

ANNULAR IMPINGING JETS AND AN ACTIVE CONTROL OF HYSTERETIC EFFECTS

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Abstract

An annular impinging air jet with and without flow control was studied experimentally using measurements of the wall pressure and flow velocity by the Pitot probe. To investigate flow control swirling effects, eight synthetic jets were generated from the nozzle center body. The experiments cover Reynolds numbers 4000–10,000 (evaluated from the outer exit diameter of the annular nozzle). For $Re < 9000$, the bistability and hysteresis were identified and two different flow field patterns (A, B) were found under the same boundary conditions. For A pattern, a small recirculation area (bubble) of separated flow is attached to the nozzle center body. For B pattern, a large recirculation area bridges entire nozzle-to-wall distance. For higher $Re > 9000$, the hysteresis were not found.

Keywords: annular jet, impinging jet, hysteresis

1 Introduction

Forced convection heat transfer between fluid flow and solid surfaces depends on a particular arrangement of the task. In the case of a jet flow impingement, a very high heat transfer rate can be obtained. Therefore impinging jets (IJs) have been frequently investigated by several researchers [1]–[5]. Impinging jets are useful in many industrial applications such as cooling, heating, de-icing, and drying.

An *annular jet* impingement could be an interesting alternative to intensify heat transfer [6]. However, annular IJs can exhibit rather complicated features including a bistable and *hysteretic behavior*; see e.g. Trávníček and Tesař [7], Trávníček et al. [8]. Moreover, annular IJs can be *actively controlled*, as was investigated, e.g., by Trávníček et al. [8] and Danlos et al. [9].

The *synthetic jet* (SJ) is generated (“synthesized”) from a train of fluid puffs by pushing and pulling fluid through an actuator orifice [10]–[13]. The time-mean mass flux of the oscillatory flow in the SJ actuator orifice is zero, hence the other common terminology for SJ is a zero-net-mass-flux jet [14], [15]. SJs have a wide range of potential applications, most of which are directed at flow control (jet vectoring, active flow control in external and internal aerodynamics) and heat and mass transfer applications (cooling), see Trávníček and Tesař [7], Arik [16], Timchenko et al. [17], Chaudhari et al. [18], Persoons et al. [19]. The main subject of this study is an experimental research of the annular impinging jets under an active flow control by means of synthetic jets.

2 Experimental setup and methods

Experiment with a tested annular nozzle and air as the working fluid is presented in Figs. 1 and 2. The outer and inner diameters of the annular nozzle are $D_o = 30.0$ mm and $D_i = 28.4$ mm, respectively. Thus, the slot width is $b = (D_o - D_i)/2$.

The SJ actuator consists of a sealed cavity with an actuating diaphragm with a diameter of $D_D = 16$ mm, originated from the loudspeaker LP-21008 GM Electronic with the nominal electrical parameters 8Ω , 0.1W. The chamber has eight orifices, each with a diameter of $D = 1.2$ mm. The range of tested frequencies was 800 Hz – 1600 Hz (sine waveform). An in-house-built digital multimeter with a 13 kHz sampling frequency was used to measure true root-mean-square (rms) alternating current, voltage, and power; accuracies were $\pm 1.6\%$, $\pm 0.8\%$, and $\pm 2\%$, respectively.

Two cases were investigated: Case I (impinging jets) and Case II (jets without an impingement wall). The Pitot tube was used to measure air flow velocity (case II). To investigate impinging jets, a flat wall was installed perpendicularly to the annular nozzle axis. The diameter of the pressure tap hole drilled through the wall was 0.9 mm and it was attached to the manometer and pressure transmitter (range of 0-250 Pa and accuracy within 0.75 Pa).

An adjustment of the nozzle-to-wall distance and the position of the pressure tap were made by a manually operated x - r traversing system. The air is supplied by a compressor, runs via a flexible pipe with an inner diameter of 25 mm, and is maintained at a constant pressure by pressure regulators and filters. The flow rate was measured using a flow meter. The repeatability and standard accuracy are $\pm 0.25\%$ and $\pm 2\%$ of the full scale, respectively.

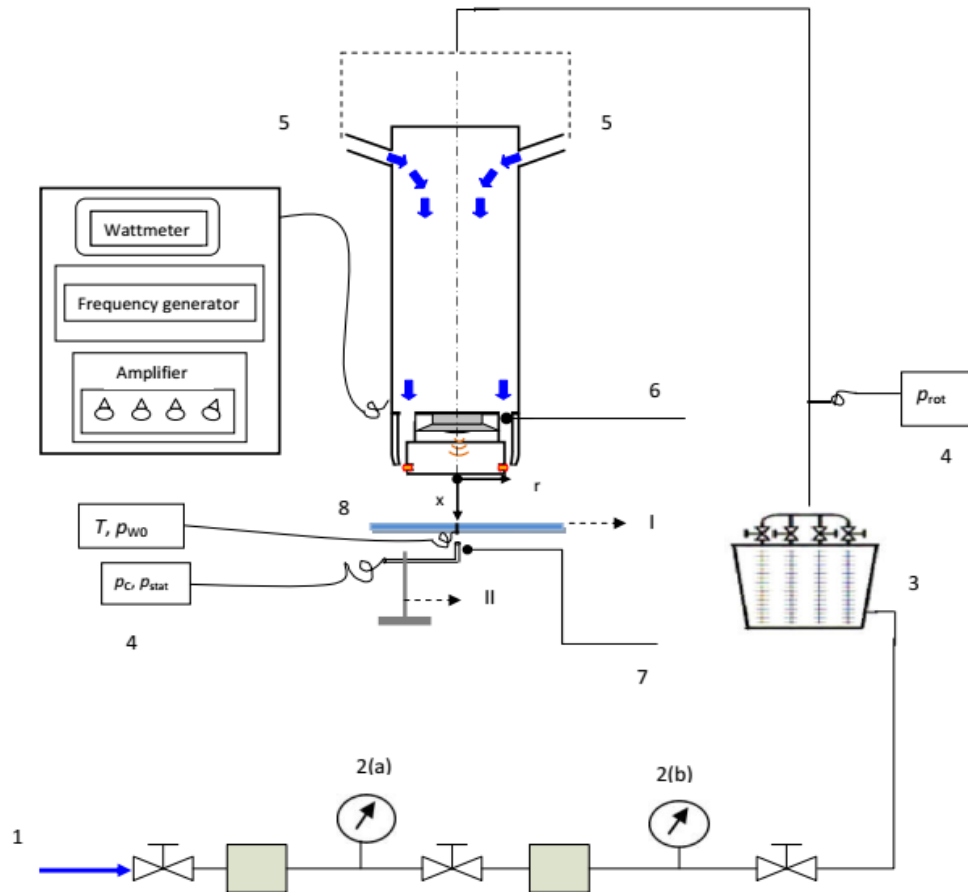


Figure 1: Scheme of experimentation: 1 – Compressed air, 2(a), (b) – Air filters and regulators of pressure, 3 – Rotameter, 4 – Manometers and thermometers, 5 – Pair of radial inlets, 6 – Loudspeaker, 7 – Pitot probe (case II: jet without an impingement wall), 8 – Impingement wall (case I: impinging jet)

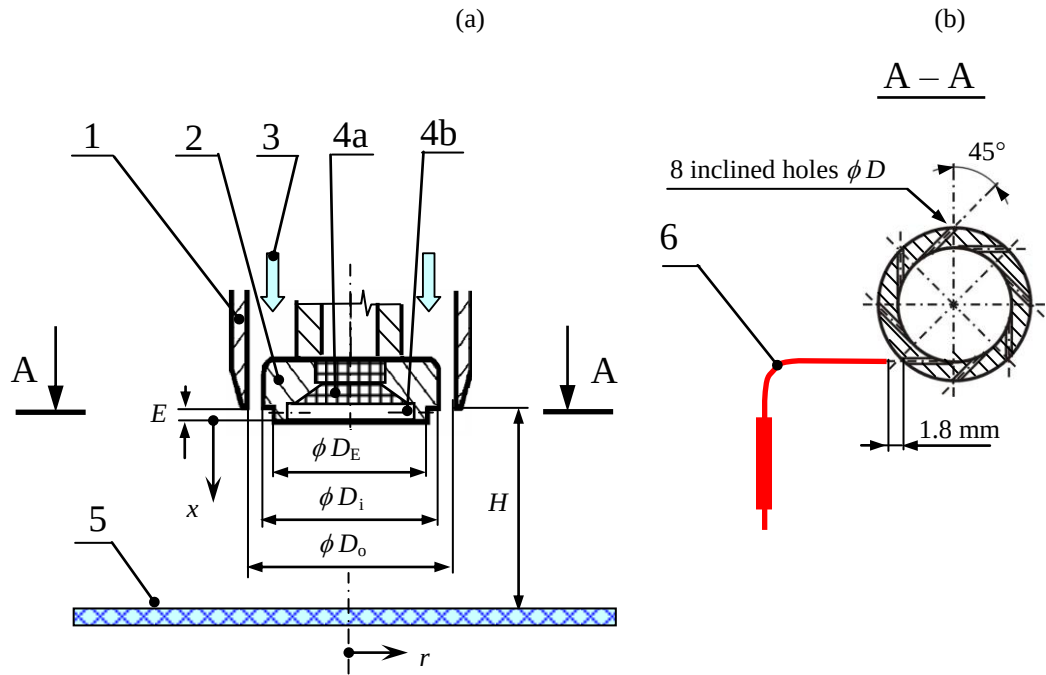


Figure 2: Scheme of the tested nozzle and configuration (case I: impinging jet), (a) central cross-section (b) horizontal cross-section; 1: outer nozzle body, 2: nozzle centrebody, 3: air flow supply, 4a: loudspeaker, 4b: actuator cavity, 5: impingement wall, 6: Pitot probe. Dimensions: $\phi D_o = 30.0$ mm, $\phi D_i = 28.4$ mm, $\phi D_E = 25.0$ mm, $E = 3.5$ mm, $\phi D = 1.2$ mm.

3 Results and discussion

3.1 Wall pressure in the stagnation point, hysteresis loop

Experiments were conducted with annular impinging jets (case:I) to evaluate the wall pressure at the stagnation point by varying the nozzle-to-wall distance H . Two Reynolds numbers were defined: the Reynolds number based on nozzle outer diameter D_o , $Re = U D_o / \nu$, and Reynolds number based on the annular slot width b , $Re_b = U b / \nu$. For the present experiments, $Re \approx 4000$ – $10,000$, i.e. $Re_b = 107$ – 267 . Due to the low Reynolds numbers, the laminar flow can be expected at the annular nozzle exit. However, the jet flow is developed towards the transition to turbulence further downstream - cf. [20].

Figure 3 presents typical findings of the stagnation point pressure measurement at $Re = 5170$ and $r = 0$; p_{w0} denotes the wall pressure (relative to the barometric pressure) at the point where the nozzle axis intersects the wall, and q is the dynamic pressure calculated from the average time-mean velocity in the nozzle exit, U : $q = \rho U^2 / 2$.

Figure 3 shows sudden changes in relationships between p_{w0}/q and H/D_o , which were evaluated for gradual changes of the nozzle-to-wall distance H . Namely:

- The quick drop in the wall pressure was found for decreasing H ; p_{w0} dropped from approximately 2 Pa to 0.5 Pa (i.e. p_{w0}/q from 0.48 to 0.12).
- The sudden rise of p_{w0} was found for increasing H ; p_{w0} raised from 0.6 to 1.9 Pa (i.e. p_{w0}/q from 0.14 to 0.45)

The hysteretic behavior was identified (the loop area on Fig. 3) as the result of the gradual increasing and reducing H distances, as is depicted by the arrows in Fig. 3. The hysteretic behavior occurs in the range of $H = 22$ – 26 mm, i.e. at $H/D_o = 0.73$ – 0.87 . The two flow patterns A and B can be recognized from the results, which are consistent with the previous results by Trávníček and Tesař [21]. Under the same boundary condition, two different flowfield patterns were found:

- **Pattern A:** the small recirculation area (bubble) of separated flow is located just downstream from

the nozzle center body.

- **Pattern B:** the large recirculation area of separated flow reaches up to the impingement wall, on which there is a stagnation circle.

The existence of the higher-pressure central stagnation point for A pattern and the big recirculation bubble for B pattern correspond to the higher and lower stagnation pressure levels in Fig. 3.

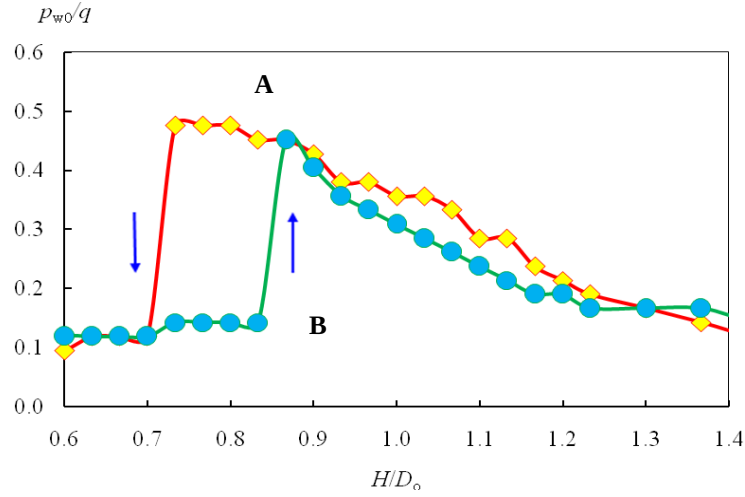


Figure 3: Effect of nozzle-to-wall distance on the stagnation point wall pressure (in dimensionless forms), $Re = 5170$

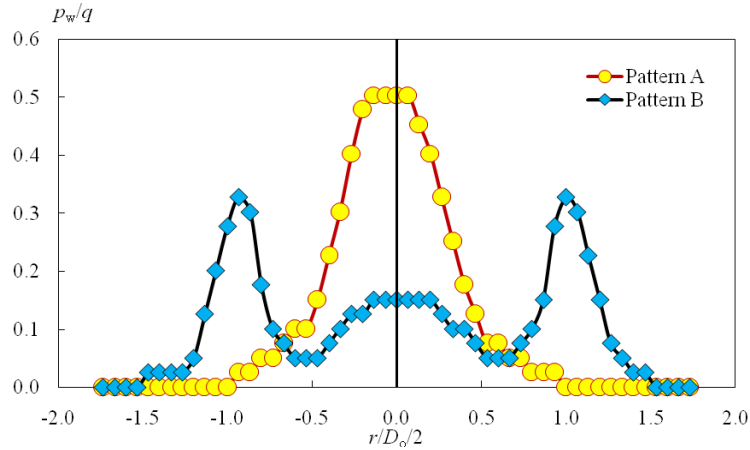


Figure 4: Wall pressure distributions measured at $Re = 5050$

3.2 Wall pressure distribution

The wall-pressure distribution of annular impinging jets (case:I) was measured for $H/D_o = 0.8$, i.e. at the nozzle-to-wall distance $H=24$ mm when the jet is bistable in character, as was discussed in the text above (Fig. 3). Two types of the wall-pressure distributions were obtained as is shown in Fig. 4:

- One distribution is bell-shaped with the maximum at the central stagnation point. This distribution was obtained when the H was gradually reduced (i.e. the nozzle was gradually moved to the impingement wall). The flow-field pattern A can be supposed.
- The second distribution is saddle-shaped one with two off-axis maxima and smaller local maximum at the jet axis. This distribution was obtained when the H was gradually increased. The pattern B can be supposed with the stagnation circle and the central reverse stagnation point.

The findings well agree with the bistability results by Trávníček et al. [8].

3.3 Effect of the Reynolds number

Experiments were carried out with an annular IJ (case I) and the results are shown in Fig. 5. The hysteresis loop is clearly observed from $Re \approx 4000$, and the result obtained at $Re \approx 10,000$ indicates a switch from pattern A to pattern B without the hysteresis loop. In other words, there is no hysteresis behavior at $Re \approx 10,000$. It was shown by additional experiments that the hysteresis effect disappears for the given $H/D_0 = 0.8$ for higher Reynolds numbers, $Re > 9000$.

The described Reynolds number effect can be interpreted as the effect of fluid viscosity. Namely, the viscous forces at lower Re are sufficient to preserve flow-field patterns even in the case of gradual changes of the nozzle-to wall distance H , thus the hysteresis loop can occur. On the other hand, the inertial forces overcome viscous forces at higher Re , thus the hysteresis loop cannot occur and the gradual changes of H cause nearly sudden switch between patterns A and B.

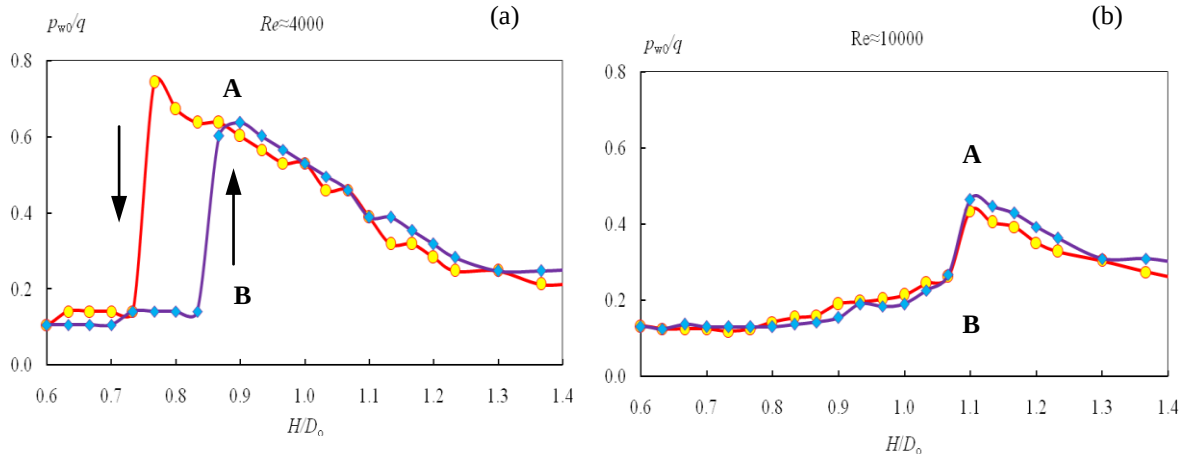


Figure 5: The occurrence of the hysteresis loop at (a) $Re \approx 4000$ & (b) $Re \approx 10,000$

3.4 Frequency characteristics of the SJ actuator

The time-mean orifice velocity U_0 of the extrusion averaged over the entire period can be evaluated by spatial-temporal integration, see Holman et al. [11]. Considering the slug flow model (i.e., the uniform velocity profile issuing from the actuator orifice), the definition can be substantially simplified. Following Smith and Glezer [10], U_0 can be evaluated as

$$U_0 = \frac{1}{T} \int_0^{T_E} u_0(r=0, t) dt \quad (1)$$

where t is time, T_E is the extrusion time ($T_E = T/2$ for a common sinusoidal waveform of $u_0(t)$), T is the period, $T=1/f$ and f is the frequency, and $u_0(r=0, t)$ is the velocity in the middle of the orifice exit.

Experiments were performed to evaluate the natural frequency of the synthetic jet actuator. Frequency characteristic was measured for the real input power $P = I V \cos \varphi = 0.1$ W, where I , V , and $\cos \varphi$ are the real current, voltage and power factor. During the Pitot probe measurements, the probe was located approximately at $1.5D = 1.8$ mm downstream the orifice, see the Fig. 2. It is known fact from the previous study [22] that such a distance is suitable for of SJ velocity measurements by the Pitot probe, because an unidirectional flow without a reciprocating velocity component exists there.

The frequency and power characteristics are presented in Fig. 6(a and b). The tests were performed with the constant real input power of $P = 0.1$ W. The maximum velocity was identified in Fig. 6(a) at frequency 1120 Hz. It indicates the first resonance of the actuator. Figure 6(b) shows that the velocity increase is approximately stable and nearly linear up to $P = 40$ mW. On the other hand, the slope of the velocity increase is much lesser for higher $P > 40$ mW.

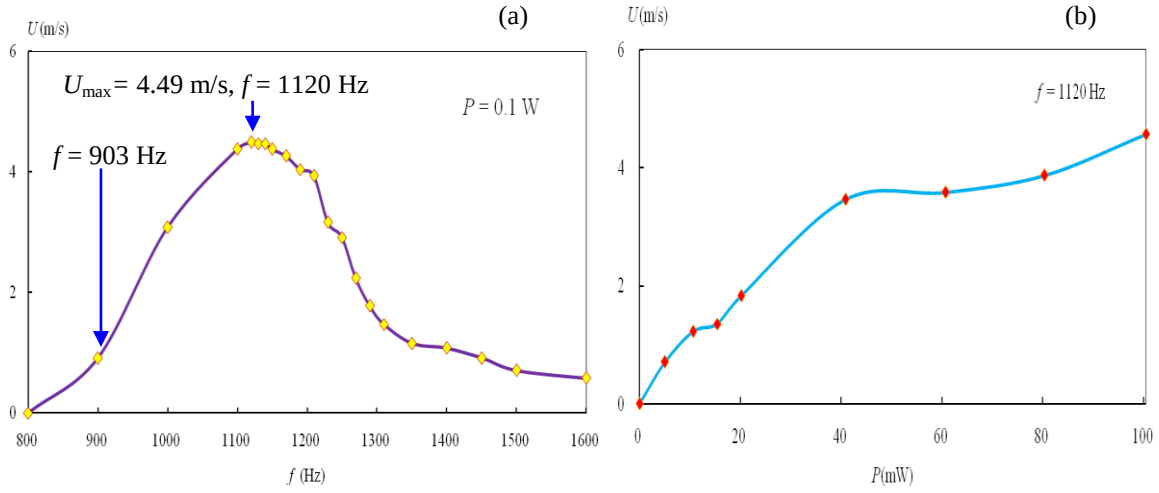


Figure 6: (a) Frequency characteristics of SJ at $P = 0.1$ W, (b) Power characteristics of SJ at $f = 1120$ Hz

3.5 Annular impinging jets with flow control, parameters of experiments

Experiments were performed in the range of nozzle-to-wall distance $H = 18$ – 25 mm, i.e., $H/D_o = 0.60$ – 0.83 and $Re \approx 5000$. The characteristics of the synthetic jets were kept constant at the driven frequency f of 1120 Hz and the real input powers P of (0, 27, 40, 60, 80 and 100) mW.

The typical results of the stagnation pressure measurement (case I) in the central point on the wall ($r = 0$) are shown in Fig. 7. Flow field patterns A and B correspond to higher and lower stagnation pressures, as labeled in Fig. 7. The vertical arrows represent the changes between patterns A and B. When the real input power is increased further to $P = 0$ – 100 mW, see at $P = 100$ mW there is no hysteresis loop. It means, the control SJs are enough powerful to suppress the hysteresis.

3.6 Effect of the synthetic jet magnitude

An influence of the control SJs was evaluated (case II) with various real input power of SJs ranging from 0 to 100 mW. The total pressure p_c (relative to the barometric pressure) was measured by the Pitot probe. Figure 8 shows that the peak value is 3.3 Pa at $P = 0$ (without SJ). The control effect of SJs causes a monotonic decrease of the maximum to 1.1 Pa at $P = 100$ mW. Note that the peak values of p_c are (3.4, 3.4, 2.8, 2.5, 1.8, and 1.1) Pa for (20, 27, 40, 60, 80, and 100) mW, respectively.

Figure 8 shows that the stepwise increase of the SJs power P causes that the reattachment point is moved downstream from $x/D_o = 0.5$ (at $P = 0$) to $x/D_o = 0.75$ at $P = 100$ mW.

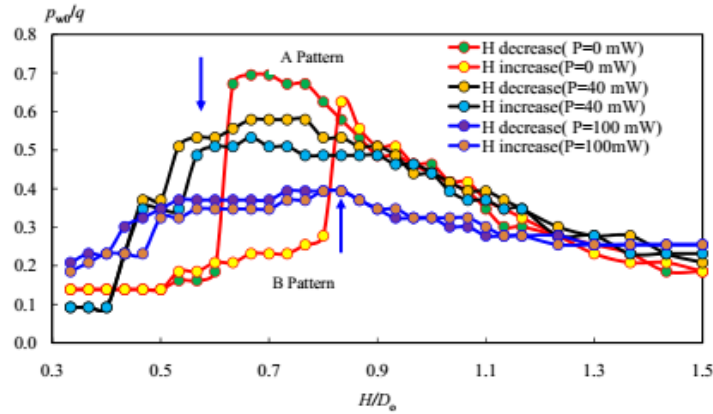


Figure 7: Effect of SJs on the occurrence of the hysteresis loop

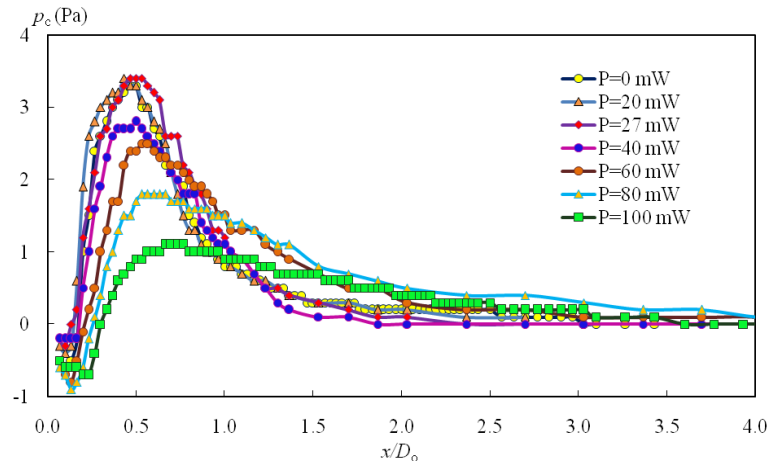


Figure 8: Effect of various control SJs on the main annular jet

Conclusions

An annular jet with and without flow control was studied experimentally. The jet without flow control was initially studied using techniques for measuring stagnation pressure on the impinging wall and the bistability and the hysteretic behavior were identified. Two different flow field patterns exist under the same boundary conditions. The pattern A is the small recirculation area (bubble) of separated flow located just downstream from the nozzle center body and the pattern B is the large recirculation area of separated flow reaches up to the impingement wall, on which there is a stagnation circle.

The investigated Reynolds numbers based on the annular slot were relatively low, $Re_b = 107\text{--}267$ (i.e., Re based on the outer diameter of the annular nozzle was $Re = 4000\text{--}10,000$). Therefore the laminar flow occurred at the annular nozzle exit and the jet flow was developed towards the transition to turbulence further downstream. The initiation of the transition process was promoted and triggered by pulsations of the control synthetic jets. The effect of the Reynolds number was evaluated: increasing Re from 4000 to 10,000 causes the hysteretic behavior to disappear completely. The viscous forces at lower Re ($Re < 9000$) are sufficient to preserve flow-field patterns even in the case of gradual changes of the nozzle-to-wall distance H , thus the hysteresis loop can occur. On the other hand, the inertial forces overcome viscous forces at higher Re ($Re > 9000$), thus the hysteresis loop cannot occur and the gradual changes of H cause nearly sudden switch between patterns A and B.

The power and frequency characteristics of control jets were reported. The used actuator is capable of creating a jet with a maximum velocity of 4.9 m/s at a frequency of approximately 1120 Hz. The effects of real input power ranging from 0 to 100 mW were evaluated. It was revealed that the control jets suppressed the hysteretic behavior, and switching between patterns A and B was reported.

Acknowledgments

We gratefully acknowledge the support of the Grant Agency of the Czech Republic—Czech Science Foundation (Project No. 21-26232J) and the institutional support RVO: 61388998.

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