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CONTROL BY BLOWING OF THE SEPARATED FLOW IN A CHANNEL WITH A STEPWISE EXPANSION

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Summary: *This paper is concerned with prospects of control of narrow channel flow behind a backward-facing step by blowing / suction near the step foot at high value of Reynolds number $Re_d = 5.10^4$ (based on hydraulic diameter d_h of the inlet channel and the bulk velocity U_e just upstream the step edge). The slots differ in both the orifice shape (rectangle or serrated) and area ($50 \div 375 \cdot 10^{-6}\,\mathrm{m}^2$) of its cross-section.*

1. Introduction

A stepwise expansion of a channel occurs in many sundry engineering applications starting at several fluidic elements over cooling of turbine blades, air-conditioning pipelines and 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 under separated flow). Many papers were presented on this type of flow owing to its practicable ness and due to its importance for the basic research of complex shear flows, e.g. Biswas et al (2004), Lee et al. (2004) and Sakuraba et al. (2004).
The presented paper is a continuation of the previous ones, e.g. (Jonáš et al., 2005 and 2006), relating to flow in a channel with a rectangular cross section (width w, height H upstream the step) and stepwise expansion (step height h) drawn up in the Institute of Thermomechanics AS CR. It has been ascertained that the investigated flows are well symmetrical towards the plane of geometric symmetry. A 3D-vortex system arises in a region adjacent at the step root. The mechanism of the vortices occurrence has not yet been fully explained however they birth has been confirmed also by various calculations, e.g. Příhoda & Sedlář (2006). Initially a couple of broadly stable contra-rotating vortices near sidewalls are passing to the plane of symmetry and at least they form together only one footstep on the bottom in the record of the flow pattern near the wall. This arrives at about w/h = 3/2. Then, the contra rotating vortices align themselves in the plane of symmetry and oscillate fast between two relatively stable positions. This is going on inside the mentioned one footstep on the bottom downstream the step. The dimensionless distance x_v/h, from the step-root up to the limit of 3D-vortices region, decreases with increasing ratios h/H or, probably, with variation of the ratio of the height h to the step span. The reattachment position x_r is fast fluctuating in the strip of width from about 15 to 20 millimetres. The time mean distance of the reattachment region is $x_r/h \approx 6.3$ regardless on Re and $h/H \leq 1$. Clear dependences of the investigated re-attachment zone characteristics on Reynolds number of order of 10^4 and more were not observed if various

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length dimensions were chosen (step height, h or height of the channel upstream the step H, downstream the step, H+h or hydraulic diameter, d_h of the channel upstream from the step edge) in the velocity range from 5 up to 55 m/s.
The aim of the subsequent investigation has been to prove and refill conclusions of the preliminary study of Jaňour & Jonáš (2004) by means of more sophisticated experiments and examine the effect of the form of the blowing/suction slot on the flow control effectiveness.

2. Experimental Apparatus

The blow down wind tunnel of the Institute of Thermomechanics AS CR was modified for experiments with the separated flow in a channel with a stepwise expansion. The tunnel has rectangular cross section with filled corners (to suppress corner vortices), honeycomb and a system of damping screens. The working section is 0.31 m in length, 0.25 m in height and 0.1 m in width. The contraction ratio is 16.5. The departures of the time mean velocity from homogeneity in planes perpendicular to the tunnel axis are of order tenth of percent with the exception in the very immediate vicinity of corners where signs of corner vortices rising are visible. The natural turbulence level is about 0.1 percent across the flow upstream from the working section output. The channel with the step expansion (1.4 m in length and w = 0.1 m is the width) is smoothly connected with the working section. The ratio of the step height to the input channel height, h/H = 0.1 is modelled in the primary arrangement (H = 0.25 m, h = 0.025 m). A detailed description can be found in Jonáš et al. (2004).
The interchangeable step-face allows us to vary slots designed for suction/blowing in the corner of step. This allows modelling different area and/or form of the slot-cross section. The layout is schematically shown in Figure 1.

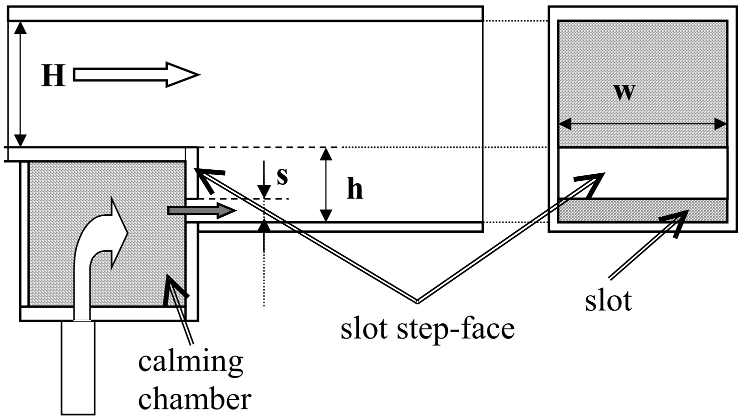

Figure 1 – Experimental set-up

Slots with rectangular and serrated shape of cross section were tested. The sketches of slots with fundamental dimensions and denominations are indicated in Table 1 and Figure 2; a, F_s and d_s are the effective width, the area and hydraulic diameter of the slot cross section.

Table 1 – Important parameters of slots

No.	a [mm]	F_s [mm^2]	d_s [mm]	shape
1	0.95	95	1.88	rectangular
2	2.25	225	4.40	rectangular
3	3.75	375	7.23	rectangular
4	0.50	50	0.83	serrated
5	1.00	100	1.66	serrated
6	2.00	200	3.31	serrated

A separate exhauster/ air pump serves for suction/blowing through slot. The air passes through a system with the metering nozzle and next conveyed by a tube (inner diameter equals 24.5 mm) into the calming chamber before the slot (Fig. 1). A simple switch over of few valves changes the blowing in suction and vice versa.

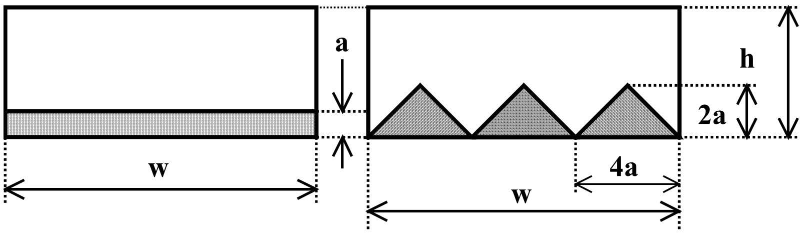

Figure 2 – Scheme of the slot step faces

3. Measuring methods and instruments

The main flow parameters were measured by means of a Pitot-static tube (Prandtl type, dia 4 mm) and a Pt-resistance thermometer inserted upstream the step. The bulk velocity U_e upstream the step and Reynolds number, Re, based on U_e and the proper length, were calculated. The mass flow through the slot was calculated from pressure differences measured on the metering nozzle (output section: dia = 14 mm, the contraction ratio is about 20) and from temperature measured upstream from the inlet of metering nozzle. The estimate of the mass flux measurement error is of about ± 0.5 %.

The velocity in the slot output was calculated with the regard to the static pressure value in the calming 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 less than ±0.2% FS (OMEGA Technologies Ltd., England) and BHV 5355, range 10 kPa, error less than ±0.1% FS and range 100 kPa, error less than ±0.1% FS (BHV Sensors, Czech Republic). The pressure transducers were calibrated in comparison with the Betz type micro manometer (AVA Göttingen, Germany, range 4 kPa, direct reading 0.1 mm H_2O).

Three independent measuring methods were applied at investigation of the flow downstream from the backward facing step: a flow visualization method, measurement of wall static pressure distributions and flow direction measurement by means of a thermo anemometer with three heated films probe.

The flow visualization method applied was originally described in Rosenhead monograph (1963) and improved by Jaňour (1972) later. The surface is covered using a paintbrush by the suspension of magnesia (MgO) particles mixed into kerosene (7:100) with the addition of few drops of transmission oil. The motion of the suspension is governed by gravity, inertia and pressure force. The coating dries after some time of the flow duration and the particles group themselves in formations characteristic for transition, separation, reattachment and occurrence of vortex structures. Above all the distances from the step-root: x_1 and x_v of the boundaries of footprints of the 3D-vortex structures and x_r the distance of the reattachment region were evaluated from the records of visualization. As the reattachment is an unsteady process the region of reattachment display itself as a strip with a characteristic drawing. The distance x_r is measured in the middle of the strip.

Static pressure distribution downstream from the step was measured with 0.4 mm-diameter orifices (near the bottom wall centreline spaced 0.01 m) gradually connected with the sixteen-channel pressure transducer (Pressure Scanner Model 9010, fa Pressure Systems, range up to 10 kPa, accuracy ±2.5 Pa). It should be mentioned, the flow reattachment downstream a backward facing step is highly non-stationary dynamical process, so a 10 seconds time averaging of pressure measurements was performed. The pressure distribution was originally analysed according to Chandrasuda & Bradshaw (1981). Then the length of the separated region x_r is determined from the position x_e of the maximum value of the pressure coefficient

$$C_P(x) = \frac{P(x) - P_0}{0.5\rho U_0^2}; \quad \max C_P = C_P(x_e) \tag{1}$$

Later Příhoda (1991) recognized (after the wall friction measurement) that maximum C_p appears farther downstream from the reattachment x_r and proposed the empirical formulae derived from measurements of numerous authors

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

and similarly Jaňour & Jonáš (2004) and Jonáš et al. (2005) noticed that the time mean position of reattachment lies between the locations x_e and x_d of max C_P and max dC_P/dx. Another empirical formulae was presented recently

$$\frac{x_r}{h} \cong 0.49\left(\frac{x_d}{h} + \frac{x_e}{h}\right)(1 \pm 0.04); \quad \max C_P = C_P(x_e); \max \frac{dC_P}{dx} = \left(\frac{dC_P}{dx}\right)_{x=x_d} \tag{3}$$

The accuracy of formulas (2) and (3) is comparable and quite satisfactory. More details see in the paper Jonáš et al. (2006).

The third approach to detection of the flow reattachment is based on measurement of the flow direction by means of a thermo-anemometer with a split-film probe. Uruba et al. (2005) applied, for preliminary study of recirculating flow in separation region, a two-sensors probe that could detect direction of the velocity vector in plane perpendicular to the sensor's axis. The probe (DANTEC t. 55R58; both sensors heated to 200°C by DANTEC Stream Line 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 from the wall. The method breaks down in case of blowing from the slot; then the probe lies in the blown off wall jet. But it works well in the configuration with suction at the root of step. The forward flow fraction coefficient distribution $\gamma_S(x)$ is calculated from the anemometer output voltages ($\gamma_S = 0$ corresponds to the backward-flow - direction oriented to the step root; $\gamma_S = 1$ corresponds to the longitudinal-flow, the local flow direction is the same as the outer stream). The reattachment position x_r is defined as the point where the probabilities of the occurrence of the backward-flow and the longitudinal-flow are equal, that is $\gamma_S(x_r) = 0.5$.

All mentioned methods were carefully tested. The reattachment positions evaluated from the distributions of pressure, C_P and fraction, γ_S coefficients agree well with the position determined from the records of flow visualization. Therefore the evaluation from pressure distribution with the help of formulae (2) was frequently applied as less laborious procedure.

4. Results

The bulk velocity U_e upstream the step and Reynolds number, Re_H (based on U_e and the input channel hydraulic diameter d_H) were kept at magnitudes U_e = 16.4 m/s and Re_H = 7.78E04 with departures less than 1% in the course of experiments. The intensity of blowing/suction is characterized by the coefficient C_Q defined as the ratio of mass-flux through the slot over the amount of the incoming flow through area equal to the area of the step-head

$$C_Q = \frac{\text{massflux through the slot}}{\text{massflux above the step}} = \frac{\rho_s U_s F_s}{\rho_e U_e F_e}; \quad F_s = w.s; \quad F_e = w.H; \quad w = 0.1\ \text{m}. \tag{4}$$

The coefficient is positive in state of blowing from the slot and negative for suction. The maximal mass flux through a slot was 0.02 kg/s.

An example of the effect of blowing/suction on pressure coefficient distribution is shown in Figure 3 for the configuration with the slot No.2 with the rectangular cross section. Another example, the distributions of C_p in configuration with the slot No. 6 that has the serrated cross section, is shown in the Figure 4.

Apparently the value of pressure coefficient maximum increases and on the contrary the minimum of pressure coefficient decreases with the increase of blowing/suction intensity. Simultaneously both extremes move towards the step. The effect of the slot-shape is noticeable only if the blowing affects the flow over the backward-facing step.

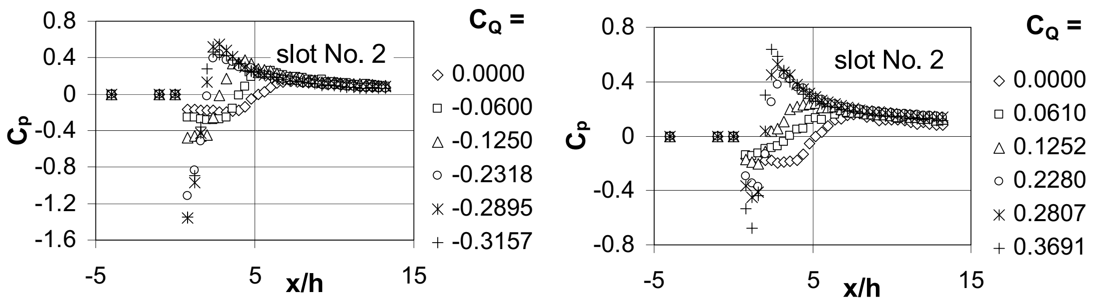

Figure 3 – Pressure coefficient distributions at suction (left) and blowing (right); rectangular shape of the slot No. 2

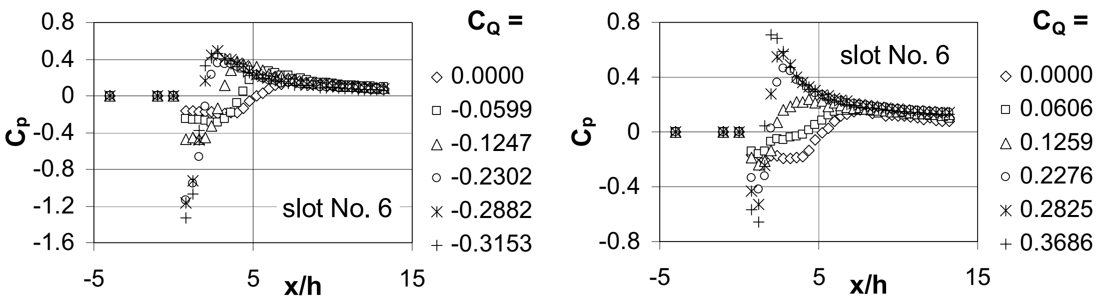

Figure 4 - Pressure coefficient distributions at suction (left) and blowing (right); serrated shape of the slot No. 6

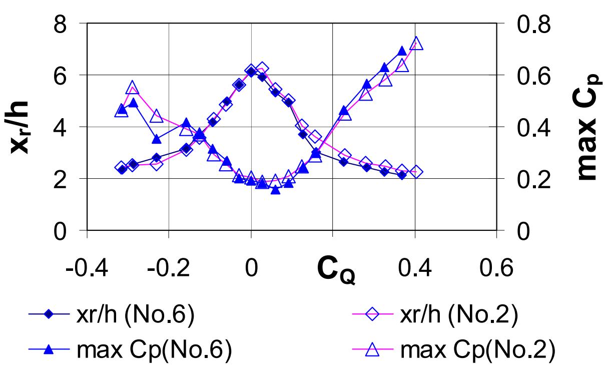

Figure 5 – An example of the effect of the slot shape

Effect of suction does not depend on the slot shape. The serrated shape of the slot cross section apparently amplifies the entrainment of fluid in contact with the wall jet from slot as has been awaited. Thus the length of the separated flow region, x_r downstream from the step becomes a little shorter (of about 7 %) at a given value C_Q when the control by blowing from a serrated slot is applied. A comparison of distributions of the length x_r/h and value of maximum C_P demonstrating the effect of the slot shape is shown in Figure 5. Let us remind, slots No. 2 and 6 have about the same area of cross section (Table 1).

The effect of blowing/suction in reducing the length of separated zone was described formerly, e.g. Sakubara et al. (2004) and Jaňour & Jonáš (2004). The presented results clarify the role of the slot shape and area of its cross section. The hydraulic diameter d_S is including both factors the slot section shape and the area as well

$$\begin{aligned} d_S &= \frac{4 * \text{area}}{\text{perimeter}} = \frac{2aw}{a+w} \rightarrow \text{rectangular section} \\ &= \frac{4a}{1+\sqrt{2}} \rightarrow \text{serrated section} \end{aligned} \tag{5}$$

The effect of the slot hydraulic diameter on the length of flow separation downstream the backward facing step when the control by blowing/suction is applied is shown in Figure 6. The data plotted into the figure were evaluated from interpolation of measurement in the vicinity of the chosen value of C_Q. Black marks denote results obtained with rectangular shape of slot, empty marks are relevant to serrated slots. A small shift of the flow reattachment to the step root indicates the increased effectiveness of suction with decreasing slot hydraulic diameter (left part of Figure 6) however only at d_S less than about two millimetres. Effect of the slot hydraulic diameter was not observed at d_S >2 mm by suction.

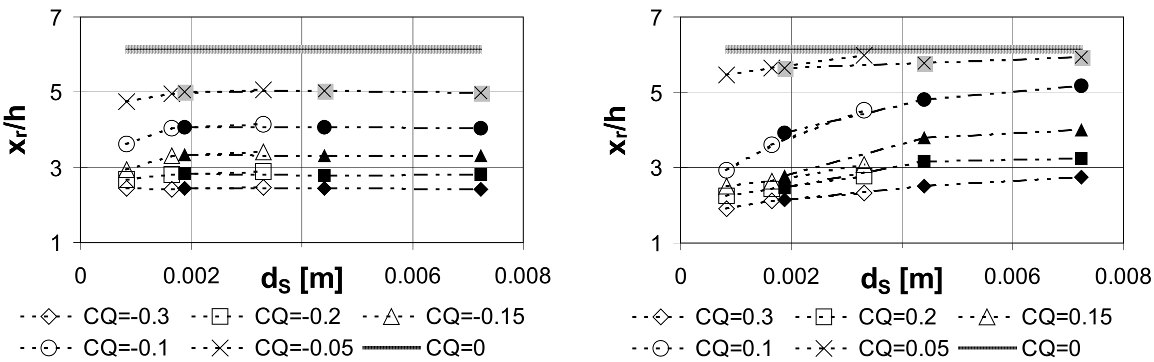

Figure 6 – Effect of slot hydraulic diameter on control of the flow separation length

Well pronounced effect of decreasing hydraulic diameter on increase in effectiveness of blowing from a slot at the root of the backward facing step can be seen in the right part of the Figure 6. Particularly remarkable shortening of the separated flow region arose at the blowing coefficient $C_Q = 0.1$. A special investigation would be interesting in the region $0.05 < C_Q < 0.1$. But it was not yet done.

The pressure distributions were measured for all configurations of slot described in the Figure 2 and Table 1 and in entire interval of flow coefficient values. The length x_r of the separated flow region 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 e.g. Jonáš et al. (2006). The effect of blowing/suction in reducing the separated zone length is shown in Figure 7.

From Figure 7 it is clear that both suction (negative C_Q) and blowing (positive C_Q) induce the recirculation zone shortening. The suction effectiveness is relatively insensitive to the slot shape whereas the blowing one strongly depends on the slot section geometry. Reduction of the recirculation zone length is more effective for smaller slot cross-section when keeping a chosen value of C_Q. Shape of the slot orifice is less important, serrated shape gives slightly shorter recirculation zone (less than 7%) than rectangular one for the same blowing rate and orifice cross-section. The most effective is the slot No.4 producing the fastest jet outflow

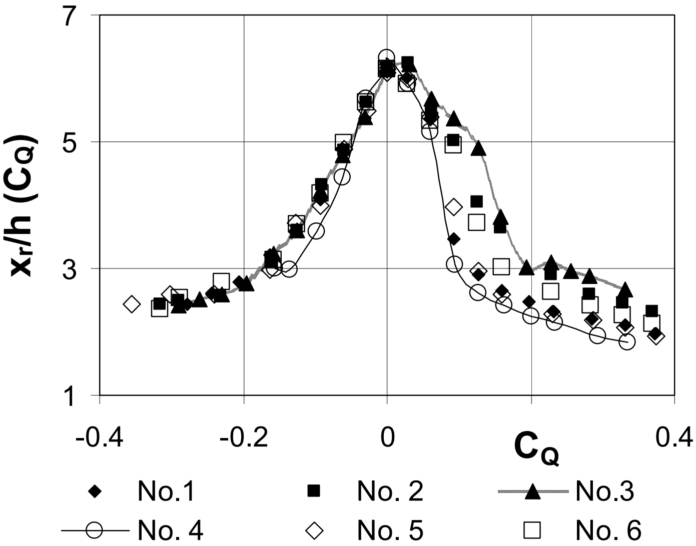

Figure 7 – Reattachment length at blowing/suction from different slots

(minimal area of the slot section; maximal outflow velocity in the slot outlet section of about 210 m/s) for a given flow rate, while the longest recirculation zone produces slot No.3 with the biggest rectangular cross-section (maximal outletvelocity of about 30 m/s).
A part of pressure measurements results, plotted in Figure 7, was approved by visualisation method (the application is more difficult at $C_Q \neq 0$ than at $C_Q = 0$). . The detailed study of dynamical behaviour of the reattachment process has been carried out for suction control only by CTA with the dual-film probes method, Uruba et al. (2006). Time mean characteristics correspond to the presented results well.

5. Conclusion

Suction and blowing through a slot at the foot of a backward-facing step in a rectangular channel are able to shorten the separated flow region more than to about one third of the original length without blowing/suction. The suction effectiveness, the size of shortening at a given value of the blowing/suction coefficient, is only a little sensitive to the intake velocity and to the shape of the slot cross section.
The effectiveness of blowing increases with increasing velocity in the slot outlet section. Additional reduction of the separated flow region can be achieved, up to about ten percent, when the slot with a serrated shape replaces a rectangular slot with the same cross section area.
The mentioned effect is related to the flow entrainment into the wall jet from the slot. A much-jagged free boundary of the jet from the slot will improve the control by blowing.
It would be interesting to study the slot optimal position at the edge and face of the step.

6. Acknowledgements
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