

VALVES WITH FLOW CONTROL BY SYNTHETIC JETS

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Abstract: *Synthetic jets are currently in the focus of attention as means for flow control in external aerodynamics. Less known and studied is their use in internal aerodynamics, where several existing papers discussed separation control in diffusers. The subject of this paper, however, is a completely new idea — using the synthetic jet in flow control valves having no moving components. The valve considered would operate as a bistable diverter: by the action of the synthetic jet, the controlled fluid is deflected into one of available two flowpaths. A preliminary experiment performed with an axisymmetric valve version demonstrated viability of the idea.*

1. INTRODUCTION

Characteristic feature of present-day fluid mechanics is shifting the emphasis of analysed problems. Earlier, the efforts were directed towards understanding the fluid flows. Today, the task is increasingly often to control the flow and change its properties. Another characteristic aspect of the development is a change in the means by which the control action is applied. Traditionally, the flow control was made by mechanical actuators, usually inserted into the flow – such as various flaps or agitators. Recently, preference is typically given – because of lower price, higher reliability, long lifetime, and robustness with which the actuator device withstand adverse conditions – to actuators acting on the controlled boundary layer by fluid jets. Available comparisons show unequivocal effectiveness advantage of periodic jets over their steady counterparts and this development towards higher unsteady component of the jet flow has resulted in the recent interest concentrating on the case of synthetic jets [2], with the purely alternating nozzle flow – i.e. zero time-mean flow component, Fig. 1. The idea is not altogether new. In association, e.g., with the attempts at power transfer by alternating flow it was found possible to perform the rectification of the alternating flow into the steady output by the innate nonlinear properties of jet flows [3]. It is this rectification effect that produces the synthetic jet (in the sense of being synthesized from the individual vortex ring generated at each outflow part of the period) as a flow applicable for the action suppressing boundary layer separation or control transition into turbulence [1, 4] or perhaps even decrease turbulent friction drag by suppressing the hairpin vortices in turbulence. Nevertheless, the real impetus behind the current popularity of the studies of synthetic jets was by the work of Professor Glezer as discussed in [2].

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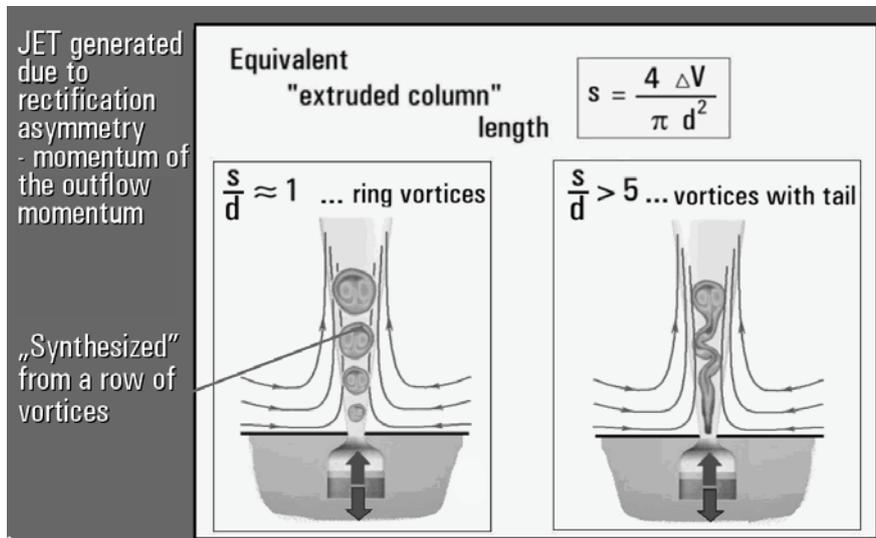


Figure 1: Schematic representation of synthetic jets issuing into stagnant fluid. The system of ring vortices moves away from the nozzle (and carries with it entrained outer fluid) because of the inflow and outflow asymmetry: the outflow carries away more momentum than the subsequent inflow in the suction phase.

Overwhelming proportion of the synthetic jet investigations nowadays are aiming at their use for boundary layer control in external aerodynamics. Less known and incomparably less studied is the use in internal aerodynamics. Several existing papers (such as, e.g., [5]) discussed control of flow separation in diffusers. The present paper also aims at the use of synthetic jets in internal aerodynamics, but this use is based on a completely new idea — for control of fluid flows in diverter valves having no moving components.

2. SEPARATION CONTROL IN A DIVERTER VALVE

The absence of moving components – apart from those in the actuator generating the synthetic jet (if such components are necessary; there are actuator principles not needing them) – brings a considerable number of advantages. The valve life may be practically unlimited as there is no danger of the moving components becoming worn or stuck. There is no need of maintenance, otherwise necessary for replacing worn gaskets or seals. With proper design of the actuator – which does not need passing the mechanical motion through the valve walls – there may be no danger of leakages. The proposed valves, in general, may be lighter and easier to manufacture.

These advantages, after all, are those associated with the no-moving-part fluidics, as discussed, e.g., in ref. [1]. In fact, the proposed valves have very much in common with typical jet-type fluidic diverter valves – the bistable and monostable ones based on the attachment of a fluid jet to a wall by the Coanda effect [1]. The difference is in the mode of control. In standard fluidic valves with the main jet, formed from the fluid entering through the supply terminal and attaching to a wall, is switched by a control action of a steady, usually substantially weaker, control jet issuing from the control

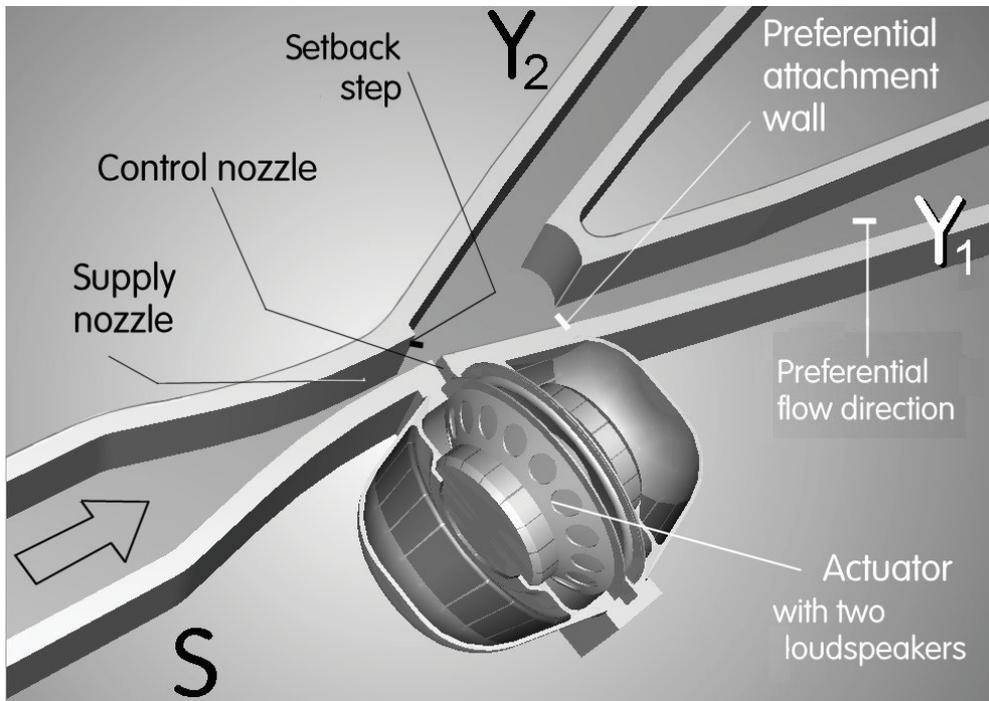


Figure 2: The basic idea of this paper: the powerful flow from S is controlled by the alternating flow generated in the actuator and issuing as synthetic jet from the control nozzle. The main flow attaches by the Coanda effect, if no synthetic jet is generated, to the preferential attachment wall. This guides the fluid into the output Y_1 . The action of the synthetic jet then eliminates the attachment and sends the main flow into the other output Y_2 .

nozzle. This control jet causes separation of the main flow from the attachment wall, associated with the change of the main flow direction towards another output terminal. As shown in Fig. 2, in the newly proposed valves controlled by the synthetic jet, the steady flow from the control nozzle is replaced by the alternating inflow and outflow generated by the actuator. The actuators are the same as those used in the external aerodynamics applications. In the example presented in Fig. 2 there is a large-scale valve its actuator representing a typical layout used by investigators in an aerodynamic laboratory. The essential component of this actuator is a standard mass produced low-cost loudspeaker – in fact there are two loudspeakers operating in unison shown in Fig. 2, the intention being to obtain a higher control power level. The conventional loudspeakers are cheap, but may be not a really good solution for the real life applications, since their conversion efficiency, typically at 50%, is rather poor. Their essential component - the diaphragm - is made from rather frail material with limited mechanical stability. Also, loudspeakers are designed for good linearity and a defined electrical impedance to preserve sound quality over a large frequency range - while the use in an actuator would call for a fixed frequency device that can tolerate non-sinusoidal waveforms and achieving high efficiency. The other common choice, a piezoelectric

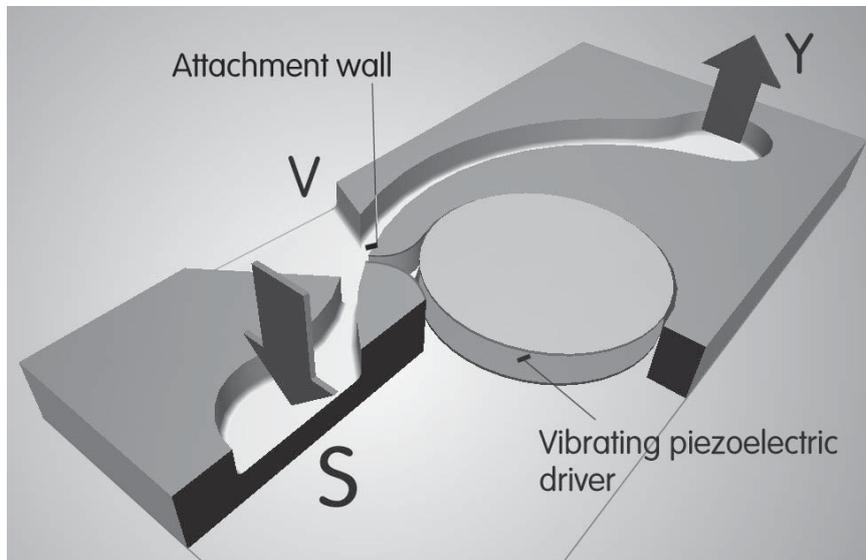


Figure 3: A variant of the same idea as shown in Fig. 2, here applied at a small, microfluidic scale. The loudspeaker actuator of Fig. 2 is here replaced by the piezoelectric driver. The Coanda effect attachment guides the fluid supplied through S into the output Y. If the synthetic jet is generated, it eliminates the attachment and sends the main jet into the vent V.

transducer, is suitable for small power levels and is similarly produced to suit other applications. Nevertheless, these are problems typical for all synthetic jet actuators and are not specific to the valves discussed here.

The valve presented in Fig. 2 is intended for applications in which the fluid flow supplied into the supply terminal S is required for the majority of operation time to pass into the valve output terminal Y_1 - and only occasionally is to be switched into the other output terminal Y_2 . To suit this requirement, this valve is designed as monostable. This means it remains, without control action, in only one stable state - the one leading the fluid flow into output terminal Y_1 . This is achieved by asymmetric valve design. The preferential attachment wall, to which the flow from S always attaches if the actuator is switched off, is a direct continuation of one of the lips of the supply nozzle exit. There is also an attachment wall on the other side of the interaction cavity, but this is separated from the supply nozzle exit by the setback step. Also - even though this may be not well recognisable in Fig. 2 - this other, secondary attachment wall is oriented at a larger angle relative to the axis of the supply nozzle. The fluid flow leaving the supply nozzle therefore attaches to this secondary attachment wall only if the synthetic jet issuing from the control nozzle prevents its attaching to the preferential wall.

Another alternative variant of the proposed fluid flow control valves is presented in the next Fig. 3. This is a valve made at a much smaller scale, typical for microfluidics [1]. As is usual in microfluidics, this valve was made by photoetching in one face of a plate. In microfluidic systems, such a valve would be typically made not separately, but together in the same etching process with other microfluidic devices collaborating with this valve. On the top, all the cavities made by etching are covered with flat cover plate, which is not seen in Fig. 3. There is only one output

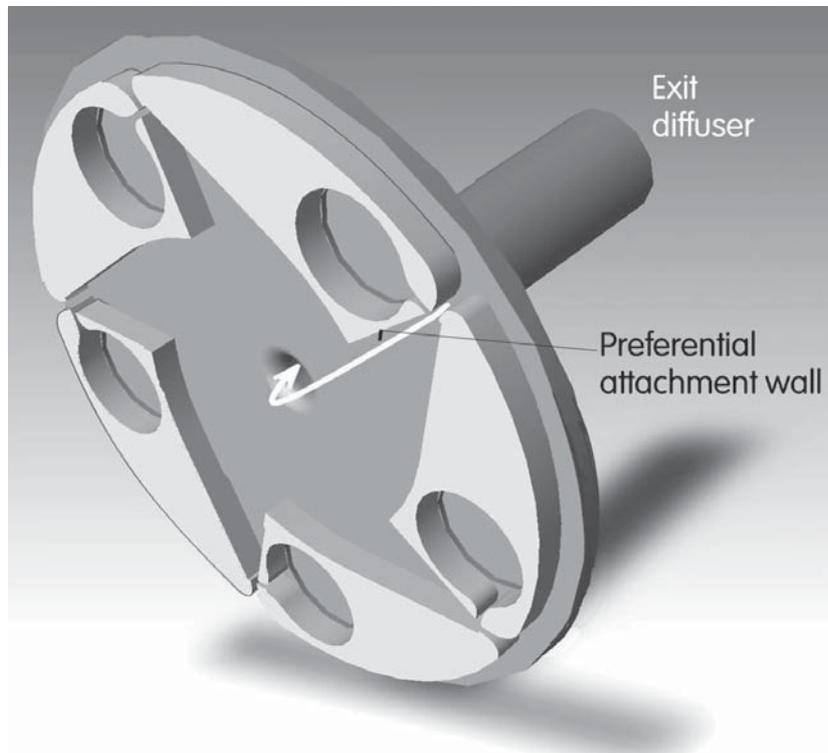


Figure 4: Five monostable diverters corresponding to the one in Fig. 3 are here distributed on the periphery of the vortex chamber. The white flowline shows the flow in one diverter. In the absence of the control signal the preferential attachment wall guides this flow into the central exit from the vortex chamber.

terminal Y to which the flow entering the supply terminal S flow is the actuator is not activated. The actuator in this example is a piezoelectric driver of round shape, inserted in the equally round cavity formed by etching in the plate. If this actuator is activated by an electric alternating current signal, it generates a synthetic jet that causes separation of the main flow from the attachment wall and its diversion into the vent V (from which the fluid, it is air, is damped the atmosphere; otherwise it leaves into the common exit from all valves).

The diverter control mode (or perhaps the control by termination of the flow by dumping it, as in Fig. 3) may be not what is exactly needed in some applications. Instead, a turning down of the flow may be required instead. In fluidics, this decrease of the flow rate (although not a complete stopping of the flow) is achieved in a vortex valve. This is a device based on the flow being opposed by a centrifugal force arising if the fluid is made to rotate in a chamber with central exit. The solution described in [7] is actually a quite old idea, already presented in ref. [8]. It consists of the vortex chamber provided with a diverter at its circumference, its output terminals adjusted so that when passing through one of them the fluid is directed towards the exit in the vortex chamber centre – while the outer terminal directs the fluid into the chamber tangentially. An example is presented in Figs. 4 and 5, which show the two operating regimes – the OPEN regime ,with small overall dissipation [1], in Fig. 4 and the CLOSED regime, with higher dissipation and therefore smaller flow rate, in Fig. 5. There are, in this example, actually five small diverter

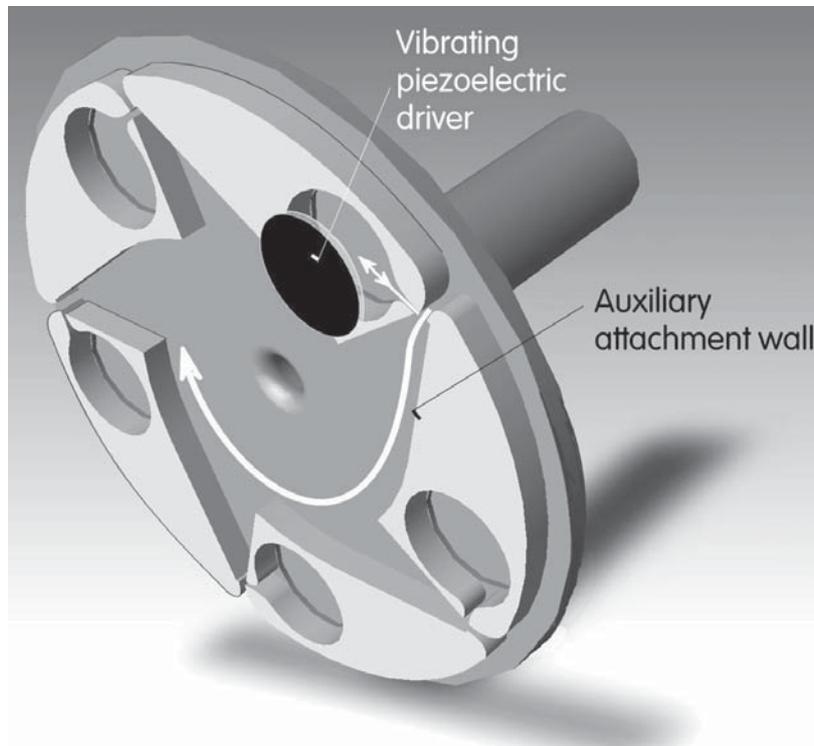


Figure 5: The same device as presented above in Fig. 4 is here shown if the piezoelectric drivers (only one of them is shown here) generate the synthetic jet. This deflects the flow towards the auxiliary attachment wall so that it enters the vortex chamber in tangential direction. As the rotating flow progresses towards the central exit, its rotation speed increases – and, as a result, centrifugal force is generated which opposes the fluid flow.

valves on the perimeter of the vortex chamber. This is preferable because of the achieved symmetry of the flow in the vortex chamber. This improves vortex chamber efficiency. As usual in vortex valves, the valve in Figs. 4 and 4 is provided with an exit diffuser. It decreases the overall dissipation in the OPEN regime while it makes possible a small diameter of the chamber exit, which (in relation to the outer diameter of the chamber) is of decisive importance for effective turning down in the CLOSED regime.

3. BISTABLE VALVES

Apart from the monostable valves discussed above, there is a useful wide field of applications also for valves which in the absence of a control signal may remain, in a stable manner, in either one of two regimes. Their appearance does not differ dramatically from the monostable versions, as may be seen from the example presented in the next Fig. 6. The characteristic feature are two attachment walls, located symmetrically with respect to the supply nozzle axis, also, there are two control nozzles and the associated two actuators generating alternatively a synthetic jet by the alternating flow in and out from one of the control nozzles. Of course, also the bistable

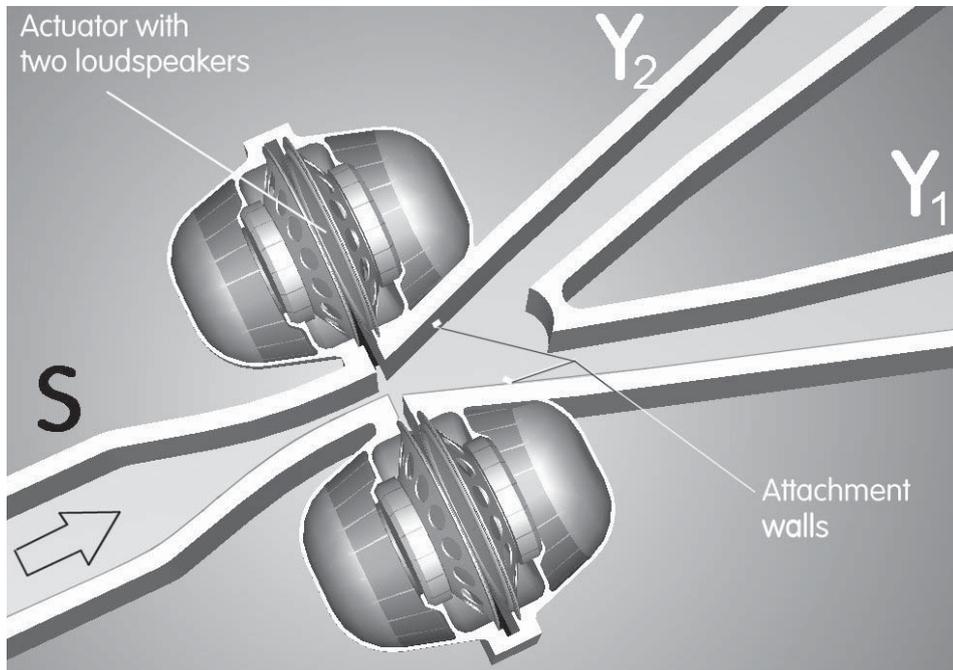


Figure 6: The diverter valves shown in previous Figs. 2 to 4 were monostable: in the absence of the synthetic jet control action the flow prefers one direction. Here is shown the symmetric bistable alternative: in the absence of control signal the fluid can enter either one of the two output terminals Y_1 and Y_2 . Two actuators are therefore necessary to switch the flow from one attachment wall to the opposite one.

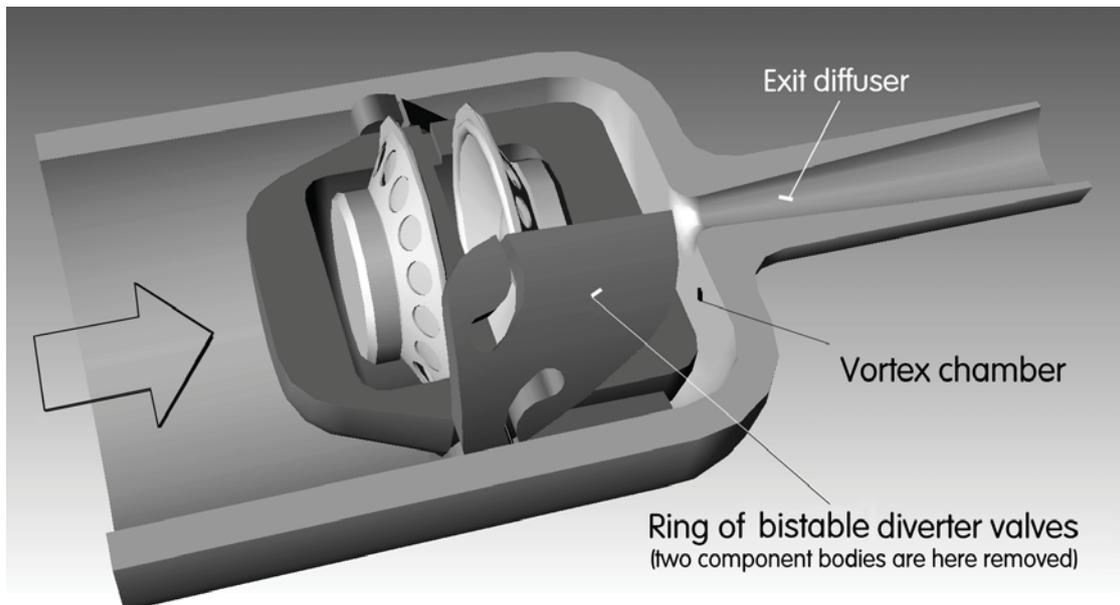


Figure 7: An example of the proposed use of synthetic-jet controlled bistable valves in the combination with the turning-down vortex valve. There are two loudspeaker actuators generating the alternative switching signals for control of the diverters positioned into a ring as presented in Figs. 8 and 9.

diverters may be used in the flow switching role at the perimeter of a vortex chamber so that the aggregate forms a bistable turn-down valve as discussed in ref.[8] - where there is also a useful discussion about the mutual matching of the two basic components of this aggregate, necessary for achieving the optimum performance. In the example presented in Fig. 7, again with several (in this case six) diverter valves operating in parallel, presented the diverters are controlled by the centrally located actuators (here again each provided with standard loudspeaker). To obtain a large outer diameter of the vortex chamber without an excessive overall size of the aggregate, the valves are here arranged in a ring-shaped configuration. This ring, shown in Fig. 8, may seem to be rather strangely shaped and it may be therefore useful to follow the explanation of this shaping in Fig. 9. It should be noted that the axes "a" of the supply nozzles (Fig. 9) are inclined with respect to the axis of the vortex chamber, so that the attachment walls "n" can lead the attached flow into the vortex chamber radially while the other set of six attachment walls "m" lead the flows into the chamber tangentially.

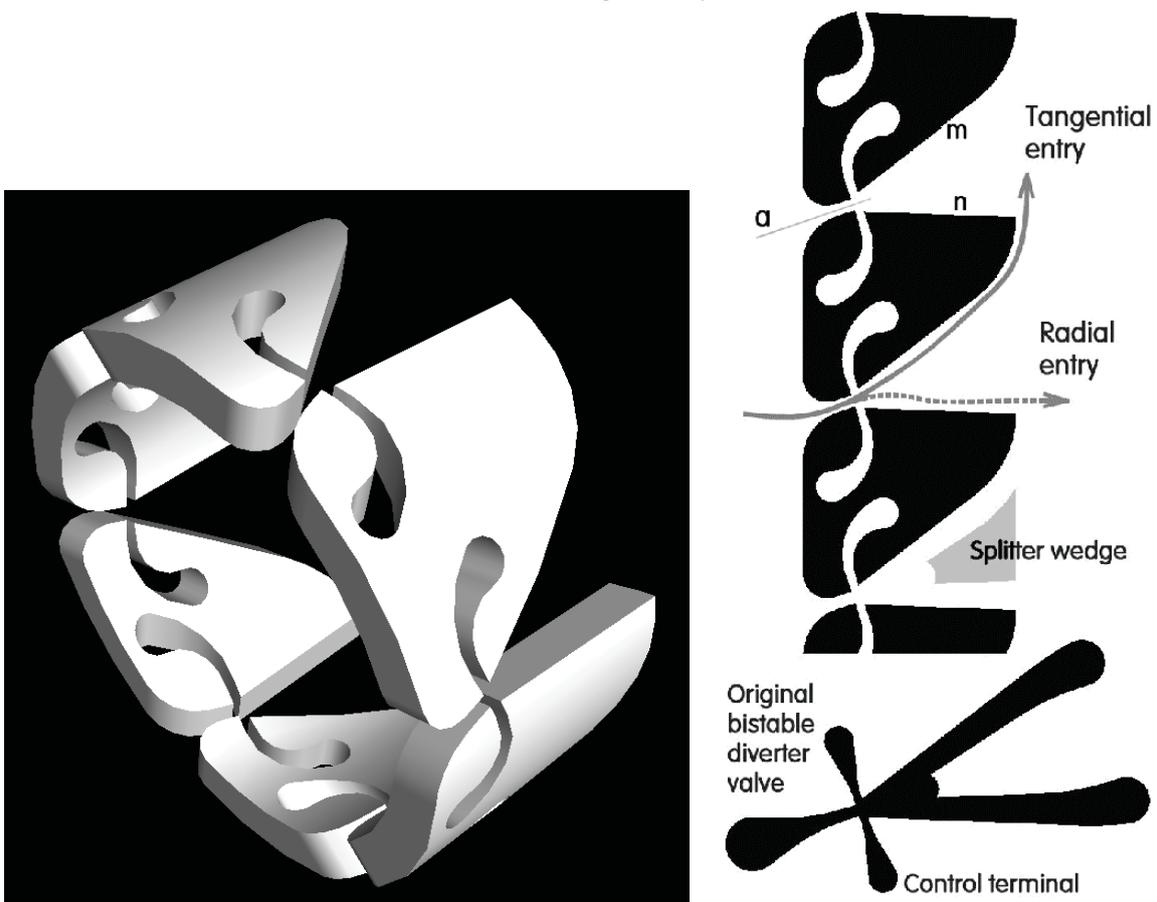


Figure 8: (Left) Detail of the ring from previous Fig. 7. It consists of six bodies with the gaps between them operating as switched bistable valves.

Figure 9: (Right) Explanation of the shape of the bodies shown in Fig. 8. The starting point is shown below: in is a standard geometry of a fluidic bistable amplifier (cf. Fig. 6). Shown above it this geometry is repeated with common supply terminals and common output exits – from [9].

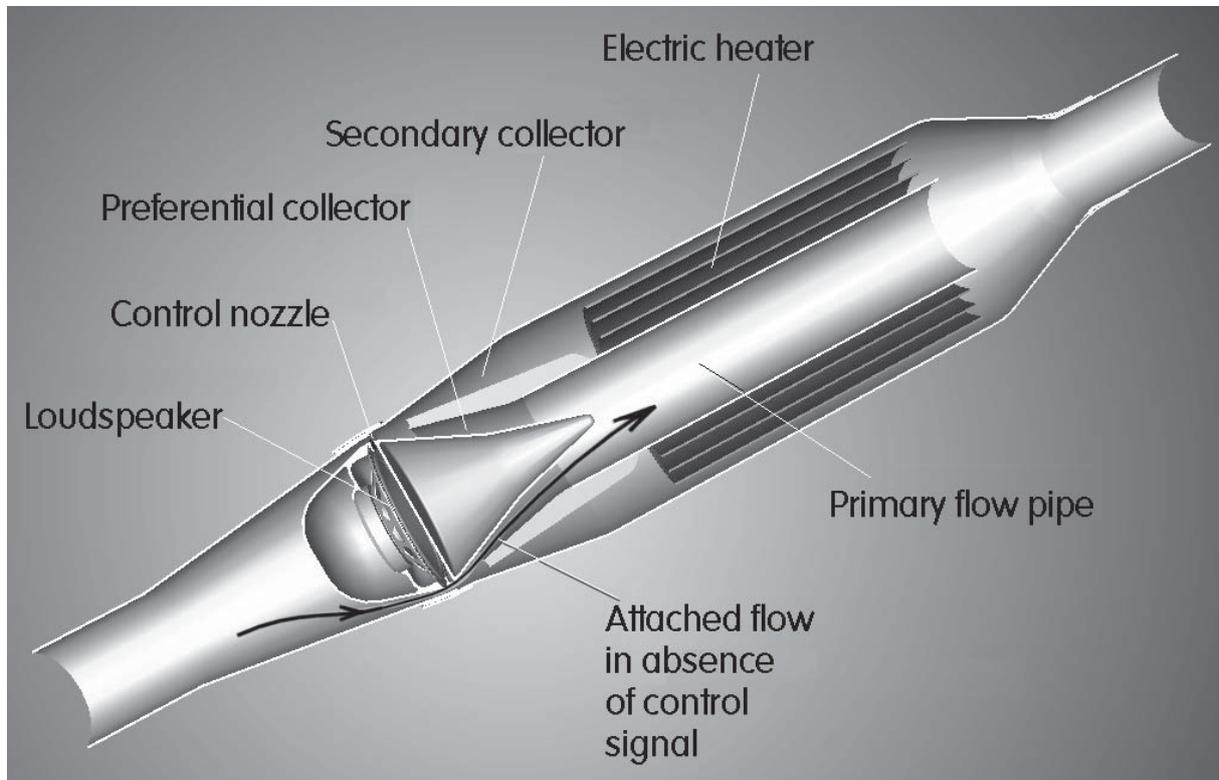


Figure 10: Yet another alternative use of the new idea: here the synthetic jet issuing from the control nozzle radially switches the annular main flow into the electric heater.

4. RADIALLY SWITCHED JETS

Even though some versions of the discussed valves may be made (as was the case of Fig. 3) at a size so small as to make them useful in microfluidics [1], it is apparent from the above discussion that the main applications of the discussed idea is expected to be found in large-scale valves of power fluidics. After all, their operation is based on the use of the Coanda effect and this is known to be not strong enough at small Reynolds numbers, below about $Re = 1\,000$. An unpleasant feature of the large valves - as those shown in Figs. 2 and 6 - is they are unwieldy and tend to occupy disproportionate space. Especially their long diffusers (necessary for obtaining reasonable pressure recovery, [10]) protruding from the central part at inconvenient angles are difficult to stow in limited spaces that are often available for the valves.

The search for compact configurations of large valves resulted in the layouts with radial switching of an annular main flow. As shown in Fig. 10, this is a particularly happy solution for the situations encountered rather often, in which one of the valve output terminals leads into a by-pass pipe, discontinuing the fluid flow through some device connected to the other output. In the example of the radially switched valve, presented in Fig. 10, the fluid is allowed for some period of time to increase its temperature in the annular heater - which for the rest of the time it by-passes through the central pipe. The

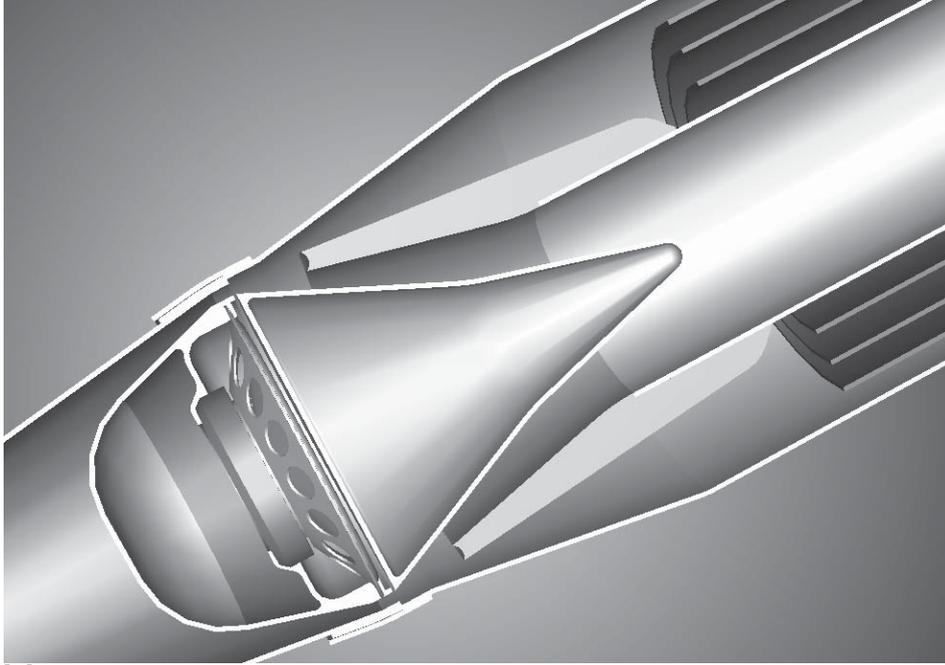


Figure 11: Detail of the radially switched valve shown in the previous Fig. 10. The loudspeaker type actuator is positioned inside the hollow central body, shaped so that the main annular jet attaches to its outer surface and – in the absence of the control signal – guides the flow into the central by-pass pipe.

annular flow is created in the ring-shaped slot between the outer skin of the heater and an inserted central body (seen in detail in Fig. 11), which houses the loudspeaker actuator. This generates a radial synthetic jet in the narrow, radially directed slit that serves as the control nozzle. The central body is shaped to form the preferential conical attachment wall. In the monostable device from Figs. 10 and 11, it is this wall to which the annular jet attaches in absence of the control by the synthetic jet, so that the heater is by-passed. To direct the flow into the heater, the synthetic jet generated by the loudspeaker forces the main flow to attach to the other, concave conical attachment wall which is a part of the valve outer shell.

Of course, in place of the heater there may be any other device that has to be by-passed for some period of time. The diverting valve is integrated into the front part of this device while the by-pass pipe comes through its axial part. The resultant compactness of this design is particularly apparent from Fig. 10 above. The layout was already suggested and investigated in ref. [11], where is discussed an application for variable configuration system for treatment of automobile exhaust gas [12]. In that case, investigated in the model presented in Fig. 12, the valve was also monostable, but its operation was in an inverse manner: without the control signal, the annular jet attached to the outer, hollow conical attachment wall (and thus passed through the catalytic reactor, into which this outer space was leading). The control signal was applied from the outside and forced the annular flow to attach to the inner cone at the trailing end of

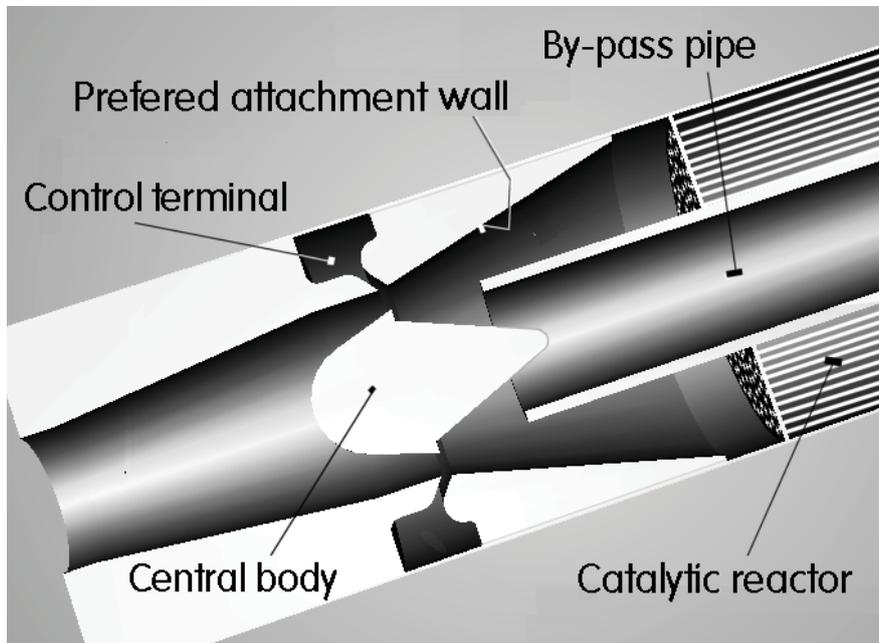


Figure 12: A valve discussed in ref. [11] with radial switching of the main annular flow into the by-pass for the duration of regeneration of a catalytic reactor. This valve was monostable, like the one shown in Fig. 11, but the preferential flow direction was into the reactor (since the regeneration, during which the control signal was applied, takes only a short time).

the central body held inside the valve on cruciform struts – and thus directed it into the centrally located by-pass pipe.

5. FEASIBILITY EXPERIMENT

Existence of the laboratory model for the catalytic reactor by-passing tests, Fig. 12, was the factor in the decision to test the idea of the valve controlled by the action of the radial synthetic jet. The by-pass pipe and the catalytic reactor were removed and the tests were run only with the diverter part of the original configuration, which was adapted (e.g. by the addition of the splitter ring, Fig. 13) so that the annular main flow remained attached to the conical downstream part of the central body. This body was made anew, adapted to contain the loudspeaker actuator and a radial control nozzle slit (Figs. 13, 14, 15, and 16). The outer control terminal, seen in Fig. 12, was closed and in these experiments not operational. The trailing part of the central body cone was removed to make space for the movement of the velocity probe traversing gear.

The outer diameter of the annular supply nozzle exit was $D_o = 84$ mm, the inner diameter was $D_i = 74$ mm (so that the annular slit width was 5 mm). Even though the central body was made anew, it could not obviously be larger than the 74 mm. This small size of the central body, of course, demanded using a very small loudspeaker. The model found suitable for fitting into the central body was electrodynamic speaker



Figure 14: Photograph of the test model shown in the previous Fig. 13 – here with removed outer jet-attachment cone.

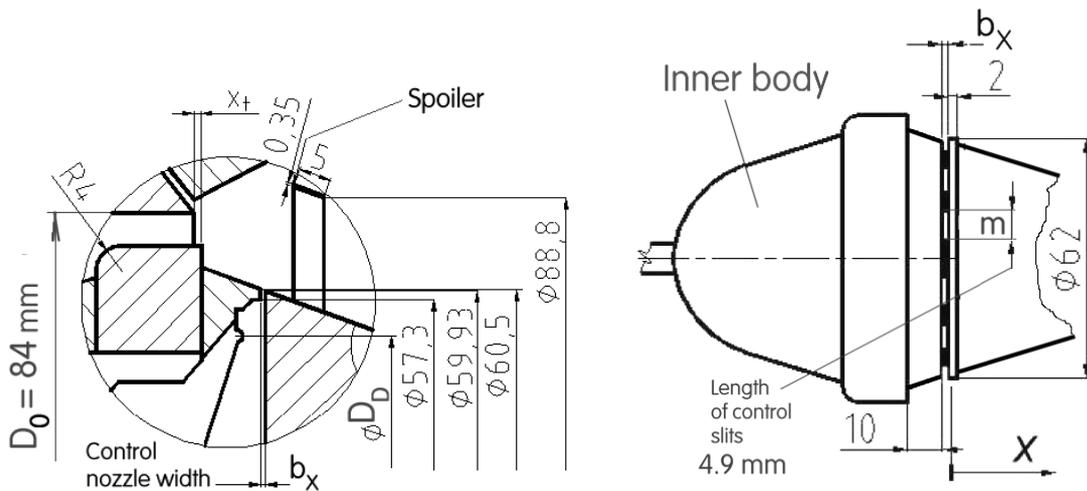


Figure 15: (Left) and Figure 16: (Right) Details of the laboratory test model as shown in Figs. 13 and 14. Since it was necessary to hold in place the inner attachment cone, the slit for generation of the radial synthetic jet had to be divided into 12 sections, each 4.9 mm long – as seen in the next Fig. 17.

nozzle slit between these surfaces – best seen in the photograph Fig. 17 – were $m = 4.9$ mm long.

All details of the performed measurements and investigations are available in the research report ref. [13] available from the authors. For the present purpose, it suffices to show the typical result: two measured velocity profiles with and without the synthetic jet control action, as presented in Fig. 18. The main conclusion extracted from the measurement result is the fact that indeed some change could be demonstrated caused by the action of the synthetic jet – and that this is a change in the expected direction: widening of the exit velocity profile as the annular flow detaches from the central cone surface and decrease of the velocity on the nozzle axis, Fig. 18, because the main flow does not so closely follow the inner attachment surface. Unfortunately – as could be expected with the very low control power level – there was no complete switching of the annular jet from the central attachment surface to the outer cone.

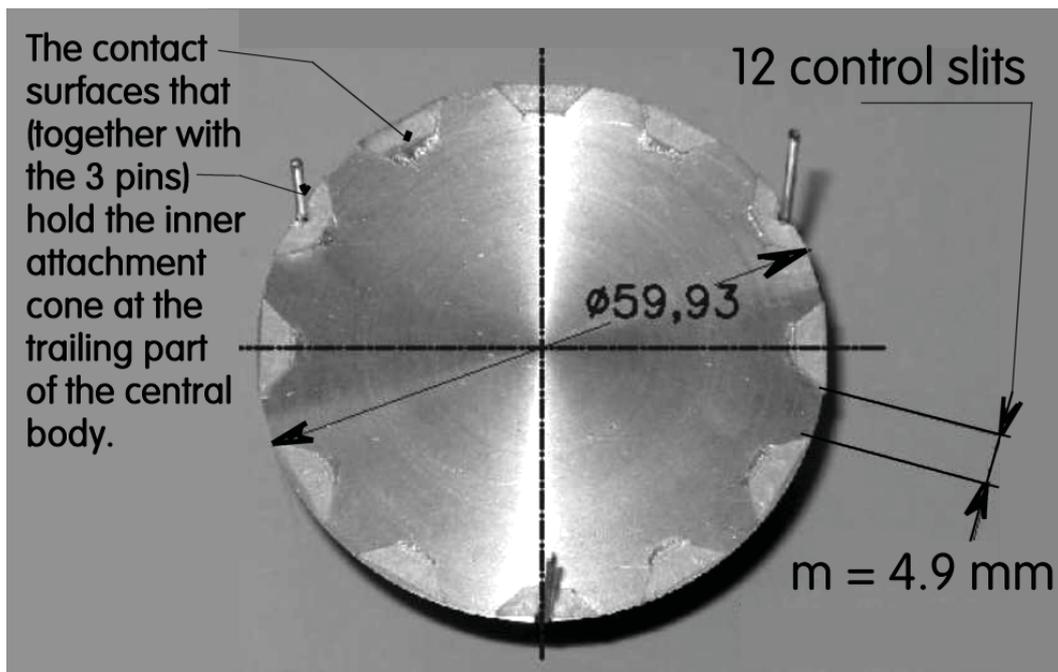


Figure 17: Photograph of the component of disassembled central body of the laboratory model. In this component were made the 12 slits for the generation of the radial synthetic jet.

6. CONCLUSIONS

This paper provides an information about the proposed new type of no-moving-part flow control valves – covered by the Patent Application [7] – in which the control action is achieved by synthetic jet that causes separation of the flow from an attachment surface.

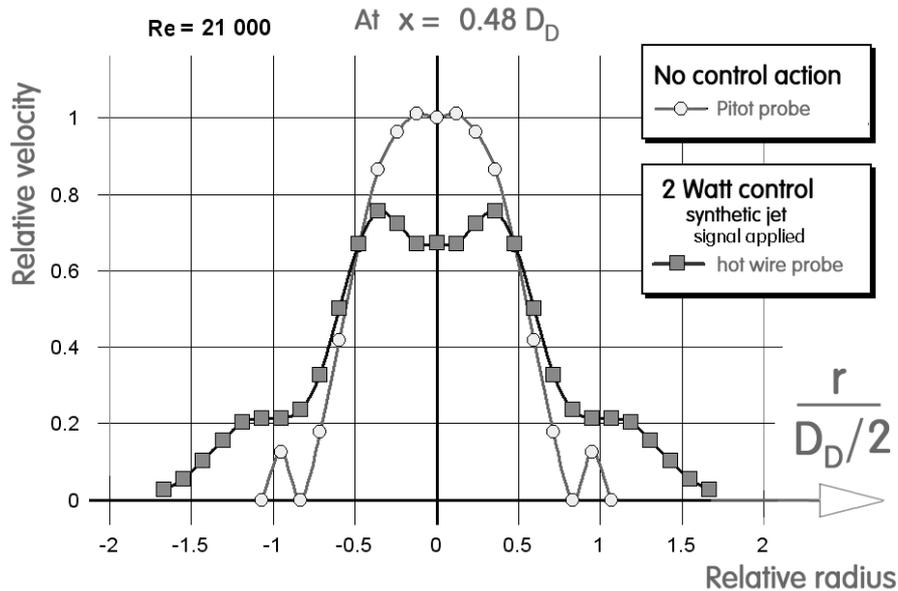


Figure 18: Results of preliminary investigation: the velocity measured at 40 mm axial distance (cf. Fig. 16) downstream from the radial control nozzle. In this case the electric power of mere 2 Watts supplied into the small loudspeaker did not suffice for complete switching of the annular jet flow. Nevertheless, the decrease of the velocity on the axis and the widening of the outer part of the flow demonstrated the control of the flow in the valve is feasible.

There is a considerable range of possible design layouts, in some cases diverting the fluid flow between two available output flowpaths, in other cases – combined with a vortex valve – achieving a turbing down of the flow. Authors have prepared a demonstration experiment, using existing hardware from another project (which limited the achievable control action). Although this failed in demonstrating the full flow switching, this experiment documented the feasibility of the flow control in this novel method of operation.

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