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TRAPPED VORTEX RING

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Abstract: *Paper discusses an almost unknown and yet interesting operating principle of fluidic no-moving-part devices for flow control. The principle is based on the properties of vortex rings. A standing vortex ring is kept in a semi-toroidal recession positioned opposite to an annular nozzle from which issues an annular fluid jet. The ring can exist in the recession with two alternative senses of rotation so that the annular jet is led to either the central exit through the centre of the vortex, or to the outer space past the outer vortex circumference.*

Keywords: ***Fluidics, vortex ring, fluid flow control.***

1. Introduction

Fluid flow control valves are indispensable components in innumerable systems working with fluids. Their standard layouts with mechanical moving components are produced in large quantities. There are, however, situations in which the mechanical motions bring problems or disadvantages so that it is desirable to control the flow by phenomena taking place inside solid, constant-geometry cavities.

A typical situation is control of hot gas flows: the high temperature makes questionable the operation of bearings and sealing gaskets. A solution brings the little-known branch of fluidics, called "power fluidics" (Tesař 1983, 1998). A typical large-scale fluidic diverter is based on idea of deflection of a jet formed in a nozzle. The nozzle is usually of rectangular cross section and the generated jet is diverted by the action of small control flows acting on the main jet form one or other of its sides. A particular branch of these diverter valves operates in switching regime, with bistability (or monostability) achieved by the Coanda-

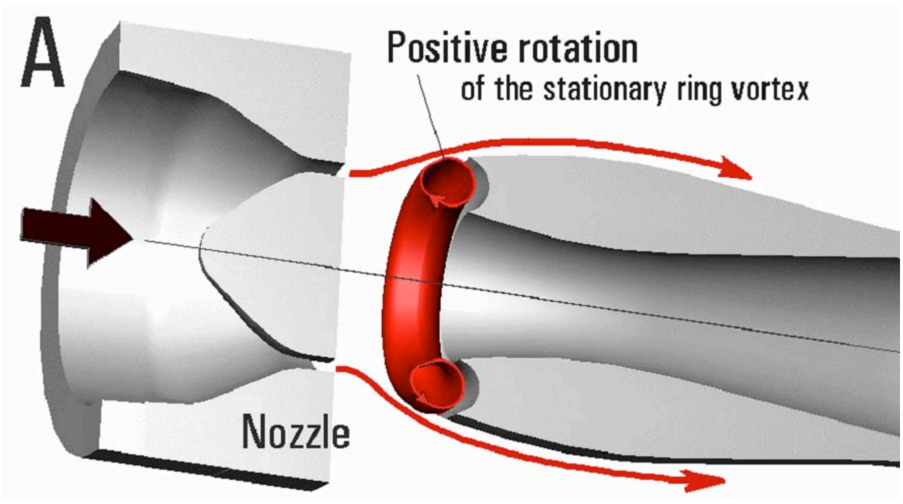

Fig. 1 The idea of flow control by the vortex ring trapped in the semi-toroidal recession. The annular jet impinges on the vortex which deflects is depending on the sense of the vortex ring poloidal rotation. Shown here is the positive rotation which causes the jet to move outside the annular body.

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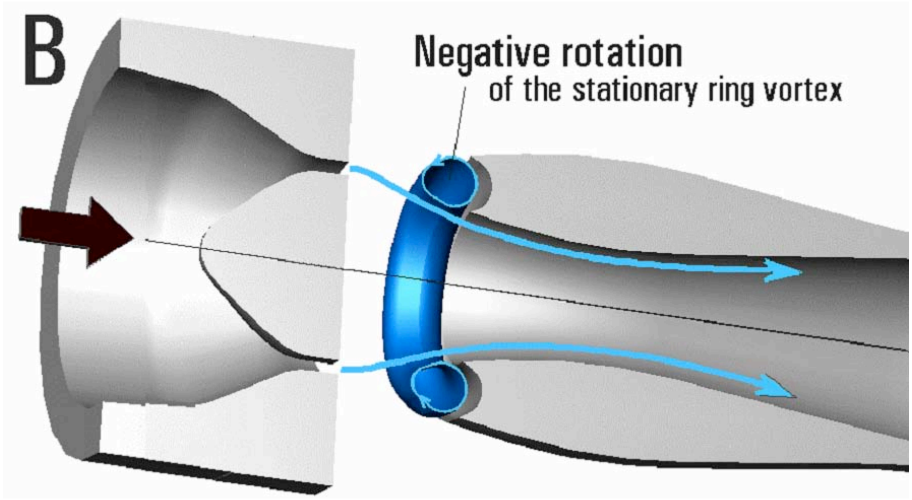


Fig. 2 The action of the negative poloidal rotation, which causes the impinging annular jet to move through the central hole inside the annular body. At the same time, the jet keeps the vortex ring in the rotation.

effect attachment of the jet to attachment walls. This approach was, e.g., applied to their high-temperature gas flow control valves by Pereira and Syred, 1983. The deflected gas flow is captured by a pair of collectors downstream from the deflection section. The collectors are shaped as diffusers in which the kinetic energy of the gas accelerated in the nozzle is re-converted back into the pressure rise (Tesař, 2009). The main disadvantage is the nozzle and even much more the small divergence angle diffusers occupy a considerable streamwise length and make the control valve difficult to stow in the often limited available space.

The fluidic flow control principle described here is an even less known idea. It is based on the special properties of vortex rings (Maxworthy, 1972) – particularly stable structures formed spontaneously in fluid flows. They are well known since antiquity since they can be easily blown from the mouth – and became well visible after the introduction of tobacco smoking.

In the fluidic flow control valves discussed here, a vortex ring is used in a role similar to that of the Coanda effect: it secures bistability — alternative existence of two different flow

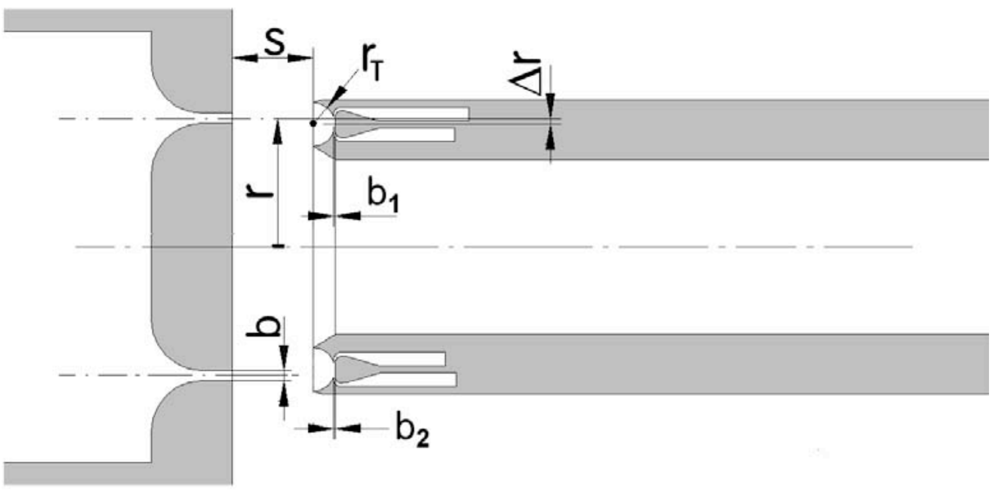


Fig. 3 The basic parameters of the model used in the feasibility tests. Note the difference Δr between the central radius r of the nozzle and the radial position of the centre C of the smallest circle on the torus that defines the geometry of the semi-toroidal recession.

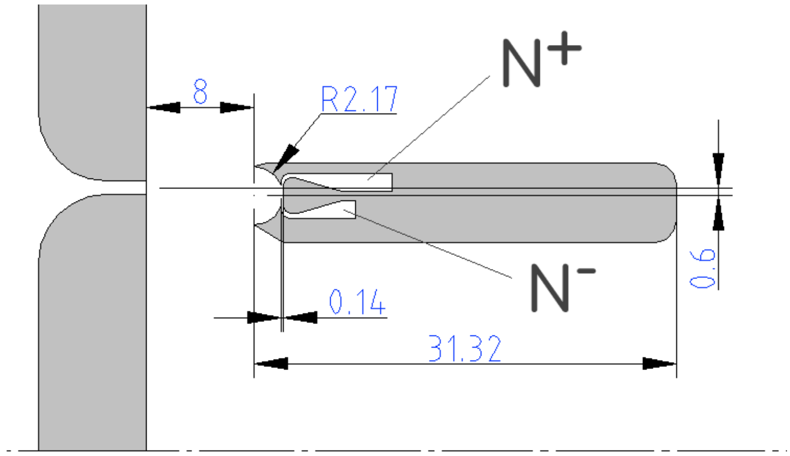


Fig. 4 Detail of the control nozzles and several dimensions (in millimetres) of the annular body used in the feasibility testing numerical flowfield computations. Bringing the control flow into one of the control nozzles N+ *or* N- *decides the sense of the poloidal rotation of the vortex ring. For example, a small control flow into* N+ *produces the positive rotation as shown in Fig. 1.*

regimes in spite of the same set of boundary conditions. The vortex ring is "trapped" - held stationary inside a semi-toroidal cavity. This idea of keeping a vortex in a semi-open cavity follows to a degree the unsuccessful Ringleb's idea (1961) of using stationary vortices (but not a vortex ring !) in a diffuser. This keeping in a semi-open recession prevents the ring from escaping by being shed and carried way with the flow. The two different stable regimes differ in the sense of the poloidal rotation of the vortex ring in its cavity. The incoming flow is in the form of an annular jet, produced by an annular nozzle. The nozzle is designed and positioned so that the jet it generated is directed against the semi-toroidal cavity, made in an annular body coaxial with the nozzle. When the jet leaves the annular nozzle, it collides with the vortex ring. Unable to continue in its original flow direction, the jet is deformed by the interaction with the ring and forced to divert as shown in the cases A and B presented in Figs. 1 and 2.

The sense of the poloidal rotation of the vortex ring presented in Fig. 1 is here described as ***positive***. Upon the interaction with the vortex ring the jet is directed outwards and flows past the outer surface of the annular body. It should be noted that when flowing tangentially around the vortex ring (and acting on it by the shear stress between them) the jet provides the energy that keeps the vortex ring in rotation.

On the other hand, the other sense of poloidal rotation of the vortex ring presented in Fig. 2 is described as ***negative*** (this naming is arbitrary). In this case the interaction of the annular jet with the vortex ring forces the jet to move inwards so that it flows into the central hole in the annular body. As in the case A, also in this case the jet when moving tangentially around the vortex ring keeps it in its rotation.

2. Flow control by stationary vortex ring

In flow control applications, of course, the space outside the annular body and its central hole lead to different locations in which the presence of the fluid flow is desirable. The setup will be provided with means for controlling the rotation direction of the vortex ring. There are several alternative possibilities achieving this control action. Perhaps the most obvious arrangement of this ring vortex control is the use of an auxiliary small control flow entering the semi-toroidal recession through nozzles directed tangentially to the poloidal motion. An

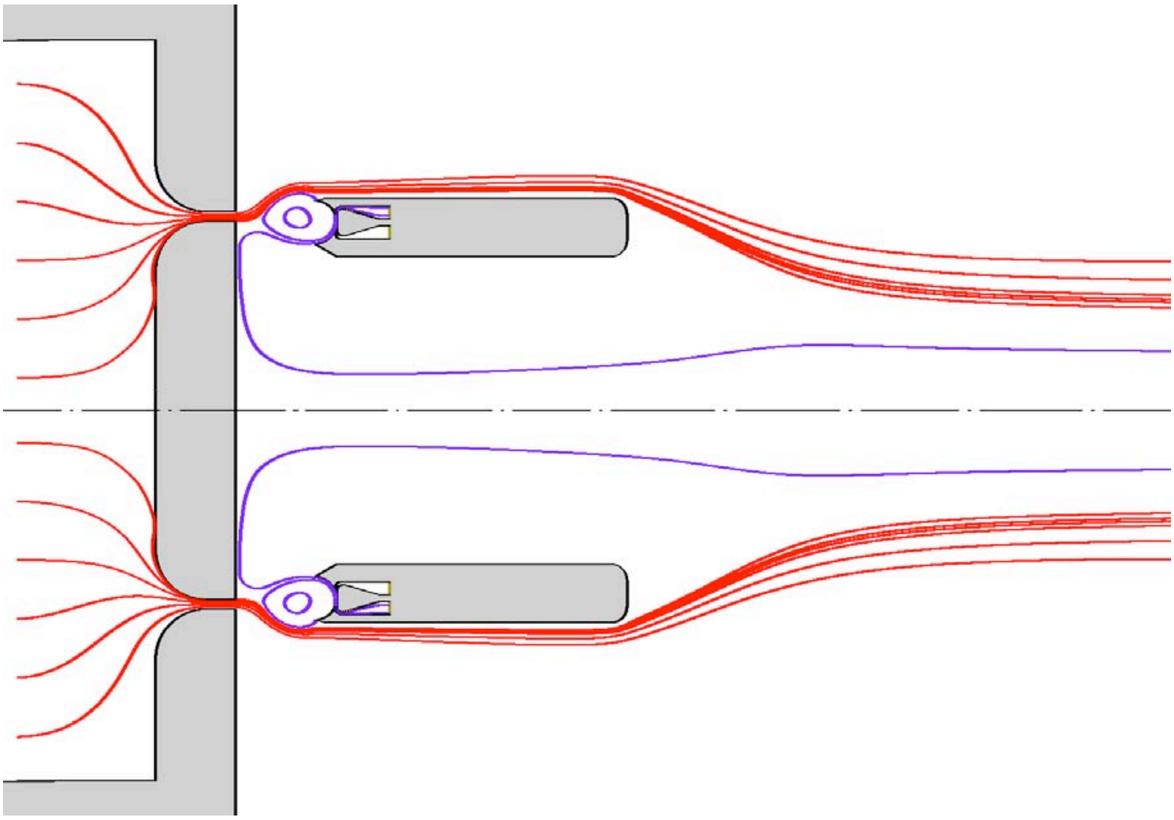


Fig. 5 Computed pathlines of the of the flow responding to a very small control flow fed into the positive control nozzle N$^+$. All the flow coming from the annular nozzle at left continues past the outer surface of the annular body . Only a very small percentage of the flow leaving the control nozzle (pathline coloured blue) here escapes through the central hole.

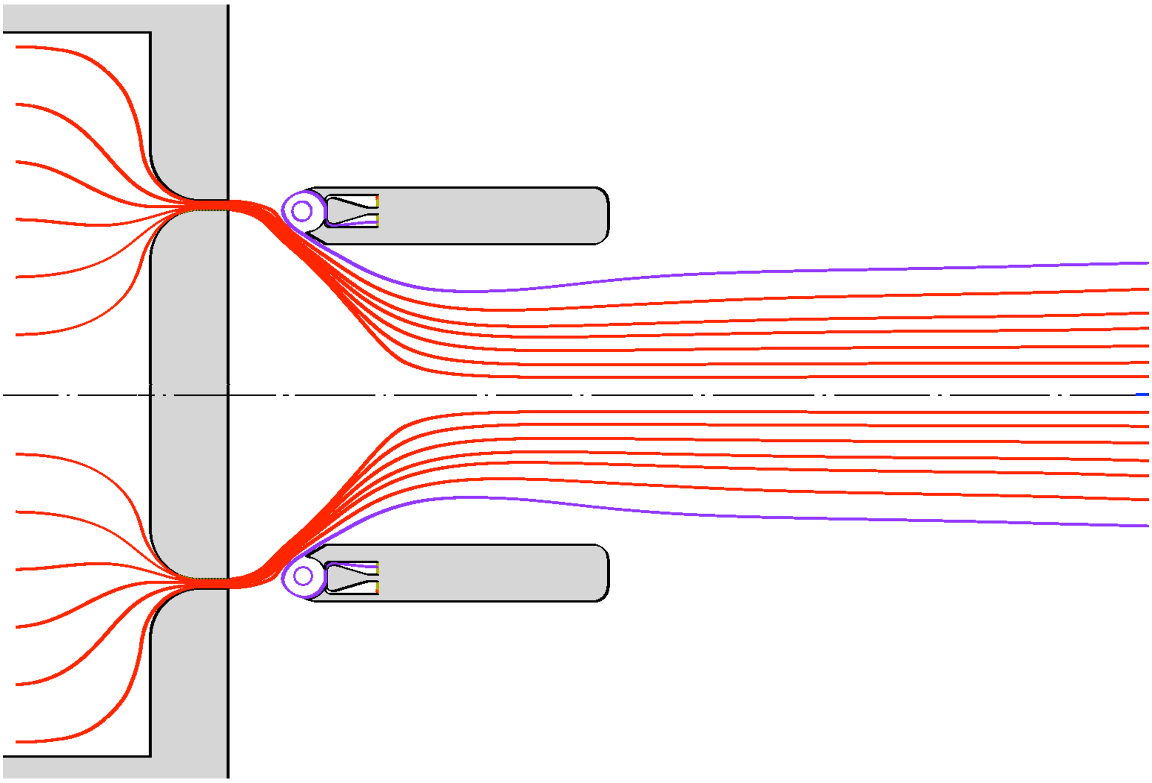


Fig. 6 Computed pathlines in the investigated device as it is formed in response to a very small control flow from the negative control nozzle N$^-$. All fluid flow passes through the central hole in the annular body.

example of such control nozzles — the positive nozzle N^+ and oppositely directed negative nozzle N^- is presented in Fig. 3 and Fig. 4.

The character of the two alternative flows described above may be considered an unsupported conjecture. To demonstrate the reality if the idea, the two alternative flows were evaluated in a series of extensive numerical flowfield computations. They were performed for the mathematical model the geometry of which is shown in the illustrations Fig. 3 and Fig. 4. The computational results are presented by means of evaluated pathlines in the following two illustration Figs. 5 and 6. The pathlines coloured red are those coming through the annular nozzle at left. There are also pathlines coloured blue – these are released alternatively through either one of the two control nozzles. Well discernible in these illustrations are the closed pathlines of the section through the vortex ring. The parameters (dimensions and velocity) correspond to a typical application considered: central radius r of the nozzle was 19.5 mm, the nozzle slit width was $b = 1$ mm, the distance $s = 8$ mm of the annular body from the nozzle body (Fig. 4). The radius of the semi-toroidal cavity in the annular body was $r_T = 2.17$ mm. Both control nozzles were of the same exit widths $b_1 = b_2 = 0.14$ mm.

It should be kept in mind that the entrainment into the annular jet decreases the internal pressure in the space inside the flow – so that even without the interaction with the vortex ring the annular jet flow has a tendency to approach the configuration shown in Fig. 6. As a result, if the radial position of the centre C (Fig. 3) of the poloidal motion were flush with the central radius r of the nozzle, the annular jet would be at the distance s at a smaller diameter than r and the outwards and inwards deflection of the jet would not be hydraulically symmetric. This is why the illustration in Fig. 3 emphasises the difference $\Delta r = 0.6$ mm.

The outer diameter of the annular body was 43.6 mm, its overall axial length 31.3 mm, and diameter of the central hole in this body was 31.8 mm. The computations presented in Figs. 5 and 6 were performed with the velocity of the flow from the annular nozzle $w = 19$ m/s. The fluid was air of kinematic viscosity $\nu = 14.61 .10^{-5}$ m^2/s, so that the Reynolds number of the flow in the annular nozzle exit was Re = 1 300.

3. An example of the valve

The following Figs. 7 and 8 present an example of the use of the discussed principle in a no-moving-part fluidic diverter valve. All that is necessary is providing an outer shell around the

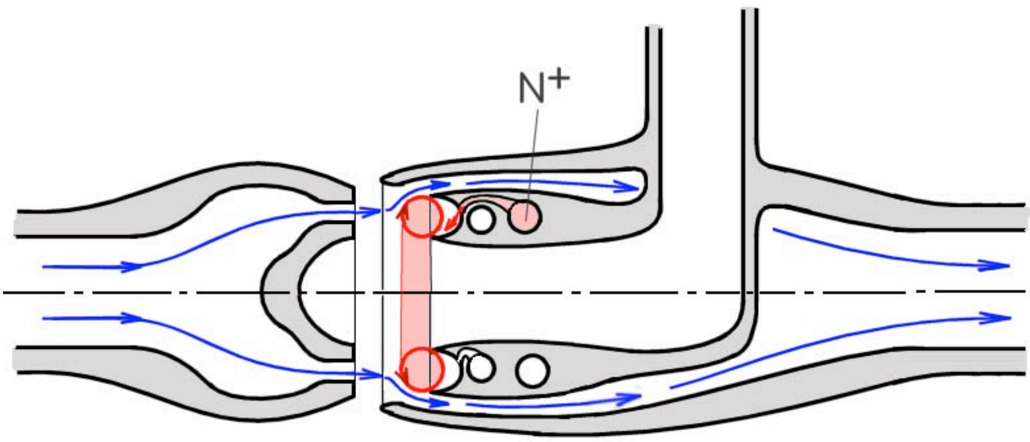


Fig. 7 Practical use of the controlled vortex ring mechanism in a no-moving-part fluidic diverter valve. This is a situation occurring in response to the a very small control flow from the positive control nozzle N^+. The fluid flow coming from left continues in the axial direction.

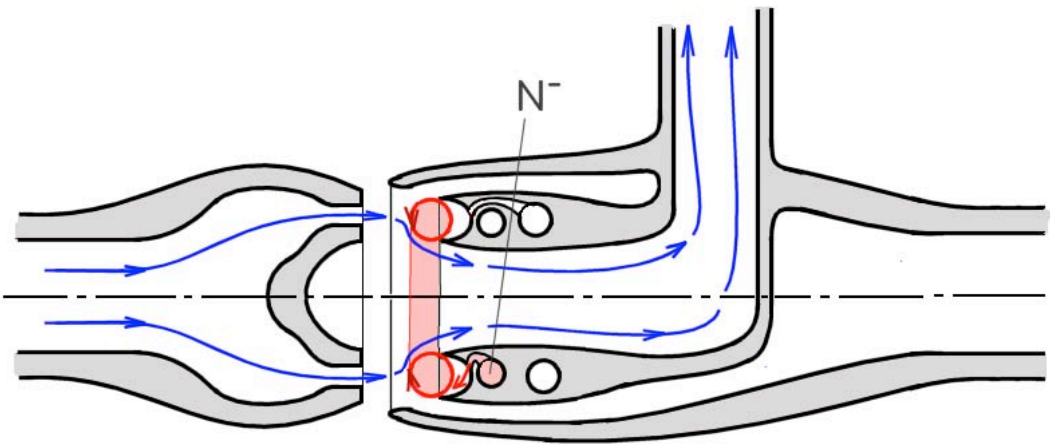
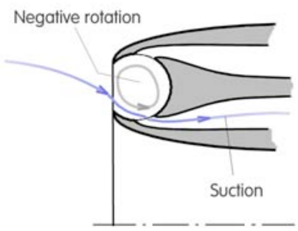


Fig. 8 The same no-moving-part fluidic diverter valve as above (in Fig. 9) in the situation that occurs in response to the a very small control flow from the negative control nozzle N⁻. The flow coming from left is diverted upwards. The control nozzles are not extended over the full 360 deg circumference of the semi-toroidal cavity, but each of them is divided into six parts mutually alternating with the nozzle slits of opposed polarity.

annular body to capture the jet flow moving across this region in its positive flow configuration (Fig. 1). Then there is to be also a different outlet as a continuation of the central hole in the annular body. In Fig. 7 there is an illustration of such a valve in the regime responding to a control flow issuing from the positive control nozzle N^+. The generated trapped vortex ring is coloured red. The fluid (lines coloured blue) supplied into the annular nozzle at the left-hand side of the picture leaves the valve on the right-hand side and continues in the original axial flow direction. The next Fig. 8 presents the flowfield in the case of the fluidic signal brought into the oppositely directed negative nozzle N^-. The oppositely rotating vortex ring forces the annular jet to enter the central hole in the body on the right-hand side. The hole is connected to the outlet that in this version leaves the valve vertically, at a right angle to the initial flow direction.

4. Alternative control by suction

In all configurations above discussed so far, the control of the vortex ring rotation was performed by a fluid outflow from the control nozzles. The two next illustrations, Figs. 9 and 10, demonstrate a different possibility: control by signals of the suction character. The basic principle is presented in Fig. 9. It shows the left-hand part of the annular body, with its semi-toroidal cavity for keeping in position the trapped vortex ring. The suction action is not so strong as the action of outflow from a nozzle, even at the same input power levels. It is therefore necessary for this control mode to arrange for the trapped vortex ring a considerably deeper, more closed cavity. This ensures the motion in the cavity is more influenced by the suction channels. These channels, as show in Fig. 9, are ended by orifices located near the rim of the semi-toroidal cavity. Suction applied into these orifices generates in the ring cavity a tangentially directed flow, indicated in the picture by a part of an air flowpath. This again acts on the fluid inside the cavity in a manner causing it to rotate. The next Fig. 10 demonstrates a result of a numerical flowfield computation, very similar to those examples presented above in Figs. 5 and 6, as a demonstration of feasibility of this control mode. The configuration differs from Fig. 6 only in the layout of the semi-toroidal recession and the suction orifices. The flowfield is in Fig. 10 also (as in Gig. 6) characterised by the computed pathlines. The consequences of the negative rotation of the vortex ring in Fig. 10 also has some resemblance



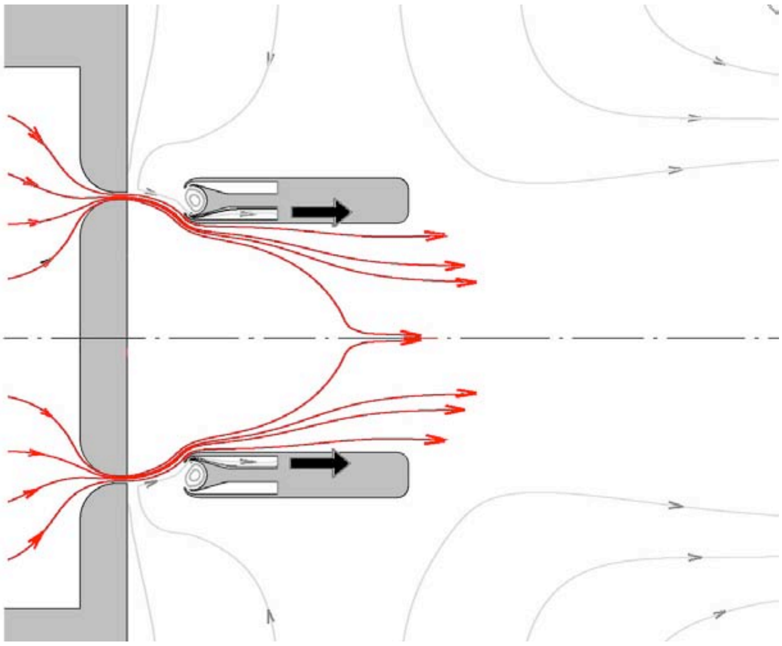


Fig. 9 (Left) *In principle, it is possible to generate rotation in the toroidal cavity by a suction signal – here producing a vortex ring with negative rotation.*

Fig. 10 (Right) A computed example of the flowfield generated in response to the suction signal, as shown in Fig. 9. All the flow coming through the annular nozzle leaves through the central hole in the annular body.

of the flow into the central hole in the annular body shown above in Fig. 6: the annular jet leaves the annular nozzle and by the interaction with the vortex ring is forced to pass through the central hole. Compared with acting on the vortex ring by flows issuing out from a nozzle, the suction is not very efficient mode of control, which is an obvious disadvantage. On the other hand, there may be situations where there is vacuum available for this control purpose and the efficiency question of the control action is not of primary importance.

5. An example of use

In the example of practical application of the discussed principle which is presented in the next Fig. 11, the trapped vortex ring secures an alternative cold or hot air flow resultant in the proper temperature and ventilation of a crew cabin. The heating is electrical: the air passes through the narrow channels between the coils of an electric heater. The configuration as shown in Fig. 11 closely resembles the geometry presented above in Fig. 3 and 4 . The main difference is the presence of the electric heating coil. This is positioned inside the central hole in the annular body.

In the regime of there being a (very small) control flow of air issuing from the positive control nozzle N^+, the air jet coming from the annular nozzle at left does not enter the central hole and thus by-passes the heating coil – as shown above in Fig. 5. The flow thus enters the cabin as a cold ventilation air. If, however, there is a control flow leaving the negative control nozzle N^- , then all supplied air is forced into the central hole in the annular body and is heated there. The temperature control was designed to operate in the pulse width modulation mode. The flow is permanently switched between the cold and hot regimes by the two flows generated in a fluidic oscillator (not shown here) with two output terminals. The oscillator is governed by a thermostat that causes an asymmetry of the switching: if it is necessary to heat

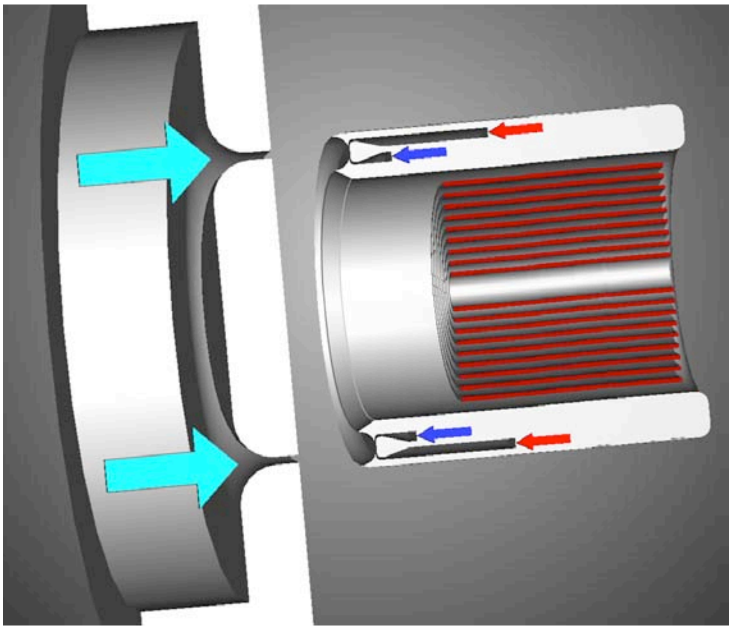


Fig. 11 *An example of application of the flow control principle with the trapped ring vortex. The electric heating coil inside the central hole of the annular body heats the air if the control flow is fed into the negative nozzle (blue colour). If the control flow is fed into the positive control nozzle (red colour), the air by-passes the heating.*

the cabin, the pulses into the negative control nozzle N^- last longer. Contrary to this, if the heating is needed less, then the flow pulses from the positive control nozzle N^+ are longer – they may dominate so that as a result most of the time the heater coil is by-passed.

5. Combined vortex ring and Coanda bistability (and monostability)

In his another practical use of the trapped vortex principle in a switched fluidic valve, the author combined the action on the annular jet by the vortex ring with another mechanism: the Coanda-effect attachment of the jet to adjacent walls. The geometry of the attachment was unusual: the annular jet was switched radially between two conical attachment walls (Tesař,

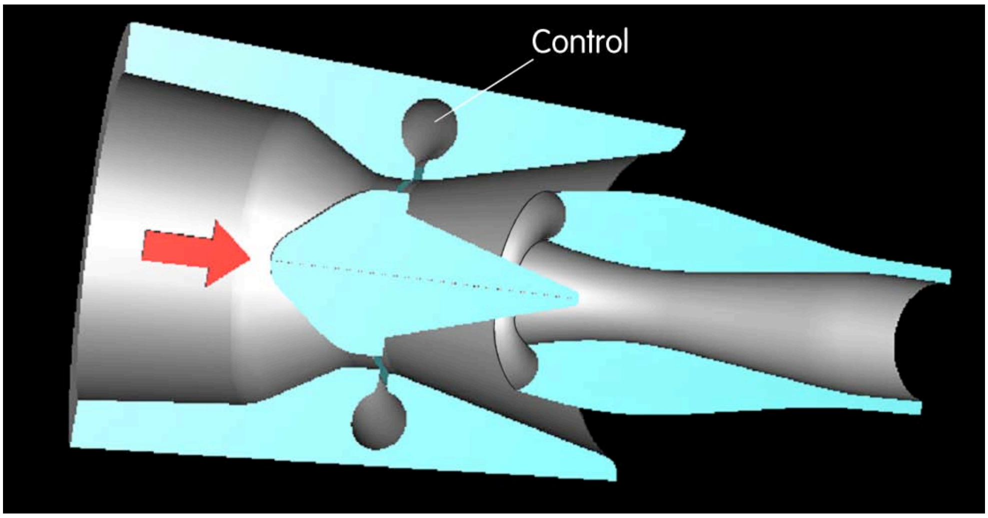


Fig. 12 *A flow control valve in which the trapped vortex ring principle is combined with the radial switching of an annular jet (Tesař, 1995) between the conical attachment walls, inner and outer one.*

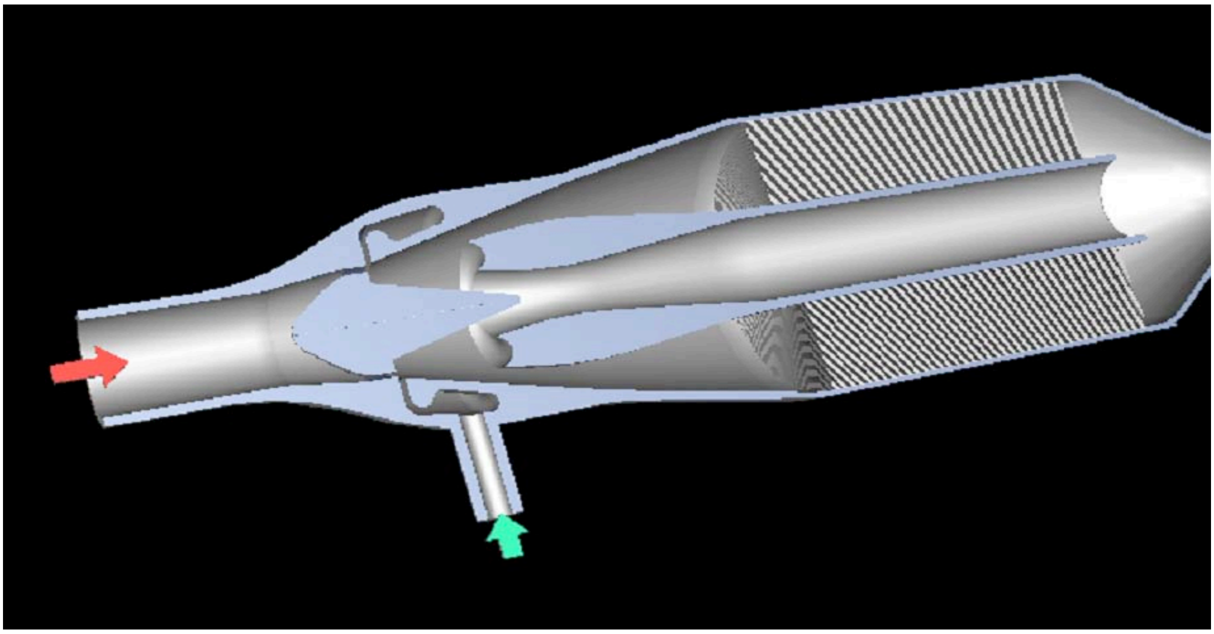


Fig. 13 The monostable flow control valve applied to the variable-configuration exhaust gas aftertreatment system developed by the author for Volkswagen A.G. (Tesař et al., 1996).

1995). The crucial parts of the valve are presented in Fig. 12. The layout was monostable: the valve remained in one of its two regimes as long as there was no control air flow signal. This regime was present for most of the time. Only exceptionally the regime was changed into the other one by an incoming signal.

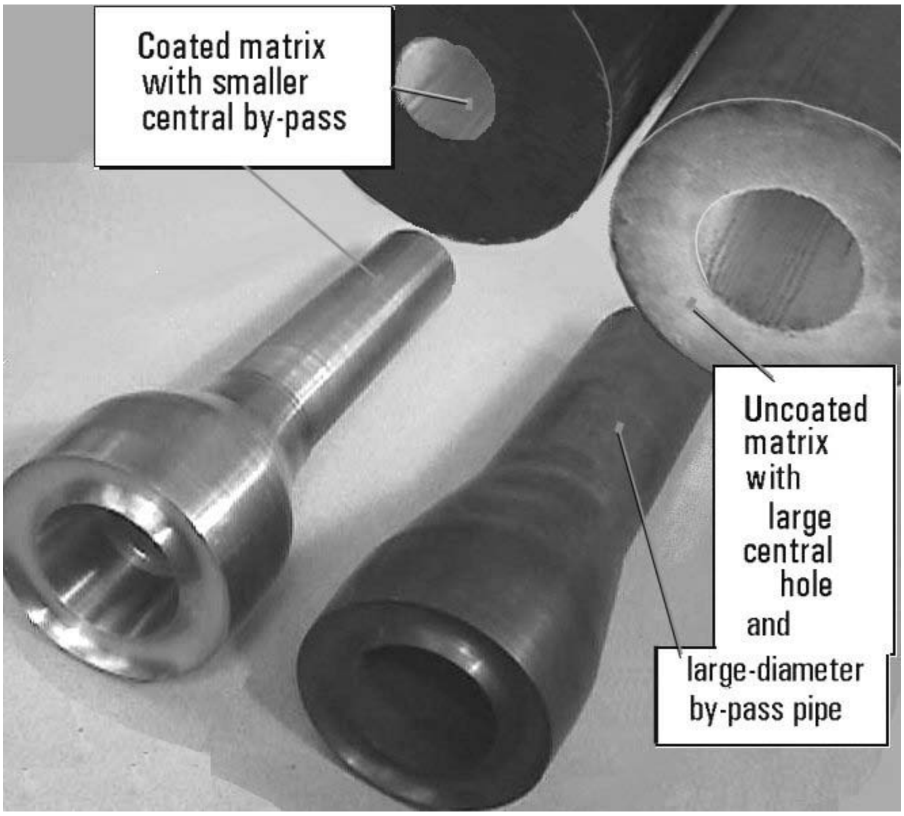


Fig. 14 Photograph of parts of disassembled test models used in laboratory investigations of the system shown in Fig. 13. The two alternative annular bodies have different size of the smallest circle on the torus that defines the geometry of the semi-toroidal recession.

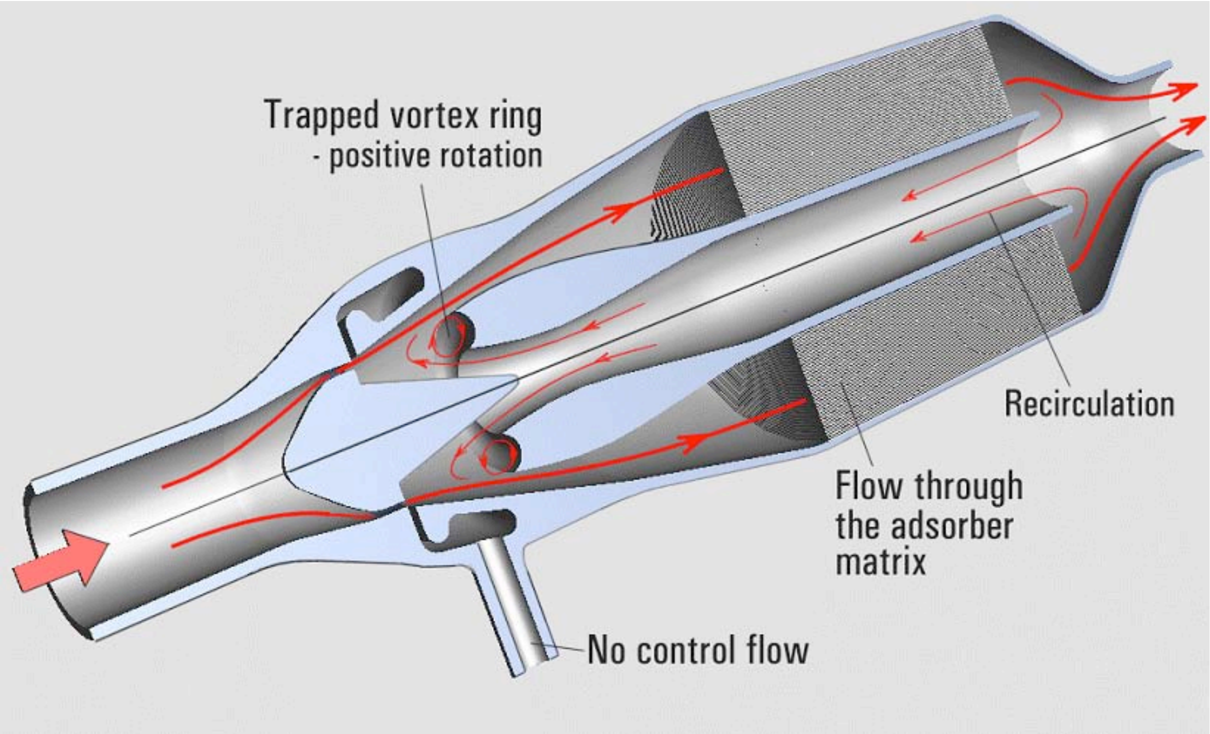


Fig. 15 The aftertreatment system in the basic flow regime without control flow signal: exhaust gas passes through the catalytic reactor matrix.

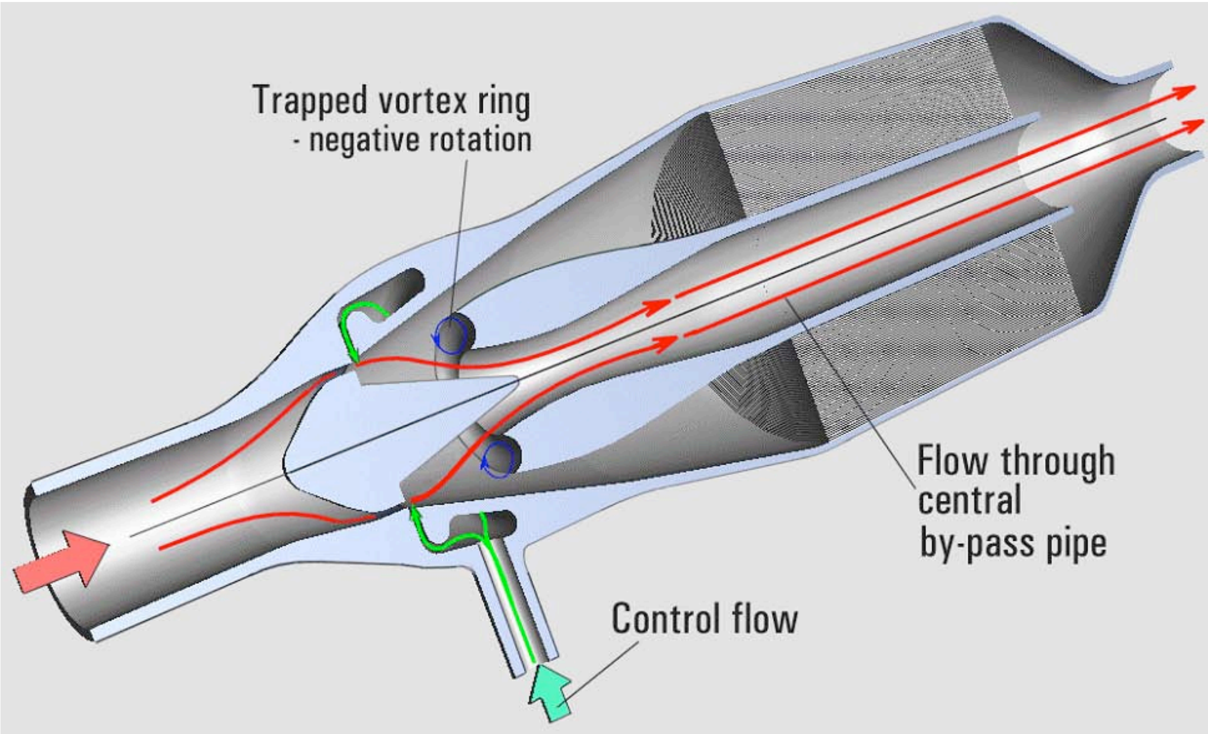


Fig. 16 The same aftertreatment system as in previous Fig. 16: in response to the small air control flow the exhaust gas flow is switched into the by-pass pipe.

It is apparent from Fig. 12 that the outer, hollow conical attachment wall dominates. The attachment to the small central cone is much less stable – and this was accentuated by the outer large concave cone wall being a flush continuation of the outer lip of the annular nozzle — while the surface of the inner small cone was separated from the nozzle inner lip by a large setback. This asymmetry of attachment was used in securing the monostable character of the valve. The valve was built – Fig. 13 — as an integral part in the upstream end of the body of an automobile catalytic converter for an aftertreatment processing of engine exhaust gas. The catalyst requested temporary by-passing of the gas flow in a layout the important requirement of which was spatial compactness. The photograph in Fig. 14 is here included as a demonstration that the valve was actually built and tested (for a car manufacturer customer in Germany). The last two illustrations – Figs. 15 and 15 provide an explanation of the operation in the two regimes.

The main factor in this application was the spatial compactness (available space in an engine compartment of contemporary car is scarce), resistance to extremely high temperatures (the valve can operate while actually glowing hot above 700 °C), and robustness securing long-time life without maintenance.

6. Conclusions

This contribution aims at spreading the knowledge of an interesting flow control principle that may find application in fluid flow control by fluidic valves without moving components. It is practically unknown despite its offering several interesting application opportunities.

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