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FLUIDICS: THE ANSWER TO PROBLEMS OF HANDLING HAZARDOUS FLUIDS – A SURVEY

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ABSTRACT

Dangerous fluids must be kept inside a containment. With standard pumps and flow control valves this may be a problem, especially in emergency situations which may be caused by material fatigue, seizing, screws getting loose, and similar situations requiring maintenance and repair. However well protected in standard regimes, during a repair and associated device disassembly the hazardous fluid may become exposed to the outside world. No-moving-part fluidics, practically maintenance-free, offers a solution – but it is, unfortunately, almost unknown. This survey aims at propagating the knowledge of these fluid-handling devices. Three classes of fluidic devices that are developed (mainly in nuclear engineering applications) specifically for handling dangerous liquids and gases are discussed: (A) Passive flow control valves, (B) Valves controlled by an external signal, and (C) Fluidic pumps driven by alternating flow.

Keywords: fluidic pumps, fluidics, fluidic valves, hazardous fluids

1 INTRODUCTION – HANDLING DANGEROUS FLUIDS

There is a principal rule of handling dangerous liquids and gases – those that are hot, poisonous, chemically aggressive, explosive, radioactive, or biologically pathogenic [1]: They must be kept at all times inside a protective enclosure. The permanence of the containment is not always given an adequate consideration, especially in exceptional situations such as maintenance or repairs. These may require disassembling the fluid-handling devices and exposing the dangerous fluid. Though relatively rare, repairs are needed sooner or later almost inevitably with classical mechanical pumps and flow control devices, which operate either by motion of mechanical components or by a component deformation (such as separating membranes). The reasons for the failures are numerous: they arise due to material fatigue, worn seals or bearings, seizure damage, or bolts, screws, and other components getting loose.

2 FLUIDIC DEVICES

A solution is offered by no-moving-part fluidic devices, which generate and control fluid flows by hydrodynamic or aerodynamic phenomena taking place inside cavities with solid, non-dismantlable walls. There is nothing that may break, seize, or be worn. As a result, fluidic pumps and valves are extremely reliable and maintenance-free.

The advantages they offer are, unfortunately, known little or not at all. One of the reasons may be that these devices were often developed for use in nuclear engineering and its association with nuclear weapons caused their being kept under the cloaks of secrecy. Another negative reason is the connotation of their name: most engineers, if they have heard about fluidics at all, know it as the rather outdated technology that attempted, without success, to compete with electronics about 50 years ago. The very name ‘fluidics’ was coined in analogy to ‘electronics’, the difference between the two is processing signals carried either by fluid or by electrons. The absence of moving components enabled fluidics to reach operating frequencies higher than classical hydraulics or pneumatics (where there were movable components). Nevertheless, the limit of signal transfer speed – which in fluidics is the speed of sound – made it incomparably slower than electronics (where the analogous limit is the speed of light). Also

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the size of fluidic devices, which cannot be simply miniaturized because of the governing limits posed by Reynolds number, made them non-competitive. Only recently a branch described as microfluidics [2] achieved the small size, taking over microfabrication methods from electronics and applying special flow control techniques.

The devices discussed here are different [3–5]. They are mostly of rather large size [3] as they handle large flows. Often, though not always, their typical feature – made possible by absence of moving components – is their being manufactured without costly machining or assembly operations. This makes them quite inexpensive. Because of no need for an access for maintenance, the components and devices may be welded together to form a single, leak-proof solid body. They may be made of resistant, refractory materials, so that their operational life may be almost unlimited. Modern materials resistant to high temperature allow working with such unusual fluids as molten metals. Author's fluidic devices were originally developed for handling extremely dangerous radioactive fluids encountered in nuclear fuel reprocessing. The unique properties of inherent safety, however, make them the answer to many problems of transporting and processing hazardous fluids in other branches of technology.

If the handled fluid is really dangerous, several protective envelopes, one inside another, may be required. In the schematic example with several fluidic devices in Fig. 1, there is – in addition to the primary containment by the device walls – also the secondary outer containment

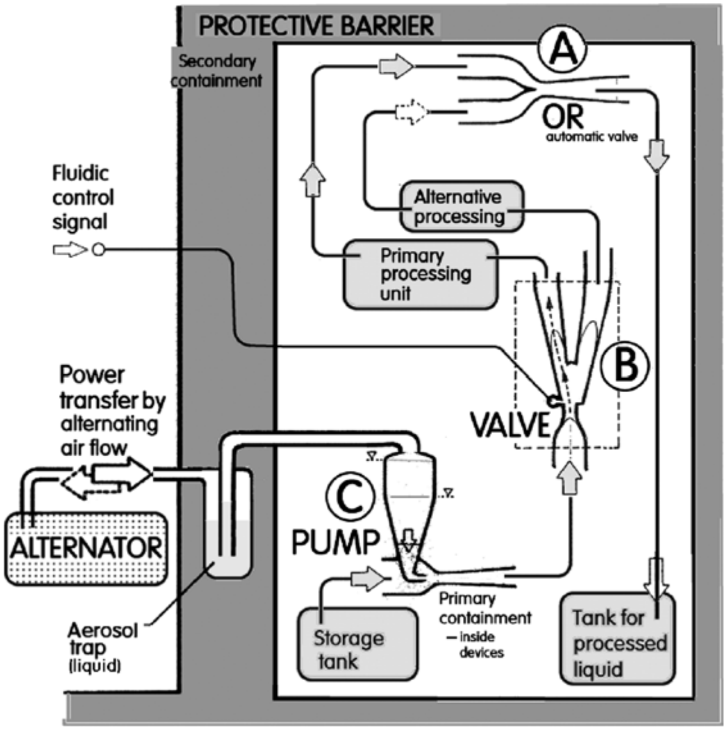

Figure 1: Schematic representation of a hypothetic fluidic system handling a hazardous liquid inside a protective enclosure. Three device classes are shown: A – passive flow control valves, B – valves controlled by small control flow from outside, C – pumps driven by alternating flow passing through the barrier.

of the whole fluid processing system inside a protection barrier. There are two fundamental requirements:

(a) Absence of any mechanical moving devices inside the barrier, because mechanical motions are the cause of the wear and fatigue problems. Ideally, no access of personnel beyond the barrier is allowed and, indeed, possible.
(b) No additional liquid is to be mixed with the processed one – to minimize the amount of what has to be decontaminated or stored at the end of the processing.

Figure 1 sorts the fluidic devices into three classes: A – fully passive, B – connected to outside by only very small control flow line, C – driven by an external flow. The capability of fluidics to make possible total separation from the environment is quite unique. It may be perhaps suggested that transfer of power across the protection barrier may be made by electric conductors. There is, however, no way of acting on the fluid inside (certainly at large scales) by electricity so that the electric transfer would break the requirement (a). The configuration of the pump shown in Fig. 1 may bring to mind another seemingly possible solution: driving the fluid flow by a jet pump. This device does not have any mechanical moving parts. However, a jet pump operates by suction effect produced by a driving fluid, necessarily brought in from outside – and thus breaking the requirement (b).

In the absence of moving components that are used in standard valves to block the undesirable flowpath, the fluidic control of fluid flow directing it into the desirable outlet is achieved by using inertial forces. To make the inertial action effective, the fluid has to be accelerated – usually in a nozzle. Of course, high flow speed brings inevitably high hydraulic losses. To avoid them, in a reasonably designed fluidic device the fluid is slowed down as soon as the inertial effects are not needed – preferably immediately downstream from the interaction cavity. This is done in diffusers, an example of which is seen, in Fig. 2. Such diffusers are, in general, a characteristic feature of most fluidic devices. They are so prominent because good diffusers with small divergence angle are long, often to an inconvenient degree. Yet their conversion efficiency is generally not as high as is desired so that improving the diffusers tends to be a perpetual challenge for fluidic device designers. In fact, recent discovery [6] shows that the conditions in a fluidic device are more complex than generally believed, because most of the conversion was in [6] actually found to take place prior to the entry into the diffuser.

3 PASSIVE FLOW CONTROL VALVES – CLASS A (FIG. 2)

Since the simplicity of physical setup is one of the main advantages offered by fluidics, there is a general trend to go quite far in this direction and use for the control actions just as the special properties of the devices, without any feedback usually associated with controllers and regulators. Absence of the feedback means the control is less precise, but this does not really matter in many applications. The fluidic element shown in Fig. 3 may be an example of this approach [7]. Its task is to prevent a loss of cooling in the rare event of failure of one of the pumps operating in parallel. The fluidic version is a simple symmetric jet pump, with two identical inlets. There is no sensor detecting the event in Fig. 3 and no actuator turning the flow down. The fluidic version is a simple symmetric jet pump, with two identical inlets. The suction created by flow in one inlet prevents a flow reversal in the other one. The same effect, also in an open-loop manner, may be obtained by placing in both flowpaths a mechanical non-return valve. Just because such safety valves are not called to action for very long periods, perhaps for many years, they may rust and remain in open position or otherwise become inoperative and fail to do their job when finally called to do so. No such situation can arise in the fluidic device, which may be relied upon.

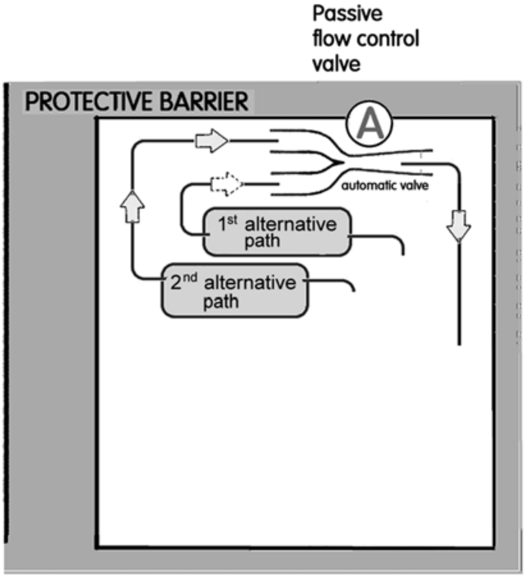

Figure 2: The first part of this discussion is about the class A valves, operating without any contact with the outside world, solely on the basis of their in-built hydrodynamic properties.

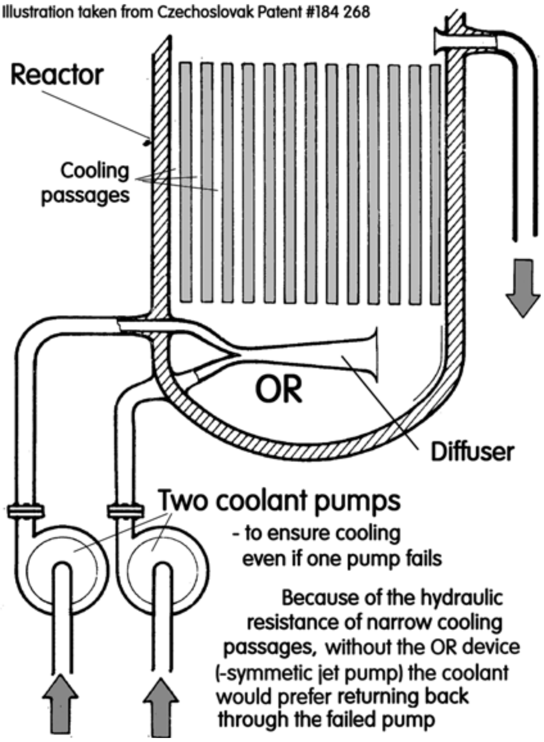

Figure 3: An example of the class A valve. Here in the case of failure-free no-moving-part “logical OR” device [7] prevents loss of coolant by backflow through a failed pump.

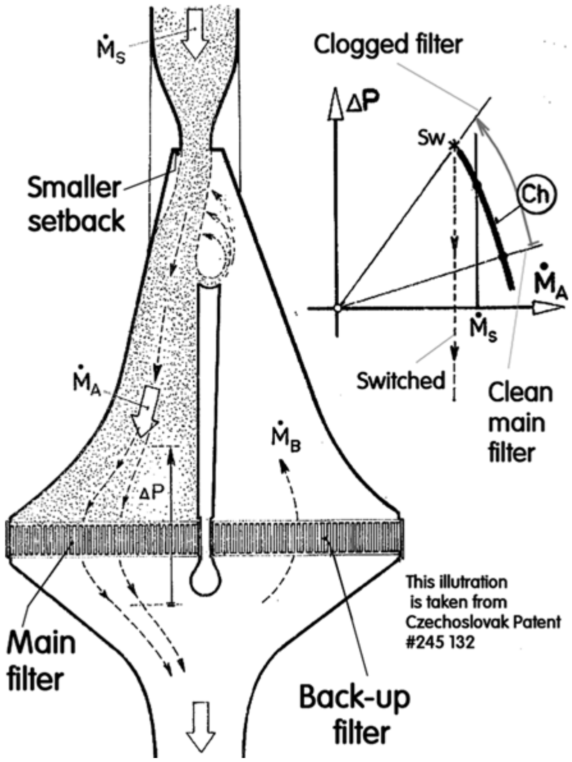

Figure 4: Another class A valve. It switches the flow into the back-up flowpath if the downstream resistance increases beyond the attachment capability of the Coanda effect. The original Patent [9], from which this picture is taken, concentrated on automatic insertion of a back-up filter once the main filter becomes clogged.

A slightly more demanding control task have the valves employing a special shape of their loading characteristic Ch, an example of which is presented in Fig. 4. What is shown there is a diverter valve operating on the idea of load-switching [8]. The jet, generated in a nozzle, is always attached to the preferred attachment wall with the smaller setback. The characteristic curve, a dependence of the output pressure drop ΔP on the mass flow rate through the load, has an end point Sw. Beyond this point, the Coanda effect attachment fails to keep the jet attached so that it switches to the other outlet. The load connected to the valve in Fig. 4 is a filter that gradually becomes clogged [9] so that the intersection of its characteristic gradually climbs up the Ch curve, finally reaching the end point Sw, when the backup filter takes over. The same idea was applied, according to Fig. 5, to automatic switching of high-temperature gas flow into the bypass as soon as the gas viscosity in the reactor (which increases as the exothermic catalytic reaction rises the temperature) reaches a limit [8, 10].

In another example, Fig. 6, the valve geometry was developed so that the loading characteristic (having no end point of the kind from Fig. 5) has a flat horizontal part. This means that the pressure in the valve output remains constant no matter where its intersection (a or b) with the characteristic of the connected load is located. The valve thus operates as a pressure regulator [11, 12] – and also as a load isolator (not reacting by pressure changes to any changes in the load).

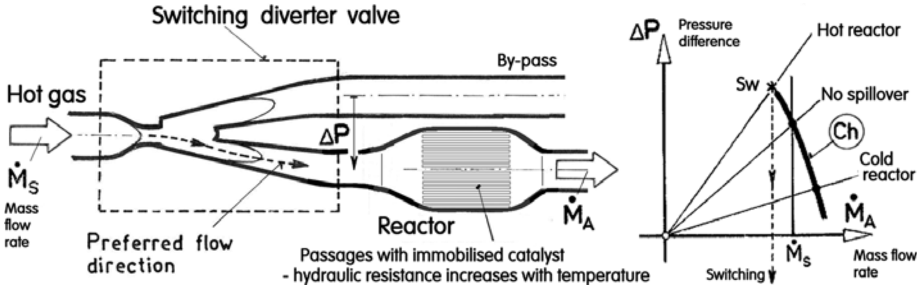

Figure 5: The same mechanism as in Fig. 4 operating with gas at very high temperature. It prevents irreversible overheating of the reactor by the exothermic reaction taking place in it - refs. [8, 10].

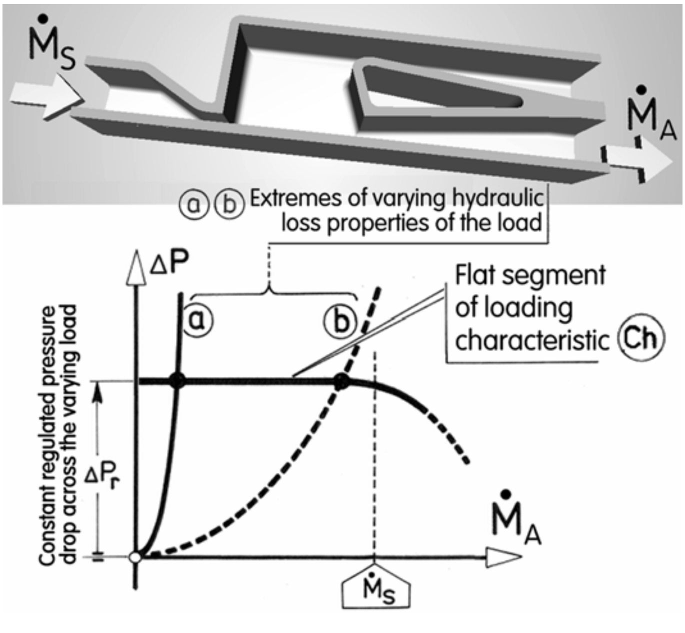

Figure 6: Class A valve in the role of pressure regulator. The internal cavity is shaped to obtain the flat part of the characteristic Ch, ensuring constant output pressure (constant vertical position for intersection of characteristics) at any load, a or b. Details are in [15, 16].

4 CONTROLLED VALVES – CLASS B (FIG. 7)

The devices of this class are essentially scaled-up versions of the standard fluidic amplifiers [2] as they were developed in the 1970s. The fluid flow in them is controlled by fluidic control signals acting on some ‘weak’, sensitive spot in the flow field. The signals are either derived from some changes that take place in the system inside the barrier, thus not breaking the rule (b) of page 3, or are brought in from outside. The amplification property ensures the control flow that in the latter case crosses the barrier is small and thus causes no problems with possible transfer of contaminant – the more so because the signals are carried almost always by flows directed into the enclosure. A particularly versatile valve type, with many uses, are the

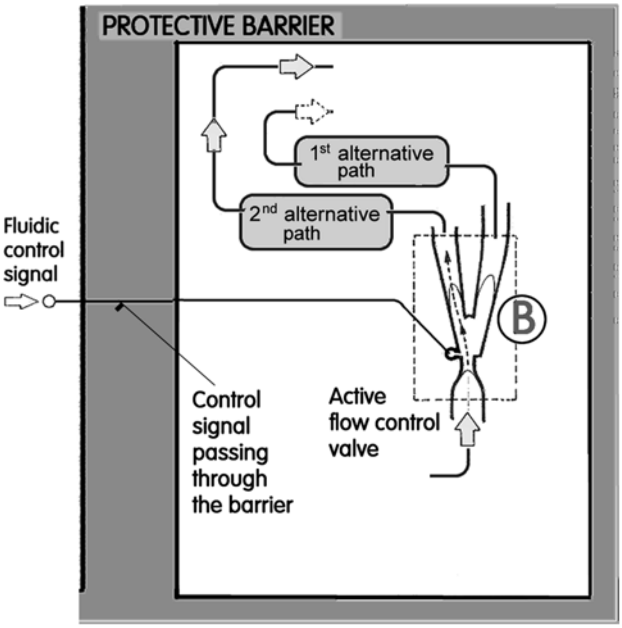

Figure 7: The second part of this paper discusses the class B valves, controlled from outside. The signal transfer is usually safe enough to be accept-able for the gained capability of direct positive influence on the handled fluid flow.

jet-deflection devices an example of which is presented in Fig. 8. They divert the incoming flow into one of the two exit terminals, shown in Fig. 1, connected to the primary processing unit and an alternative one.

The amplification property may be used for an interesting role of the valve. Addition of feedback loop channels – shown in two alternative versions in Fig. 9 – for taking some small amount of fluid from the output and bringing it to the input terminals converts the valve into an oscillator [13]. The simpler Spyropoulos alternative [14] also shown in Fig. 9 operates on slightly more sophisticated principle which uses the low pressure that holds the deflected jet at the attachment wall (and absence of this low pressure on the opposite side – the difference being the cause that drives the fluid flow in the loop). Oscillators are extremely useful devices. In some processes, it may be necessary to lead the fluid periodically into different alternative processing units – this is a case of slow oscillation, achieved by inserting a delay (a slowly filled cavity) into the feedback line. It is, on the other hand, sometimes requested to have a high-frequency oscillation – Fig. 10 shows the extreme configuration with shortest possible feedback loop length. The generated oscillation may agitate the liquid and prevent sedimentation of carried particles. It can also increase heat and/or mass transfer by destroying the conduction layer held by viscosity on, for example, heat exchanger surface. Oscillators were also used in generation of fine droplets or fine bubbles [15] and may mix reactants prior to their entry into a chemical reactor [16].

If the task is to turn down the flow rather than diverting it, fluidics offers a solution in the form of the vortex amplifiers [17]. The flow through them is opposed (though not completely stopped) by the centrifugal force acting on the fluid, if it rotates in the vortex chamber – Fig. 11.

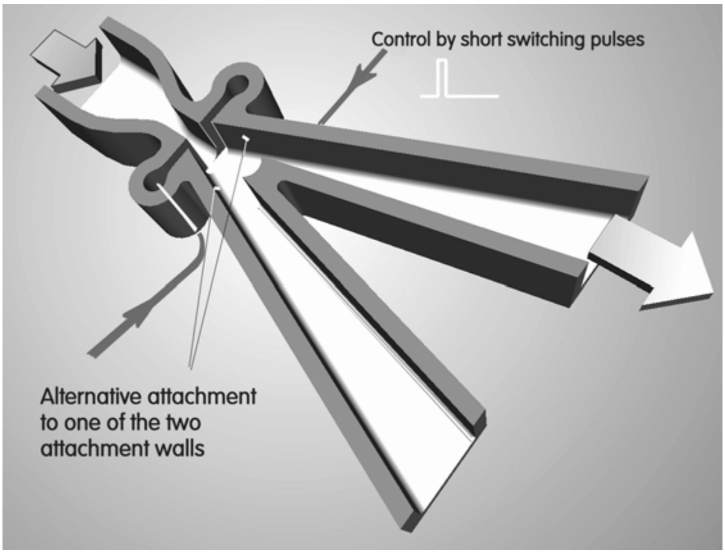

Figure 8: Typical no-moving-part flow diverter valve based on deflection of a jet. The advantage of Coanda-attachment of the jet to one of the two walls is the memory effect – the control is by just a brief switching pulse after which the jet remains deflected.

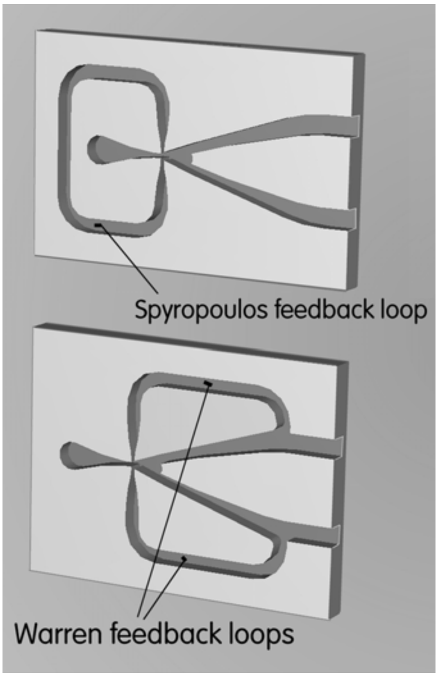

Figure 9: Fluidic valves controlled by a tiny fluidic signal are, in principle, amplifiers. By arranging a negative (destabilising) feedback, as shown here in two alternatives, the amplifier is turned onto a self-excited fluidic oscillator.

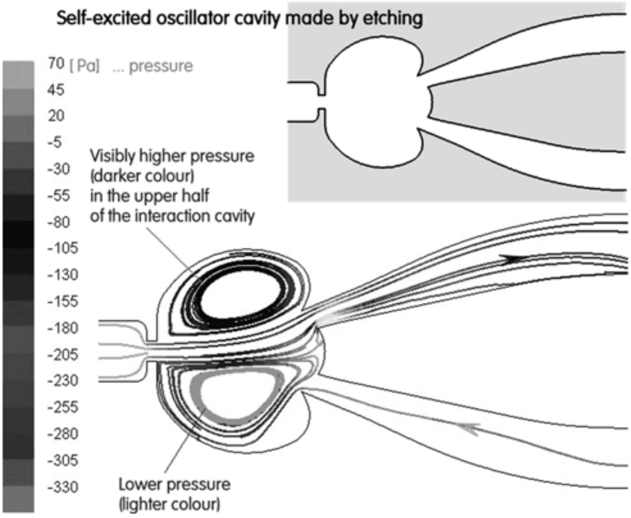

Figure 10: High-frequency fluidic oscillator: very short internal feedback loops are formed by the standing vortices, trapped inside recessions.

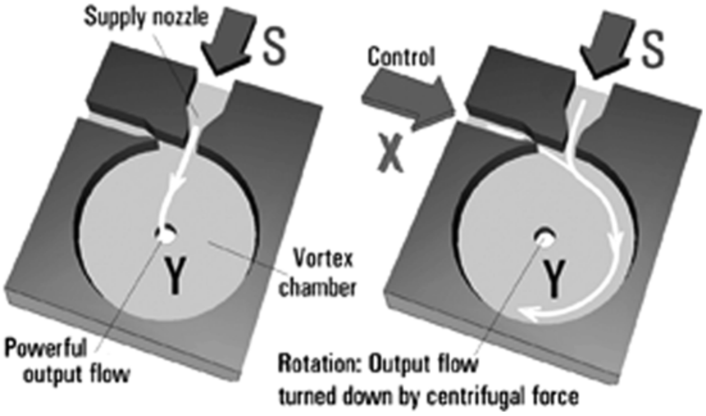

Figure 11: Vortex amplifier: In absence of control flow (left) the fluid passes through the vortex chamber without opposition. Once the control flow imparts a tangential component, the fluid rotates (right) with rotation speed increasing with decreasing radius. As a result, the centrifugal force decreases the flow rate substantially.

5 FLUIDIC PUMPS, CLASS C (FIG. 12)

Jet pumps are the oldest no-moving-part fluidic pumps, but they break rule (b) of page 3. Contrary to the small control flows in the class B, the pumps power level is generally high and would call for adding too much driving fluid to the processed one. This is avoided by transferring the power through the containment shell by an alternating flow (Fig. 12) – moving back from the containment the same amount of driving fluid previously supplied in during the first half of the cycle. If the driving fluid is air (or gas), its action on the driven flow of dangerous liquid avoids mutual mixing even without a separating piston (Fig. 13).

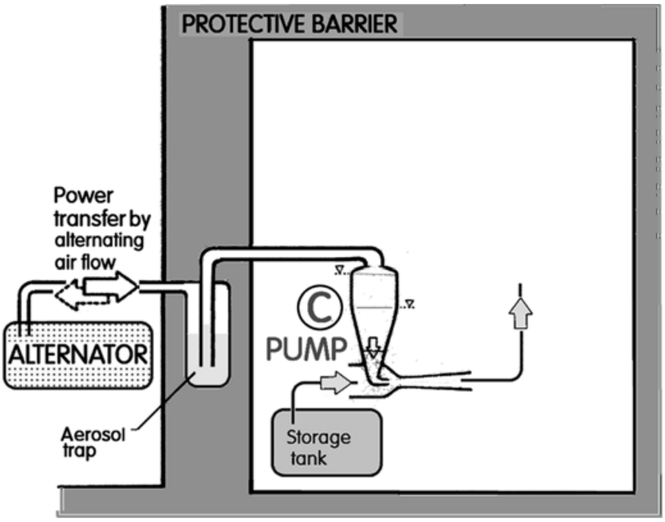

Figure 12: The last of the three classes of fluidic devices discussed in this paper: the class C no-moving-part pumps. It is necessary to transfer quite large power through the enclosure and this is achieved by means of an alternating air flow. This is converted into liquid motion in the displacement vessel and then rectified in a rectifier part of the pump.

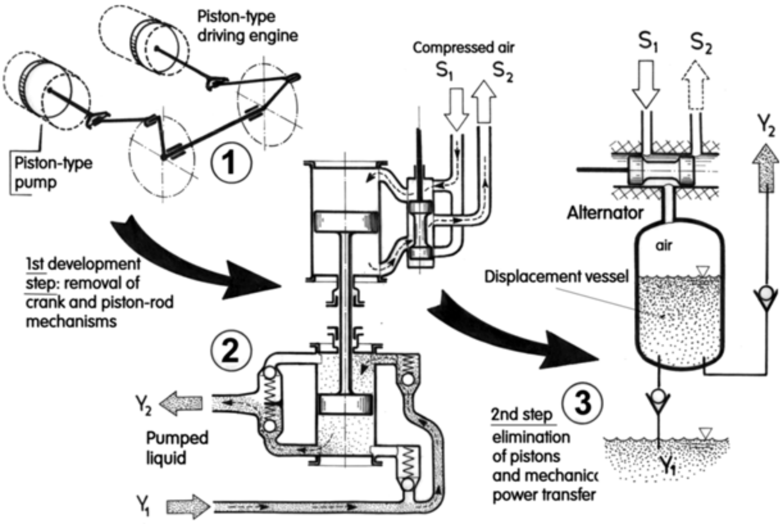

Figure 13: No-moving-part fluidic pumps were developed by simplification steps from an aggregate of piston-type compressed-air engine driving a piston-type pump.

The alternating air flow is generated by an external alternator, which may be (for reasons of higher efficiency) of the classical piston type because there are no problems with accessibility for repairs.

The components inside the containment are the displacement vessel for the gas/liquid conversion and a rectifier converting the alternating fluid motion into the requested one-way flow [18–20]. For developing the rectification without action of moving parts, considerable ingenuity was spent – with no particular success – on the labyrinth-type fluidic diodes [18] (the earliest: Patent by N. Tesla, filed 1920). Also not suitable, because of poor efficiency, at a higher handled power level are the simple Venturi-type diodes, consisting of a nozzle followed immediately by a diffuser – in spite of current popularity of this principle (Fig. 18) in microfluidics [2, 21, 22], where efficiency is not the primary factor, while the high achievable operating frequency (up to 10 kHz [2], although two decimal orders less is more typical) is important. Really successful diode rectifiers for the large-scale pumps are the vortex diodes [23], invented by Thoma [24, 25], Figs. 14, 15, 16, 17. Those used in the author's pump shown in Fig. 14 were measured to exhibit 59 times higher pressure drop in the return flow direction than in the forward direction at the same flow rate 10×10^{-3} kg/s. Weakness of vortex diode pumps is the considerable time needed for the startup of the rotation in the vortex chambers. This is why these pumps are operated at very slow switching frequency (of the order of minutes -–note the large volume of the displacement vessel in Fig. 14).

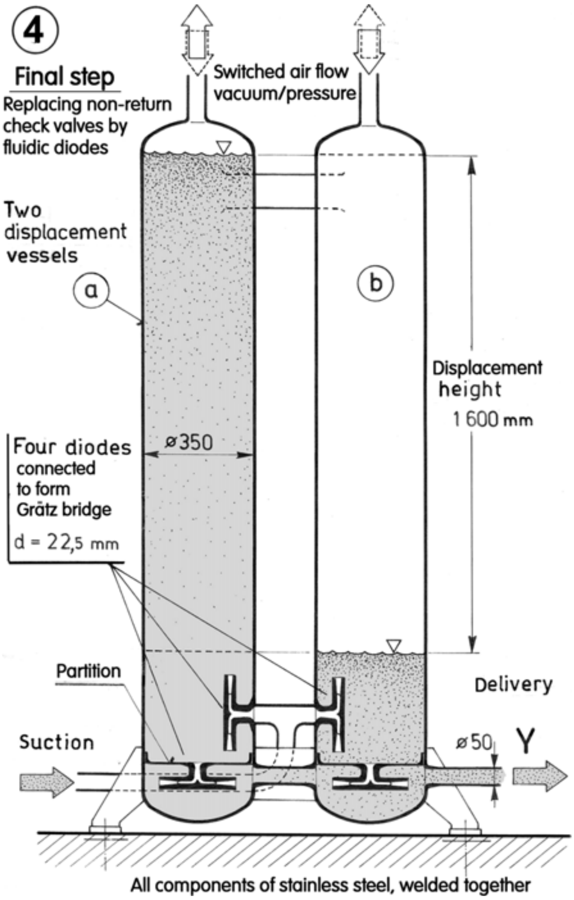

Figure 14: Author's two-phase pump with rectification by vortex diodes as an example of the low-frequency pump type.

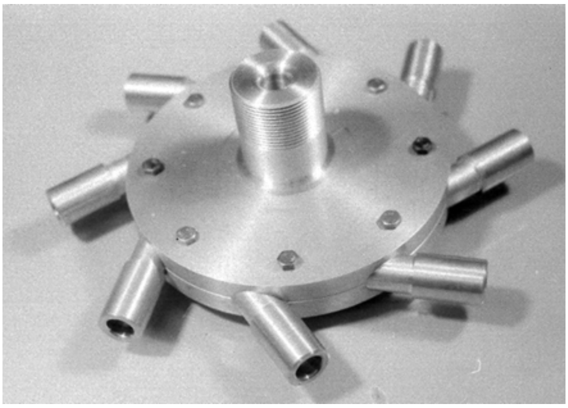

Figure 15: Photograph of the model vortex diode used in laboratory tests of the pump shown in Fig. 14. The large number of tangential inlets ensures symmetry of the vortical flow, needed for high rectification efficiency.

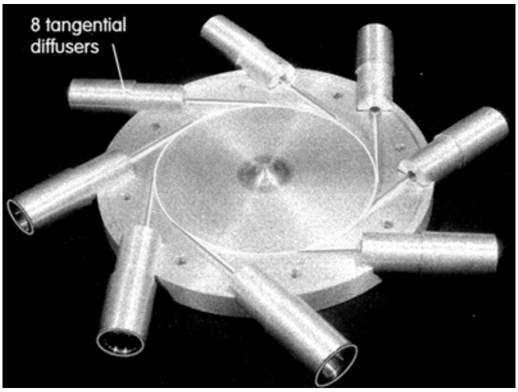

Figure 16: Photographs of the disassembled model showing the vortex chamber with circumferential groove and central protrusion guiding the flow in the vicinity of the central exit.

A special, quite popular, branch is the fluidic three-terminal rectifiers. They were known in low-efficiency cheap small units used, for example, for fish-tank aeration, already in the first half of the last century. Later developments took over performance improving ideas (diffusers, mixing tubes, properly shaped nozzles) from jet pumps. Walkden [26, 27] with collaborators introduced driving by two-phase alternating air flow in their pumps for molten salts.

At this stage, a dramatic improvement came in the pioneering work on fluidic pumps for nuclear engineering by Tippetts [28–32]. His main idea was introducing the concept of RFD – reverse flow diverter. In principle (Fig. 19), it is a symmetric Venturi (diffusers on both sides) with the third inlet in the smallest cross section (Fig. 20). This is a very popular concept, widely used [33–36] and still under development (e.g. [37]). There are improved double-acting two-phase versions [32].

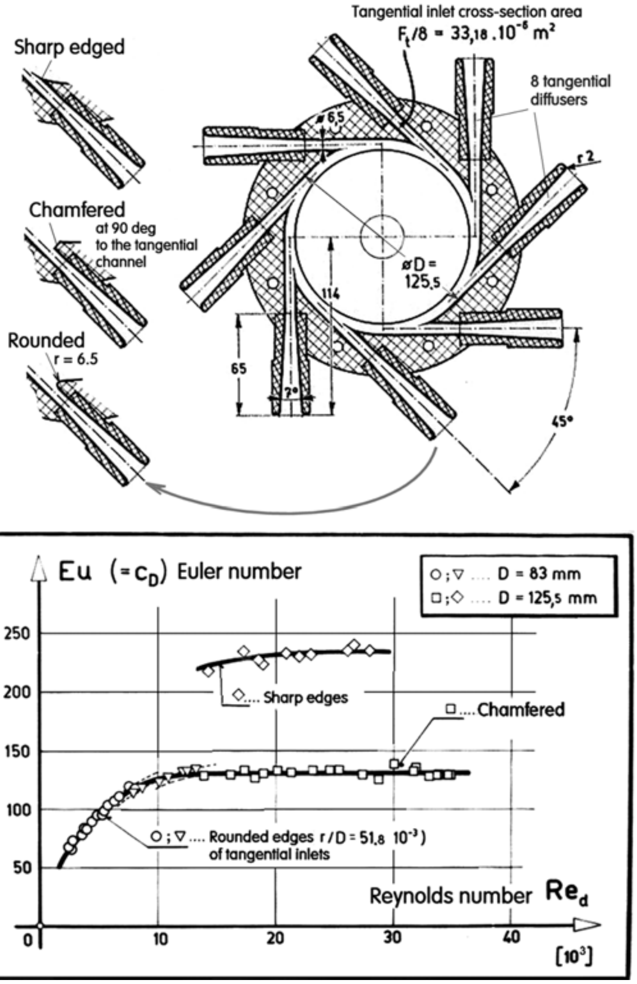

Figure 17: Both rounding or chamfering of the sharp edge at the entrance into the tangetial diffusers ("OPEN" non-rotating flow) were equally effective (the latter easier to make) in improving performance of the diode from Fig. 15.

The original operating principle of the *forward flow diverting* – not the return flow as in a RFD but the forward flow changes its direction – was already proposed in 1976 [38]. The mechanism used for the diverting is attachment of the jet to a curved wall by the Coanda effect. Initially in an attempt to increase the generated pressure difference, the pump was set up as arrangement of several stages, Fig. 21. The two-phase driving alternating flow was not rectified in the usual manner of Grätz rectifying bridge but was led alternatively into the odd and even stages set up in tandem. Thus, the pressure increases generated in each stage are summed and also produced are travelling waves, dragging the pumped fluid along – some of it not even entering the nozzles. A version of this novel pump, of 20 mm diameter bore, was recently tested as described in detail in Ref. [39].

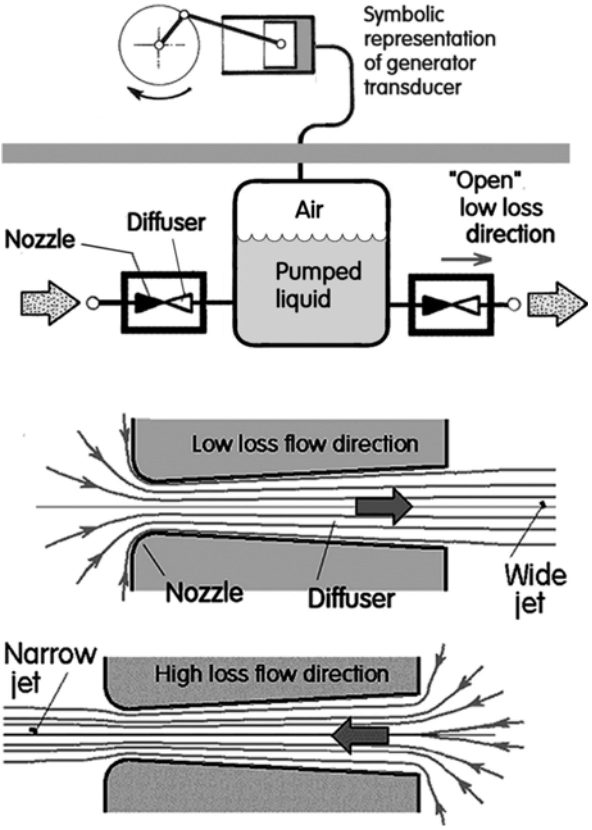

Figure 18: Fluidic pumps with Venturi diodes (nozzle & diffuser) .are currently popular in very small scale pump versions.

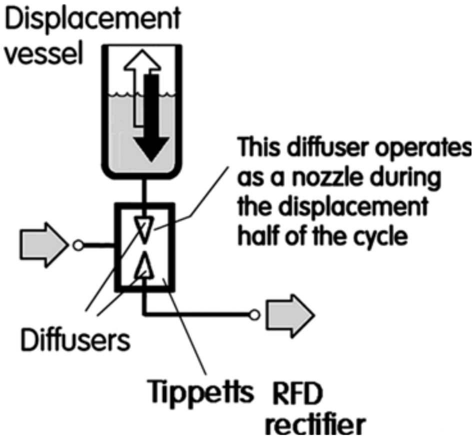

Figure 19: Basic principle of the RFD pump developed by Tippetts at the Univ. of Sheffield. Rectification is based on different character of the flowfield in the forward flow into the outlet (RFD operates as a jet pump) and the reverse flow, when the displacement vessel is filled mainly from the inlet.

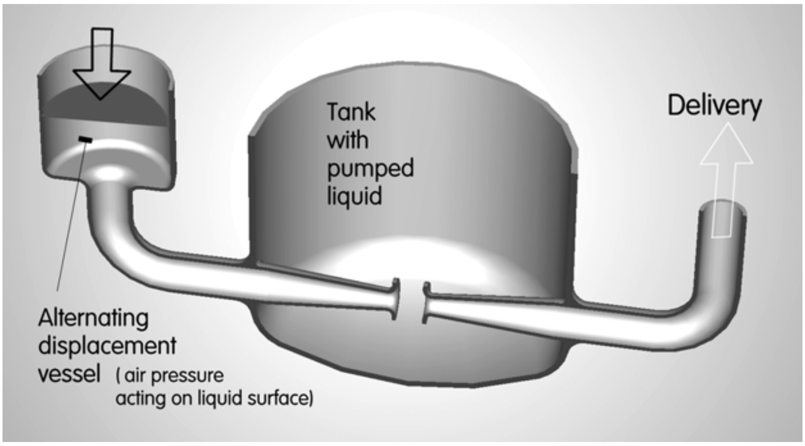

Figure 20: Typical layout of the single-phase RFD pump (patent sponsored by UKAEA atomic energy agency) as used for nuclear fuel reprocessing. Low-frequency operation (< 0.1 Hz) is standard.

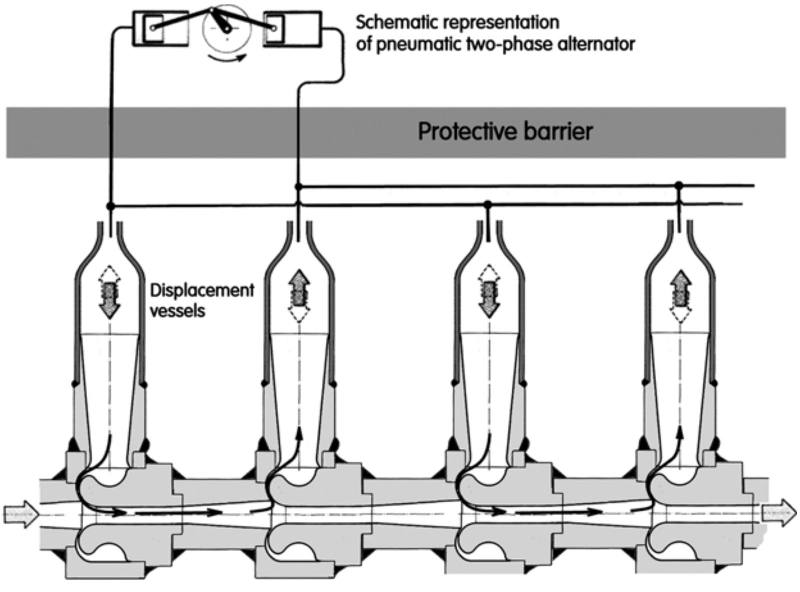

Figure 21: Author’s multi-stage multi-phase travelling-wave high-frequency pump. Rectifier consist of Monel metal components welded together into a single body.

6 CONCLUSIONS

No-moving-part power fluidics brings opportunities, so far little known, for transporting and processing dangerous fluids in an inherently safe manner. The three described classes of the devices can generate and/or control the flow inside an inaccessible containment. The secrecy originally demanded by the use in nuclear industry is now lifted and references are available with design guidelines. The long-term reliability, robustness, and absence of maintenance makes the devices described in this survey an ideal answer to many problems of handling hazardous materials.

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