparently, the secondary vortical structures mentioned in Section 1 play an important role in control process, especially in the dynamical behaviour of the flow in the recirculation zone. They should be definitely taken into account in mathematical modelling of the case.

As the reattachment is highly non-stationary dynamical process, we could rather speak about "zone of reattachment" instead of "line" or "point of reattachment". Detailed study of dynamical behaviour of the reattachment process has been carried out for suction control case. The back-flow indication method described in Section 3.4 has been applied. In Fig. 10 distributions of forward-flow-fraction coefficient for the slot no. 1 and various suction coefficients are shown. A typical S-shape of the curves is apparent.

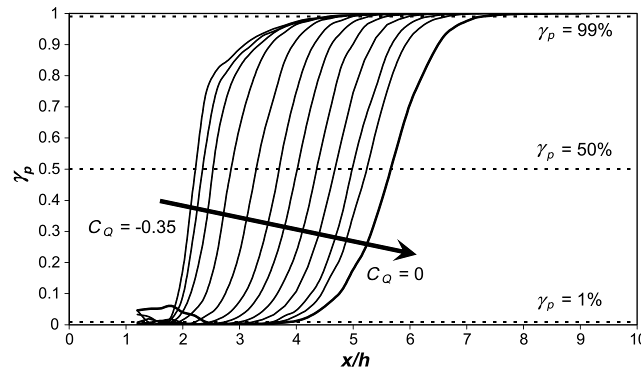

Fig. 10. Back-flow-fraction coefficient for suction control.

Position of the conventional reattachment point x_r could be defined by the γ_p value equal to 50% (0.5), the reattachment zone could be delimited by γ_p values 1% (0.01) and 99% (0.99). For low-absolute values of blowing coefficient the γ_p distributions are nearly symmetrical with conventional reattachment point nearly in the middle of the reattachment region. For greater negative C_Q values the γ_p distributions are steeper with more pronounced upper curved part resulting in non-symmetrical configuration – see Fig. 10. The positions of crossing points indicating the reattachment region and conventional reattachment point are shown in Fig. 11.

The process dynamics should be examined in time and/or frequency domain. Frequency characteristics of the reattachment process were studied from measurements of changing flow direction in a given x position. Mean time interval lengths of forward-/backward-flow are evaluated from 20 s records as well as the period of flow direction changes. Typical distribution of the mean length of time intervals and period of direction change within the reattachment region in semi-logarithmic coordinate system for $C_Q = 0$ is shown in Fig. 12. Detailed settings are given in Section 3.4. In Fig. 12 also γ_p values are indicated. Minimum of the period length, corresponding to equal forward-flow and backward-flow mean intervals, coincides with $\gamma_p = 0.5$ defining the conventional reattachment point.

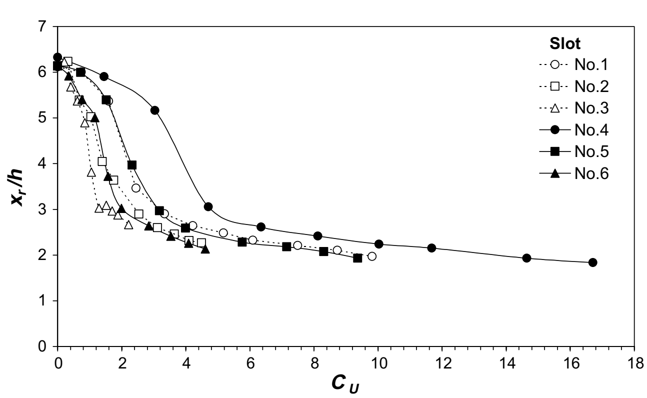

Fig. 9. Reattachment length from pressure distribution as function of velocity rate.

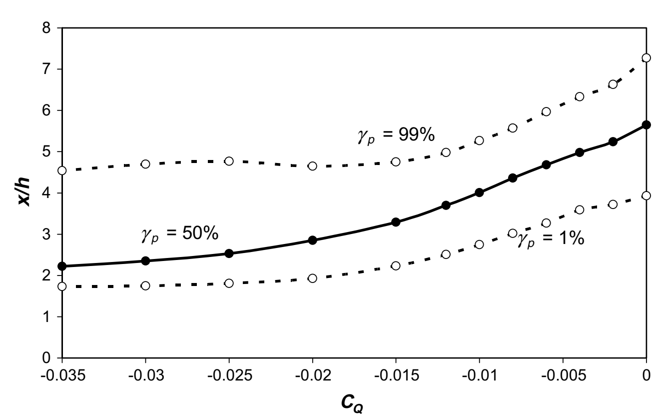

Fig. 11. Reattachment region and point for suction control.

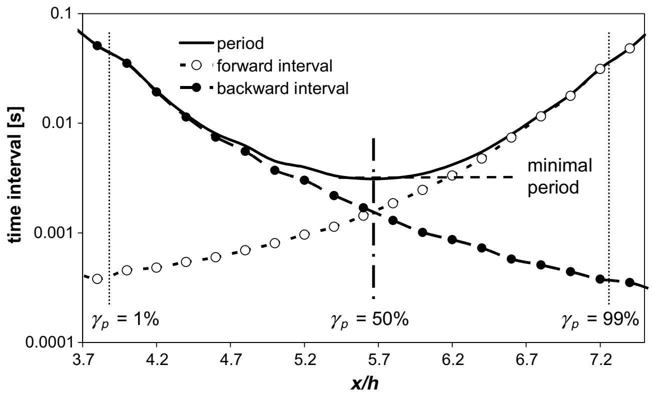

Fig. 12. Mean time intervals and period of flow direction changes without control.

The mean length of forward and backward time intervals could characterize the mean period of changes of flow direction, which is given by sum of the two intervals. The minimal period corresponds to γ_p equal to 0.5 and indicates typical frequency of reattachment point fluctuation f. In Fig. 13 this frequency is shown against the suction coefficient.

The reattachment point fluctuation is nearly constant for low-suction rates up to $C_Q = -0.012$, when the corresponding frequency is about 350 Hz. For more intensive suction the frequency f falls linearly with C_Q absolute value, for $C_Q = -0.035$ its value reaches 200 Hz.

The reattachment point fluctuations seem to be damped by suction. This conclusion is supported by steeper backflow-fraction coefficient characteristics (see Fig. 10) showing smaller amplitude of typical fluctuations.

Of course, the mean recirculation zone length could be evaluated on the basis of reattachment point dynamical measurements as well. The results for rectangular no. 1 and serrated no. 5 slots evaluated from pressure distribution measurements and dynamical moving hot-film probe data are compared in Fig. 14.

Very good agreement of both methods is evident. However the hot-film probe method gives more precise results,

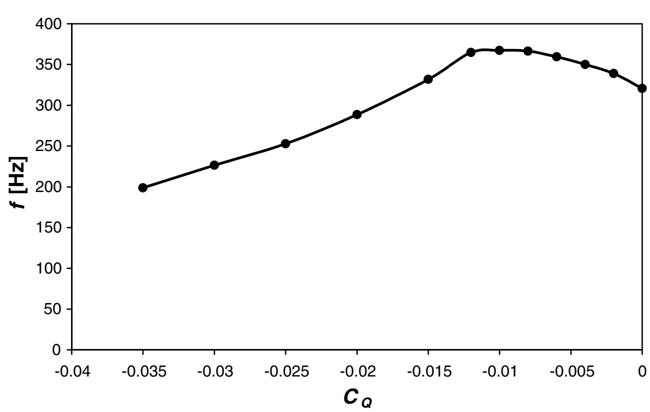

Fig. 13. Mean frequency of reattachment point fluctuations.

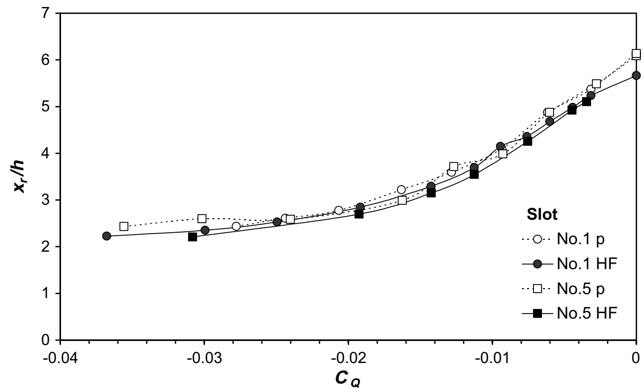

Fig. 14. Comparison of pressure (p) and hot-film (HF) measurements.

this is indicated by nicely smooth curves. Further, this is a direct method of the flow direction indication, no additional assumptions are needed, unlike the method based on pressure distribution.

Unfortunately, for the blowing control the method could not be applied, so only indirect pressure distribution evaluation method of the recirculation region length is available.

5. Conclusions

The suggested control method based on suction or blowing in the step foot seems to be effective in shortening the recirculation zone length. Shortening of the separation zone was evaluated using direct measurement only for suction, blowing relies on indirect evaluation method using wall pressure distribution.

The suction control mechanism is based on simple removing of low-velocity fluid from the recirculation zone, resulting in its reduction. This process is not influenced by the slot orifice geometry. However, the blowing control mechanism is completely different relaying on entrainment of fluid in recirculation zone into the wall jet. Then the slot geometry is of great importance as it implies the jet velocity and contact perimeter.

Energy considerations of the flow-control process are to be done to estimate its energy effectiveness. The continuous suction/blowing is rather demanding from energetic point of view, pulsating flow seems to be good alternative for future experiments. Hot-candidate is synthetic jet actuator, review of this type of actuators used for flow control could be found, e.g., in Uruba (2005) study.

In the future we intend using the time resolved PIV method for studying the non-stationary structures within the recirculation region. This seems to be necessary for checking the blowing control case results.

Acknowledgement

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