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FLUIDICS: WHAT IT IS, WHERE IT IS HEADING - AND HOW IT WILL CHANGE THE WORLD WE LINE IN

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Abstract: *Fluidics, technique of handling fluids, is usually meant to imply absence of moving components. It is less known and used than it deserves considering the advantages it offers. Recently its applications became more widespread thanks to two development directions. On one hand, it is the power fluidics, handling larger flow rates. Newly developed are no-moving-part fluidic pumps for dangerous liquids (in particular radioactive ones) — and fluidic oscillators for generation of microbubbles used in waste water processing and growth of unicellular plants. The other rapidly growing development direction is microfluidics, often integral with electronic circuitry on the same substrate. It has immense possibilities in sensors and also in handling small amounts of fluids e.g. in microchemistry.*

Keywords: ***Fluidics, microfluidics, bioengineering***

1. Introduction

Fluidics is a technique of handling gases and liquids. It is usually implied that the handling is made without action of mechanical (moved or deformed) components. This brings a wide range of advantages – and yet fluidics is little known and even less applied than these advantages deserve. In fact, some of those few engineers who have ever heard about fluidics keep it in undeserved disregard. The negative stigma is caused by fluidics' unhappy start. Its history begun with the invention of amplifiers capable of amplifying signals transferred by fluid (- this is the origin of the name "fluidics" in analogy to "electronics" where the signals are transferred by electrons). Since the absence of inertia associated with mechanical motions made possible quite wide frequency range of the amplified signals – sufficient for most industrial regulator systems — fluidic devices became initially viewed upon as a competition to electronic controls (Tesař, 1972). Indeed, fluidic amplifiers – in principle a hollow cavity with just a special shape of the walls – were cheaper than the individual transistors used at that time for the signal amplification and were able to perform the same or similar tasks.

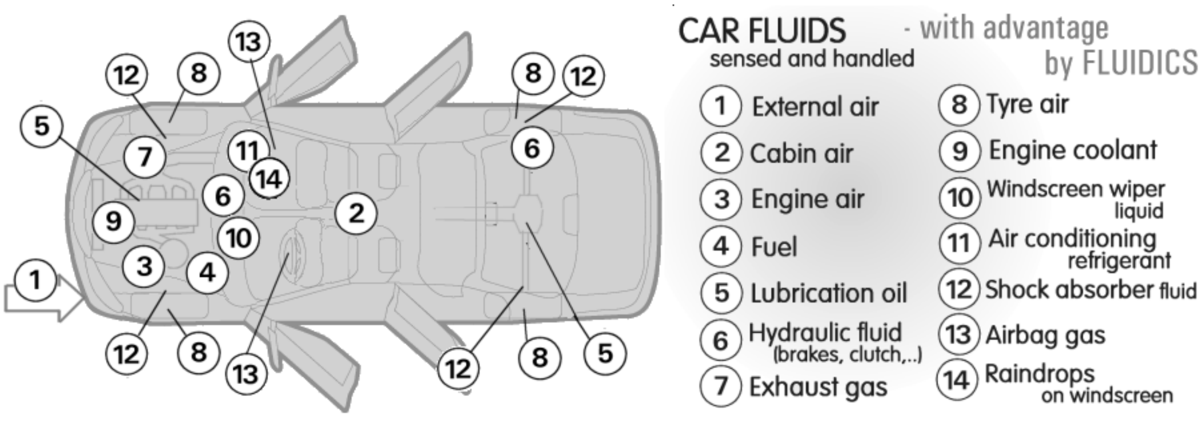

Fig. 1 Fluids are unavoidable in a large number of engineering processes and products. This illustration reminds how many fluids are transported, used for sensing, and handled in a typical product: a car. In practically all these cases it is a possible to find application for the no-moving-part fluidic devices.

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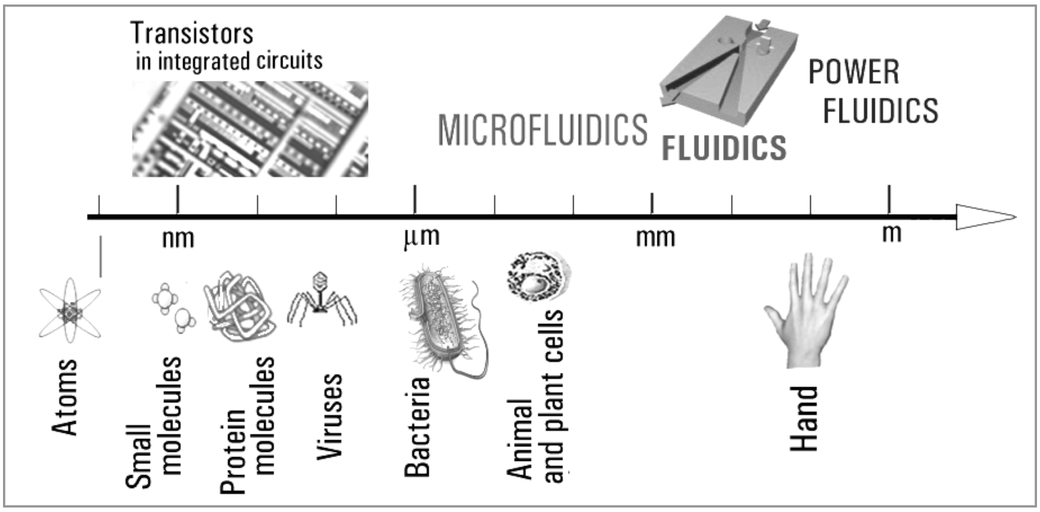

Fig. 2 The size scale of the original fluidics, nowadays nearly defunct, and of the large-scale power fluidics as well as the sub-millimetre sized microfluidics. The latter is comparable in size with living cells and bacteria and indeed, many of its present-day applications are in detection of pathogens. Wit the ease of implanting the minute-size devices, various microfluidic implants seem to be an important use.

There was a time when researchers built even fluidic digital devices for signal processing – as complex perhaps as digital circuits for performing arithmetic calculations. Inherent robustness of fluidic devices (when made from suitable material) made possible such demonstrations a the computation going on even when the device was heated in a furnace to glaring white-hot state — at a time when the then common germanium transistors required complex thermal stabilisation to prevent their temperature reaching for them dangerous 50 ^{o}C.

Fluidics nevertheless lost the competition with electronics in control systems due to several disadvantages. Fluidic devices could not be miniaturised to the degree which was gradually achieved in microelectronics (the fluid flow needs a spatially demanding smooth shaping of the channels and cavities; also fluidic devices had to contain diffusers, inherently long and tending to lose efficiency at low Reynolds numbers). The second reason was the low speed of fluidic signal transfer – its upper limit being the speed of sound while the analogous limit in electronics is the incomparably higher speed of light. Finally, there was perhaps the decisive factor of prices in electronics being subsided by the huge market of amusement industry.

In the last decades of the past century, there were only a few researchers who kept fluidics going, undaunted by the loss of the originally conceived targets. The field in which fluidics was able to show its assets was ***power fluidics***. It developed from what were earlier the no-moving-part power stages designed for the output ends of control systems. Need for fluid handling is widespread (example: Fig. 1, cf. also Fig. 3) and classical mechanical valves and other devices are at a disadvantage compared with the much less expensive and much more reliable no-moving-part solutions. Typical for power fluidics are quite large handled flow rates and the correspondingly large device size. The field particularly benefiting from the robustness and reliability of fluidics are devices handling dangerous (e.g., radioactive) liquids.

The other rapidly developing branch is ***microfluidics,*** characterised by devices that are very small – according to the common definition, microfluidics is characterised by sub-millimetre widths of the flow channels (Tesař, 2008). Typical for the ambivalent relationship with electronics - which nearly eradicated fluidics in its earliest days – is the use of microfabrication techniques that were originally developed for microelectronics. Also, whenever the handling of fluids in a fluidic system requires acquiring and processing information, fluidics usually collaborates with electronic circuits, which are often actually made together with fluidic channels and cavities on the same chip. Many of recently developed applications of microfluidics are in the biomedical field - with channels of microfluidic devices usually commeasurable (Fig. 2) with the size of investigated living cells.

2. Basic fluid-mechanical principles

In classical mechanical valves, the controlled fluid flow is directed into the desired outlet (and prevented to flow into other, unwelcome directions) by a mechanical component moved into a position in which it makes only the desired direction open and available. In fluidics, the mechanical components are absent and the directive action that forces the fluid where we want it to go is provided by inertia of the fluid accelerated in a nozzle – Fig. 4. Control action is applied in the sensitive space between the nozzle and collector. For example, the jet generated in the nozzle may be deflected so that it is prevented from entering the collector. This is achieved by a much weaker control flow than is the controlled main flow. The ratio of the flow rate that is controlled to the small control flow is characterised by the flow gain K. Values as high as $K \sim 100$ were often achieved. The flow control valve is, in principle, a fluidic amplifier. Nowadays, such amplifiers are only rarely used for amplification of signals carried by fluid flow, but the idea of the amplification remains important. It means a small part of the powerful output flow may be taken and used for the control action. If the action is made at a proper phase, the device becomes a fluidic oscillator.

There is actually a number of various principles applicable for the active device (amplifier) role. In addition, there is a wealth of principles on which are based passive devices. For example, one of the important inertial effects is the centrifugal action on rotating fluid, put into rotation by entering tangentially an axisymmetric vortex chamber (Tesař 2012). In all these principles, there is a competition between the inertial driving effects on one hand and the fluid internal friction on the other one. The ratio of these two acting factors is one of the possible interpretations of Reynolds number . Another interpretation is in its role of a parameter of hydrodynamic similarity. There is generally no problem with the large devices of power fluidics, with Reynolds numbers typically of the order of $Re \sim 10.10^3$ (in other words, viscous friction forces are $\sim 10.10^3$ weaker than the inertial forces). At these Reynolds number there is usually turbulent character of the flow (Fig. 7). This used to be a source of noise amplified together with weak signals. A solution to the noise problem was found in LPA – laminar proportional amplifiers – but for most present applications of fluidics this is not an important aspect.

In typical examples of present-day applications of power fluidics the amplification and noise aspects are irrelevant. The key factors are the reliability, ease of manufacture, long life and

FLUIDS ARE NEEDED :

○ Power generation and transfer
○ Signal transfer
○ Heat transfer (e.g., cooling)
○ Chemical reactions
○ Biomedical material
○ Food (and wastes)
○ Lubricants, paints, solvents
○ Hydraulic transport
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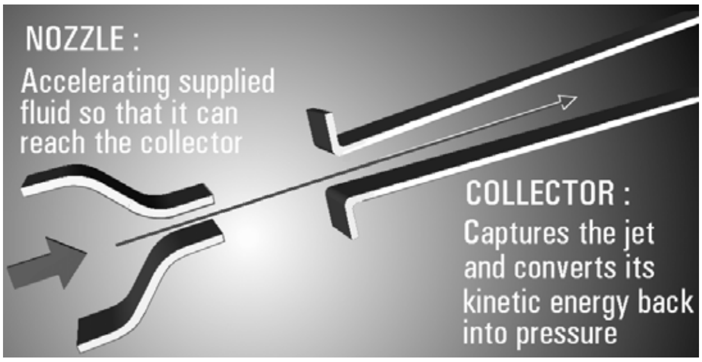
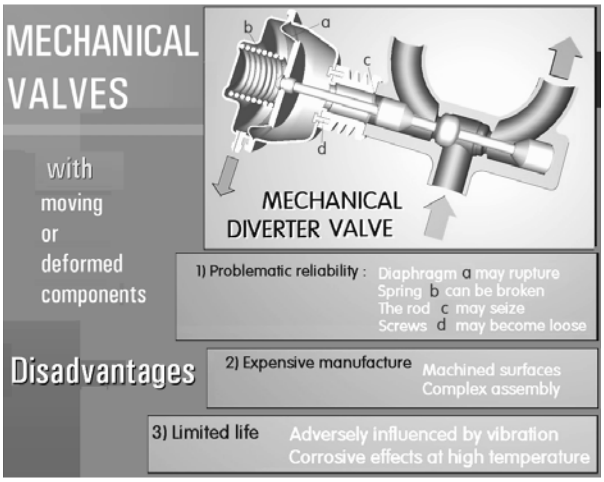


Fig. 3 (Left) However convincing are advantages of electronics in its competition with fluidic signal processing, there are many cases where fluid simply has to be there. Chemical reactions or use for food purposes accept no alternative. Power generated in turbines and combustion engines – and heat transfer in cooling and heating – are also areas where use of a fluid is inevitable. Note that chemical reactions usually take place in fluid phase (if there is a solid reagent, it is usually pulverised and hydraulically transported). Fluidics has no alternative in handling lubricants or paints. Most fluid handling is currently done by mechanical components – but pure, no-moving-part fluidics generally offers a better alternative. **Fig. 4 (Right)** In the absence of a mechanical component directing the fluid into the desired direction, fluidics typically uses inertia of fluid (accelerated in a nozzle) to get the same result. The space between the nozzle exit and collector entrance is sensitive to control actions.



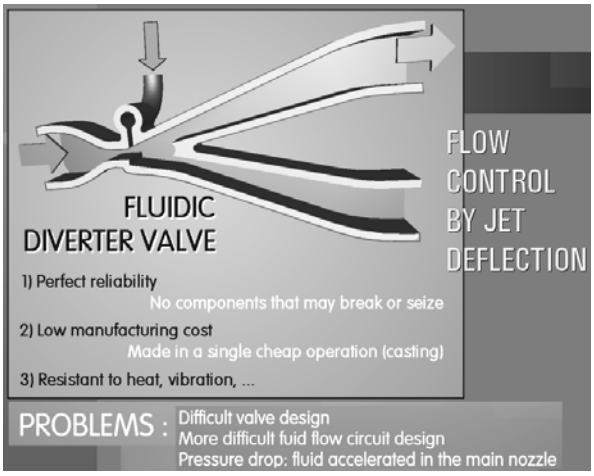
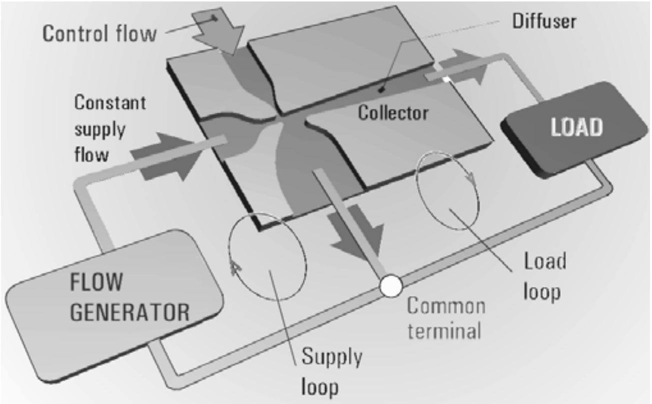


Fig. 5 (Left) A typical example of mechanical valve (this particular one was designed for switching of automobile exhaust gas flow into catalytic reactors, Tesař 2004) showing the reasons for problematic reliability, need for maintenance, and limited life. **Fig. 6 (Right)** No-moving part replacement of the valve from Fig. 5. To be fair, it is necessary to consider the more difficult design of the valve and the whole fluidic circuit and also the fact that due to the need for accelerating the gas flow (and imperfect performance of the diffusers) the pressure loss may be higher than in the mechanical valve.

resistance to adverse operating conditions. the Figures 5 and 6 present a comparison of a classical mechanical valve controlled by a fluidic signal and the corresponding fluidic valve. Shown in Fig. 5 is what may be a typical mechanical valve, of rather larger size. It is actually a vacuum controlled diverter valve for switching the flow of an automobile engine exhaust gas. Typically, like this example, mechanical valves are assembled form a quite large number of components. Of course, a manual assembly operation is expensive and implies a possibility of some components getting loose. Some of the components, like the membrane or spring in Fig. 5, are typically those that are easily broken. In this case of operation at high temperatures the design had to rely on materials preventing seizure and leaks. More often, these aspects may demand expensive maintenance: lubricating the contact surfaces and tightening the seals. On the contrary, none of these problematic aspects is present in the power-fluidics flow-diverting valve for the same task shown in Fig. 6. Note that it contains no components that may easily fail and the low price is ensured the whole valve being manufactured (by casting) in a single operation.



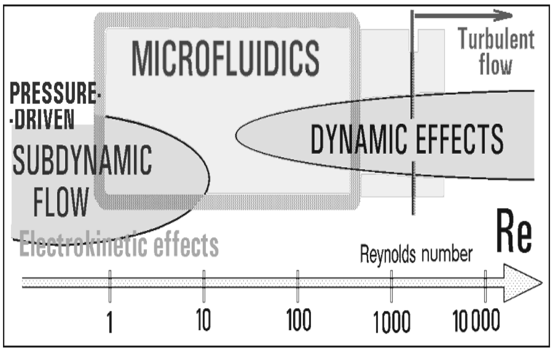


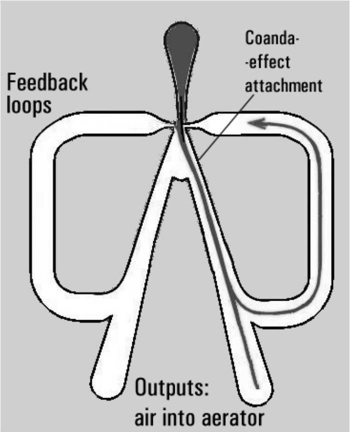
Fig. 7 (Left) The basic circuit of a fluidic amplifier, positioned between the generator (at left) and the load in which the flow rate has to be varied. This is done by an action of a control flow applied between the supply nozzle and the collector (cf. Fig. 4). This deflects a part of the main flow from the generator into the by-pass. Needless to say, real fluidic amplifiers are more complex. **Fig. 8 (Right)** The main problem of microfluidics is its occupying the range of very low, laminar-flow Reynolds numbers where the dynamic effects of Fig. 4 cease to be useful. New principles, like driving fluids by pressure (Tesař 2007a) or by electrokinetic effects, are currently developed.

To the contrary, typical conditions in microfluidics — in particular when applied in the currently very attractive biomedical applications — differ very much from those in power fluidics. The small size and the usually high viscosity of biological fluids causes the Reynolds numbers to be often of the order less then $Re \sim 10^3$ (sometime significantly less, perhaps even $Re \sim 10$). This places the operation at the very verge of conditions at which the methods of standard fluidics may be applied. As a result, present-day publications in the field of microfluidics are abundant with papers on various different, sometimes downright exotic operating principles. They may be divided into two groups. There is a hydrodynamic branch of the principles, which contains flows driven by pressure difference, by centrifugal action in mechanically rotated devices, by acoustic streaming, surface acoustic waves (travelling along elastic solid walls with an amplitude decaying with depth), thermal expansions, evaporations, and surface tension effect. In the other branch are principles further away from the standard fluid-mechanical fluidics. There are usually various direct electric actions causing the fluids to flow, like electro-wetting, electrokinetic osmotic effects, and electrophoresis.

3. Current successful uses of power fluidics

Merits of power-fluidic devices are not so much in the wide frequency spectrum (there is no limit due to inertia of mechanical components, but because of the larger size power-fluidics devices are generally slightly slower). Their advantages (e.g., Tesař 2004, 2005) are robustness, reliability, long life, low cost, no need for maintenance, and – because of the suitability to be made from refractory material - resistance to heat, shocks, vibration and even nuclear radiation.

One particular development direction of large-scale fluidic devices has been fluidic pumping. The basic idea is rectifying - by no-moving-part rectifiers - the alternating liquid flow generated by periodic action of compressed air in a displacement vessel or pipe (Fig. 10). The alternating air flow may be generated in a fluidic alternator. Initially, effectiveness of these pumps was not impressive and the applications were therefore sought in those situations where efficiency was secondary to the absolute reliability and leak-proof properties. Such an extremely demanding environment was found in pumping radioactive liquids in re-processing of nuclear fuel. The pioneering work was done at the University of Sheffield (Tippetts and Swithenbank, 1974) in contract for British Nuclear Fuels Ltd. The results - development and performance improvements of a rectifier called RFD (reverse flow diverter) were soon



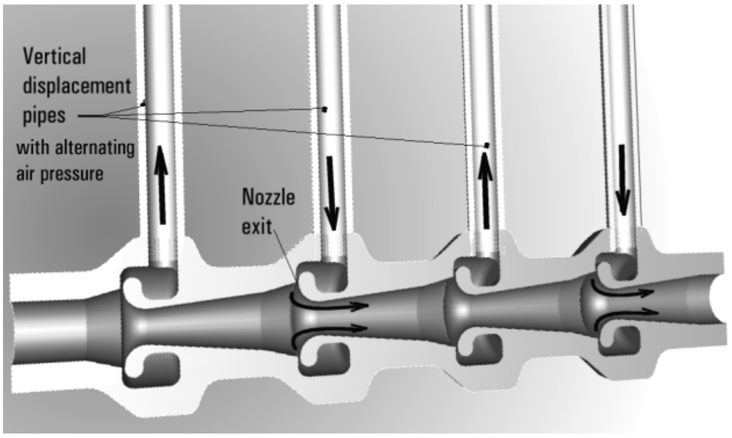


Fig. 9 (Left) A typical fluidic as they are used for pulsating the air in microbubble generators. The diverter amplifier with Coanda-effect bistability is provided with feedback loops carrying a part of the output flows to the control nozzles where they cause separation from the attachment wall (Tesař 2012). **Fig. 10 (Right)** The rectifier of a fluidic pump for transporting dangerous liquids by two-phase alternating action of air in the displacement pipes (Tesař 2011a).

imitated by others active in nuclear engineering, in particular at the Oak Ridge National Laboratory in the U.S.A. The ONRL results were later declassified (even their internal research reports became freely available on Internet). It may be this data availability that led to the recent re-newed interest (Fun 2009, Gao 2010) in the earlier single-phase designs, while there has been already a much more effective two-phase forward-flow diverter design (Tesař 2011a, 2011b).

The other area of increased activity are fluidic oscillators (e.g., Fig. 9). An interest in their use came from two directions. One of them is the active control - by jets - of flow separation and transition into turbulence on objects like aircraft wings and turbine blades. The control action is more effective if the jets pulsate — and the ultimate case are the synthetic jets, a popular subject of research activities in many aerodynamic laboratories. The pure synthetic jets are less effective than the “hybrid-synthetic” ones (Trávníček et al., 2006), which are also very effective in heat/mass transfer by jet impingement (Tesař 2011c). Special actuator versions (Tesař V. et al., 2006, 2013, Khelfaoui R., et al. 2009, Arwatz et al. 2008) of fluidic oscillators generating the hybrid-synthetic jets are currently developed.

The other development based on fluidic oscillators is their use in generation of microbubbles (gas bubbles in liquids of diameter less then 1 mm), Tesař (2012). The widespread applications of bubbles in various technological processes are overwhelming. Bubbles are the key factors in wastewater treatment, paper manufacture and recycling, oxidative leaching of plutonium, photoresist removal from silicon wafers, separation or concentration of various materials by froth flotation, yeast production, sonochemical synthesis, production of biopharmaceuticals, salvaging remaining crude oil from „exhausted“ oil wells, and extracting liquid fuels from bituminous tar sands (— estimated to contain more than two-thirds of total global fossil fuel deposits exploitable in near future). Particular attention is paid to the very promising activity in growing unicellular plant and organisms. These are expected to become the base of the near-future food chains — and is at the same time seen as the solution of the problem of removal man-generated CO_2 from atmosphere. Microbubbles are essential for success because of their high surface-to-volume ratio (an essential factor in diffusive transport) and slow velocity of rising to the surface (giving more time for the transport).

Last but not least mentioned is the use of fluidic solutions for the progress in development of fuel cells, which may change the very character of automobiles. As a side note may be mentioned the recent use of fluidics and microbial fuel cells in marketed autonomous robots catching slugs (difficult to eradicate pests, costing £ 20 million per annum only in the U. K.). The robot sees slugs as infra-red sources, kills them and processes their fermented bodies in an on-board microbial fuel cell energy source.

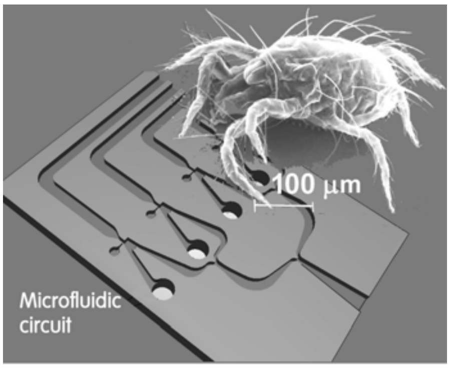
4. Microfluidics

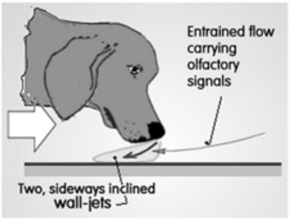
The ambivalent relationship of fluidics and electronics – the latter having nearly eradicated fluidics in its earliest days - had during the last decade developed into another symbiosis. The small size of microelectronic devices necessitated development of equipment for their microfabrication. The major concepts are microlithography, doping, thin film deposition, etching, electron beam machining, and bonding. The capability to manufacture small, submillimetre features on a substrate opened a road to making also small channels and cavities for fluid flows at the microscale. This was the birth of ***microfluidics,*** Fig. 9, rapid development of which is still continuing. There is a surprisingly large number of applications in which just the very possibility to make the fluidic devices small brings a substantial advantage – in those cases where the task involves vast numbers of simultaneously performed tests (an example being discovery of new materials and medicaments by combinatorial chemistry). Another application simple in principle is the controlled injection of liquid droplets or the delivery of medicines (Fig. 14 – with a typical collaboration with electronics).

The intensification due to the small size (and substantially improved controllability, the small devices having short time constants) have already improved substantially several processes long known but until now impractical due to large size and weight. This the case of the cooling garments for soldiers fighting in hot climate (essential improvements were in the field of portable absorption cooling units). Another case is the taking part in the expected revolutionary change in automobiles (fluidic can make more effective fuel cells as well as the on-board producing hydrogen from petrol by the steam-reforming process).

A wide field of microfluidic applications has been already found for various sensors: miniature chromatographs, measurement of olfactory (Figs. 12 and 13) and taste signals, and the most important miniature on-chip DNA analysers with multiplying the number of tested protein molecules by the integral polymerase chain reaction. The latter is not only essential for fast identification of persons (particularly lucrative is the paternity testing) but opens to fields like objective diagnoses of illnesses (Fig. 15) by means of analysing the proteins of the pathogens.

Micromanufacturing processes made possible producing arrays of hollow needles so small that they may be inserted under skin painlessly – so small that the insertion take place between the nerves of peripheral nervous system. The needles may be then used for either stimulation or transmitting under skin e.g. therapeutic proteins — or for transferring the neural signals to an external computer. The actual signal processing, of course, is the task of electronics, nevertheless fluidic delivery chips are essential for delivering anti-inflammatory





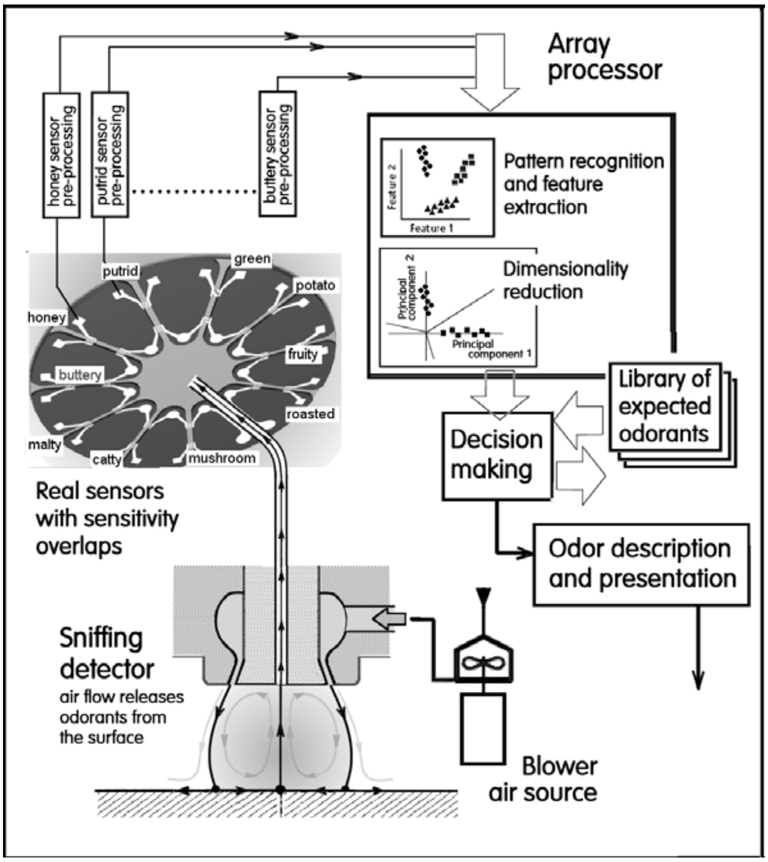
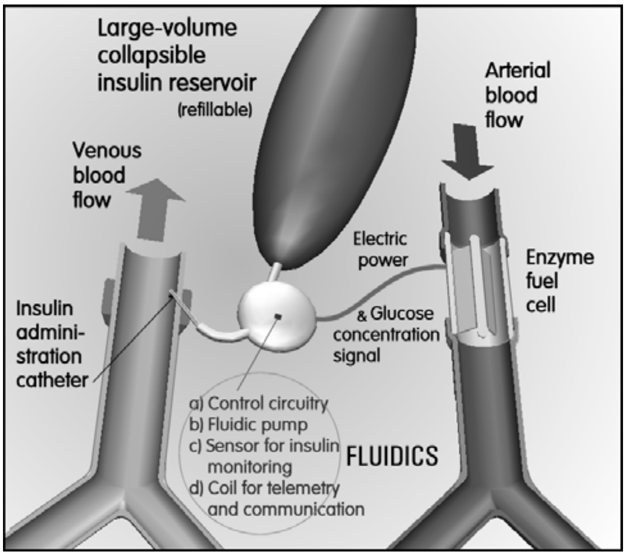


Fig. 11 (Left, top) The size of present-day microfluidic valves is comparable to the smallest living creatures, - here mites (Acari) hardly visible by naked eyes. The Reynolds number of the microvalves which are shown here may be too low and the standard working principles of Figs. 4, 7 at the very verge of their applicability. **Fig. 12 (Left, bottom)** The “fluidic nose” needs copying the Nature’s design of sniffing animals, releasing the smell traces from the solid surfaces by action of wall-jets. **Fig. 13 (Right)** The artificial nose operates by detection and discrimination between 10 basic odours. Typically, the main problem is in electronic processing of the signals and assigning the results to a meaningful denotation.



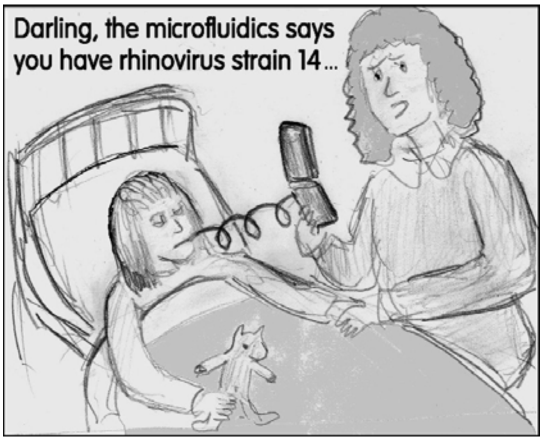


Fig. 14 (Left) An example of an implantable drug dispensing. The diabetic with this system implanted can forget completely about his/her illness (no need to adhere to any diet), microfluidics ensuring exactly balanced dosage of insulin. Typically, the system is a collaboration with electronic control, in this example driven not by batteries but by enzymatic fuel cell using glucose and oxygen contents of the arterial blood flow. **Fig. 15 (Right)** This picture is meant to be a joke — users are actually not expected to be given the diagnostic results in medical terms — nevertheless, it conveys the basic idea of the distributed domestic healthcare.

and other agents. Developed under the European Commission project were, e.g., electric connector implantable into neural axons to communicate with living objects. There are therapeutic applications like cochlear prostheses to improve impaired hearing or even deafness, retinal implants to remove blindness, and there are good prospects of managing epilepsy or Parkinson’s disease. On the other hand, the fluidics involved can ensure chemical stimulation of neurons. The implants are commonly tested on small animals like rats, the behaviour of which has been demonstrated to be remotely controlled. From there is, in

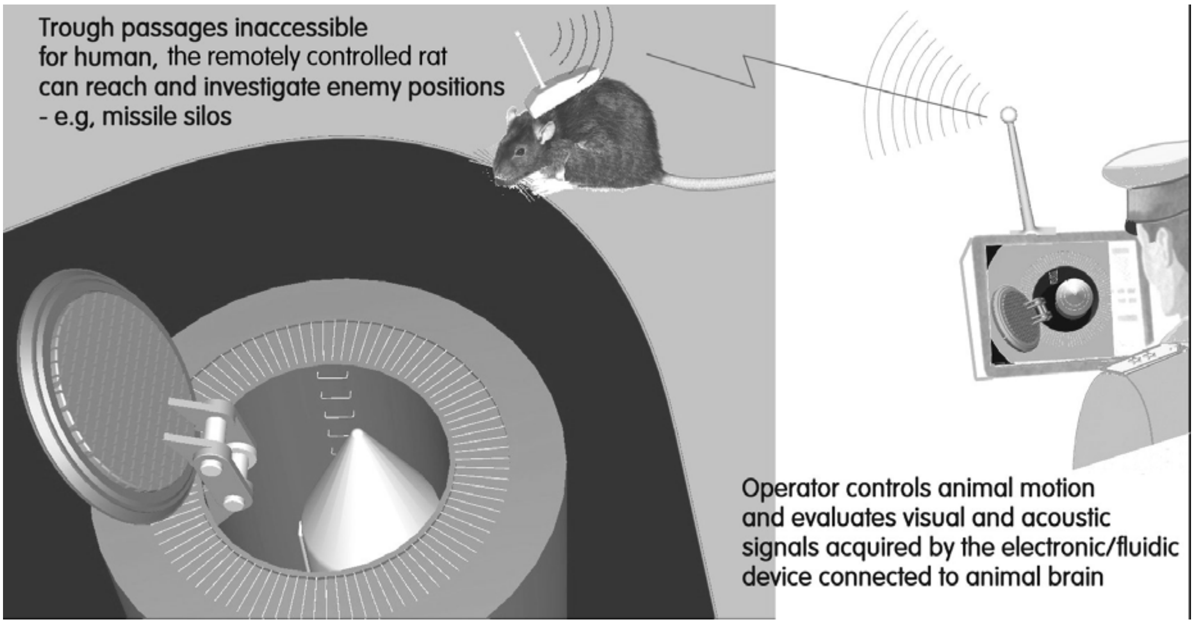


Fig. 16 Interfacing with central nervous system of animals is a reality (Tesař 2007b), using arrays of microfluidic needles implanted into the brain. Remote control of small mammals and processing signals received from their senses has been developed for military applications. The animal may receive into its blood the glucose dosed by a microfluidic pumping system so that it is not distracted from its task by search for food.

principle at least, only a small step to use the controlled animals e.g. for defence purposes – Fig. 16. Defence advanced research projects agency DARPA in the USA has already some time ago financed a similar HI-MEMS hybrid insect projects at Advanced Technologies Laboratory at Tufts University involving analogous remote control of large insects – the moth *Manduca sexta.* In the pupa ontogenetic stage in obtained in its body a transmitter, control computer, and fluidic reservoir of glucose pumped into the insect's hemolymph increasing its flight endurance and was demonstrated to be able to reach. The advantages of using unmanned devices to conduct dangerous or difficult operations are obvious.

5. Conclusions

This paper presents a brief survey of fluidics as the technique of handling fluids without moving or deformed components. Its developments were recently focused on two development directions. One of them is the power fluidics, handling larger flow rates and with devices correspondingly large. Results of these developments are no-moving-part fluidic pumps for dangerous liquids and fluidic oscillators used in generation of microbubbles (of diameter less than 1 mm) desirable in many process engineering applications. In particular, the oscillators made possible considerable progress in waste water processing and growth of unicellular plants. The other rapidly growing development direction is microfluidics, typically often applied integral with electronic circuitry on the same substrate. It has immense possibilities in sensors and also in handling small amounts of fluids e.g. in microchemistry. The brief lists of recent results includes miniature on-chip DNA analysers, artificial olfactory and taste analysers, and the communication with central nervous systems.

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