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PRESSURE-DRIVEN MICROFLUIDICS

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Summary: *Microfluidics is a new field of fluid flow generation and control at small scales, making possible fundamental changes in some engineering and biomedical fields. Particular advantages bring devices operating without moving parts – but at the usually small Reynolds number it is difficult to use jet inertia, upon which no-moving-part fluidics is based. The paper presents, on an example, a solution: flow assisted - or downright driven - by applied pressure difference.*

1. Introduction

1.1. *Meaning and Importance of Microfluidics*

Microfluidics is a technique of manipulating fluids at small scales - characteristic dimension (e.g., channel width) of microfluidic devices is less than 1 mm. The small dimensions are particularly suitable for handling objects of biological and medical interest, like bacteria and cells. Considerable part of current literature on microfluidics thus discusses detection, sampling, sorting of pathogens, and also, e.g,, DNA analysis or drug delivery in implanted devices Nevertheless, there are also important uses of microfluidics in more traditional engineering fields, like discovery of new materials (e.g., Tesař 2008), microchemistry, sensors, or fuel management for fuel cells. At the small sizebecome important - in relation to the volume forces acting on fluid. - surface effect. As a result, present-day microfluidics often uses for generating and controlling the fluid flow non-traditional surface phenomena, negligible in the large-scale hydro- and aerodynamics. The commonly used fluid driving actions are:

"Neutral" traditional fluid driving
- by pressure
- by centrifugal forces
- by surface tension

Electrohydrodynamic (EHD) driving
- electrophoresis
- electro-osmosis

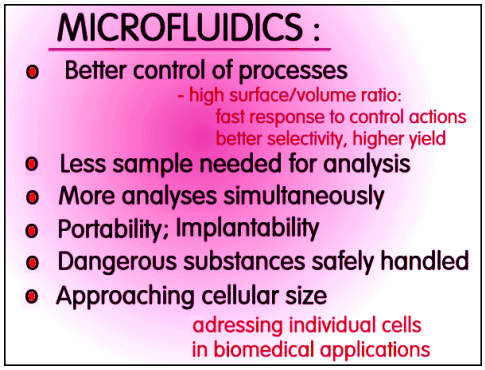

Fig. 1 Typical advantages brought by the small size are those listed here as encountered in microchemistry, which is one of the most successfully developing applications of this new field.

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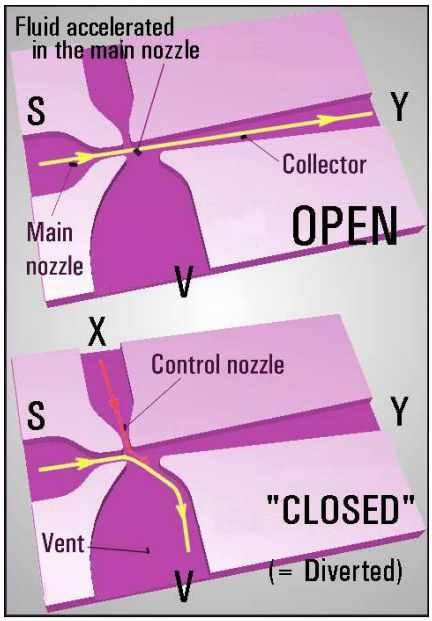
The electrokinetic phenomena applicable to the purpose occur when a charged surface is brought into contact with ions in a liquid. The surface attracts counter-ions so that a diffuse electric double layer forms on it (the layer thickness ranging from $10 .10^{-9}$ m to $2 .10^{-6}$ m). Remaining ions away from the wall may be driven – dragging along the rest of the fluid – by an applied electric field. The effect only becomes significant for channel widths on the scale of microns when the double-layer thickness is a non-negligible fraction of the channel width.

1.2. *Pressure-Driven Microfluidic Flows*

One of the reasons for remaining within the realm of the traditional "neutral" fluid mechanics is the requirement the character of the electrokinetically driven fluid: the ions are formed by dissociation of molecules of solutes only in polar liquids. This limits the applicability of the electrokinetics to practically only water. While water-based liquids are widespread, especially in the biomedical applications, there are tasks where the fluid to be handled is different – in particular, if it is a gas.

The spectrum of tasks the microfluidic devices carry out is extremely wide (cf., e.g., Tesař 2007). The most important and most often encountered task is control of flows. This is performed by flow control valves. Despite there being a range of various mechanofluidic valves – with the flow acted upon by a movable mechanical component – the most promising are the no-moving-part versions. They are easier to manufacture, more reliable, and more resistant to various adverse influences. Figure 2 presents an example. It is the simplest valve possessing all four basic terminals (supply, control, output, and vent – many valves actually have more terminals but there Are also ones operating without the vent). Typically, the valve is of planar shape, with cavities of constant dept made by some of the modern microfabrication methods, such as, e.g., etching.

Like most purely fluidic valves, the one shown in Fig. 1 is of the jet type. The fluid supplied through the terminal S from a source (a flow generator, such as, e.g., a pump) issues



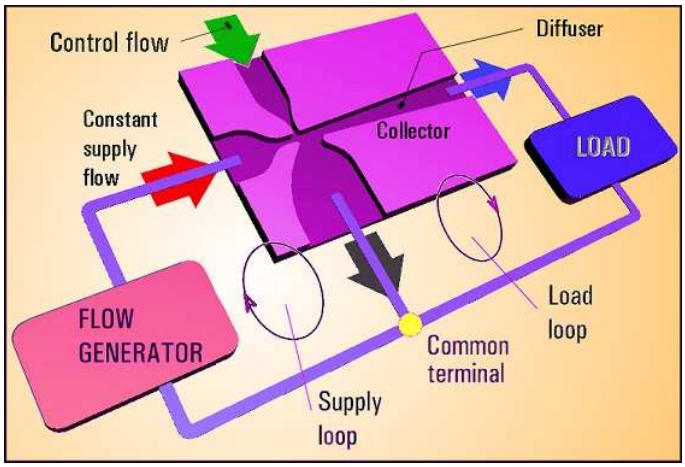
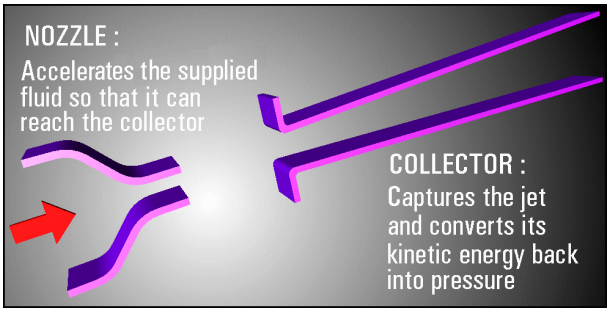


Fig. 2 (Left) An example of a fluidic valve with the four basic terminals. **Fig. 3** (Right) A typical use of the valve from Fig.1 for by-pass mode control of flow in a load. Note that the pressure drop across the load is essentially equal to the pressure rise in the diffuser of the collector.



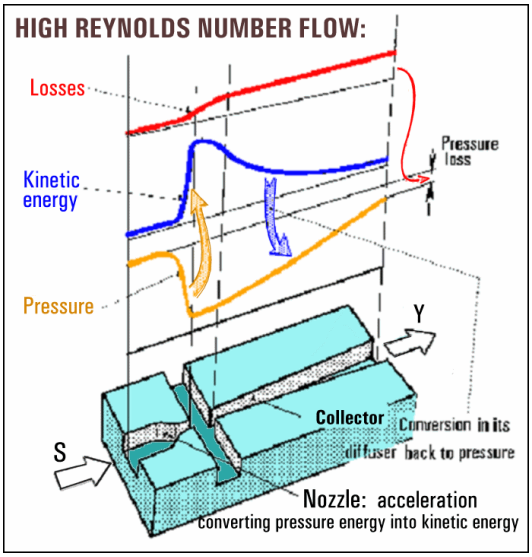


Fig. 4 (Left) The basic principle of jet-type devices: fluid accelerated in the nozzle can cross the gap and get captured in the collector still with considerable energy. **Fig. 5** (Right) A typical energy conversions in a fluidic device: high velocity would mean high losses downstream from the gap and to prevent this to happen, fluid is to decelerated in the collector's diffuser.

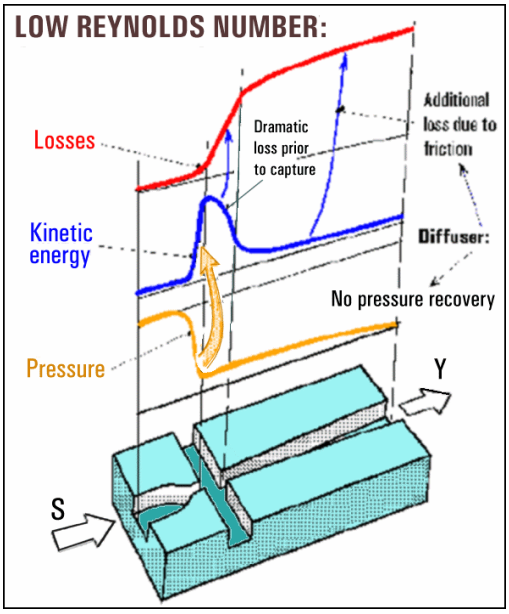
from the main nozzle in the form of a jet. This is accelerated in the nozzle so as to be able to traverse, due to its inertia, the open space between the nozzle and the collector (Fig. 4). When captured in the collector that re-converts back into closed-conduit flow in the output terminal Y, the fluid in large-scale fluidic devices usually passes through a diffuser, Fig. 5 slowing it down – because at the high velocity typical for jets the losses (proportional roughly to the square of velocity) would be inconveniently high.

The control action, in the form of the control flow brought into X (Figs. 2, 3), deflects the jet so that the amount captured in the collector becomes smaller; the output flow thus decreases. The valve, as shown in Fig. 3, is placed between the fluid source and the device in which the fluid flow is to be controlled. The valve operates in the by-pass control mode. There os no turning-down action, typical for diverter valves. For example in microchemical fluidics the load may be a microreactor supplied by reactants from a micropump source and the task of the valve is to adjust the required reactant flow rate to fit the instantaneous reactor operating conditions. The control may be either "ON-OFF" or continuous.

With the decreasing Re, typical for modern microfluidics, the friction forces acting on the fluid increase and tend to overcome the inertia of the fluid jet. It then reaches the collector entrance with insufficient convertible kinetic energy. Also the diffuser conversion efficiency deteriorates at low Re, Fig. 6. The available output pressure becomes too small to provide the required flow through the load. Too much fluid leaves the valve through the vent terminal even at zero control flow.

What can be done to improve these conditions ? The valve designer can either:

- *Decrease the nozzle-to-collector distance to give less opportunity to the jet to slow down by its mixing with the vent fluid, or*
- *Restrict the cross section of the vent terminal to make the spillover flow into the vent less easy.*



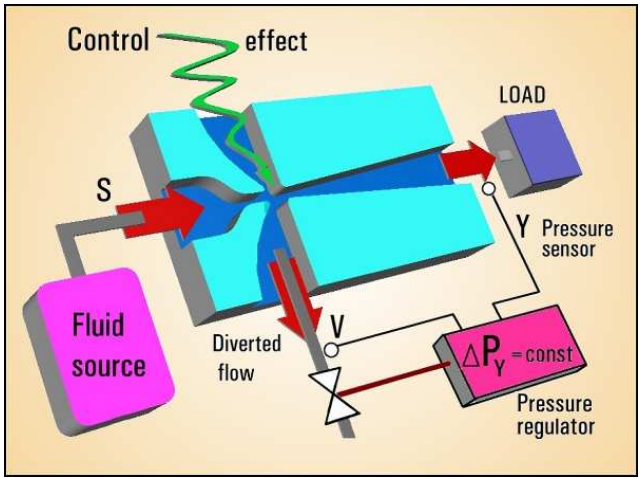
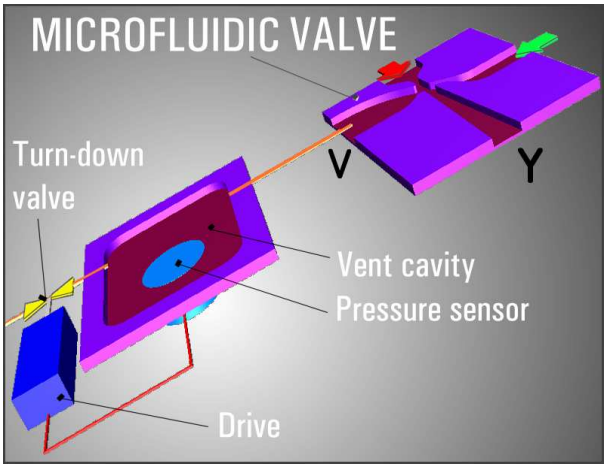


Fig. 6 (Left) Due to high friction losses at low Re, the jet fails to keep its kinetic energy and also the diffuser is ineffective. **Fig. 7** (Right) One possible solution evading the adverse low Re effect is to drive the fluid through the collector towards the load by a maintained pressure difference.

Both measures increase the pressure at the collector entrance and hence force the fluid to pass through the collector and the output connected to it. Unfortunately, both make it more difficult to perform the control action. It becomes more difficult (and calls for a higher control power level) to deflect the jet sufficiently on its short path. Also the increased resistance of the vent makes it more difficult for the diverted fluid to leave the valve. If the cross-sectional restriction is really considerable (as it is indeed to obtain a significant effect at very small Re, let us say below about 100), it is not uncommon to find a surprising reversal of the control effect: the admitted control fluid finds it easier to leave the valve through the collector rather than through the very restricted vent. Instead of the expected decrease the output flow rate tends (at least initially, before the control flow obtains a large momentum) to increase with increasing control flow rate.

2. Layouts of Pressure Control

A simple partial closure of the vent flow path by a fixed cross section restriction would cause also other unwelcome effects in the overall fluidic system circuits. Adjusting the proper restriction is far from easy. In a system with a number of mutually independent valves, the simple restricting would produce a dependence of the system on the instantaneous states in the valves. A better solution is an adaptive throttling Fig. 7. In view of the fact that in the context of MEMS it is not difficult to provide (perhaps by doping and processing parts of the same silicon chip on the surface of which are the etched microfluidic cavities) a pressure sensor and the electronic control circuits, the pressure assisted (if the pressure difference merely assists the non-negligible kinetic energy of the jet) and pressure driven valves are an acceptable choice. The regulator is in effect a variable restrictor with changing exit cross section – achieving a constant driving pressure difference between the vent gap in the control



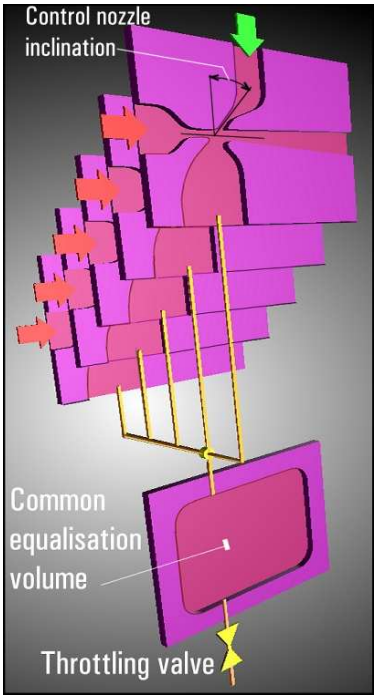


Fig. 8 (Left) The regulator generating the driving pressure difference usually operates by turning down the fluid flow leaving the valve through the vent. **Fig. 9** (Right) There are situations where the pressure difference in the vents may be maintained simply by adjusting the common turning-down (or throttling) valve.

valve and the load, see also Fig. 8. Quite often, the fluidic circuits with the valves are so arranged that the driving pressure may be maintained by a single regulator. There are rather special (but surprisingly often encountered) microfluidic circuits consisting of a large number of identical valves operated in a binary manner (in "ON" or "OFF" alternative regimes) so that a constant a constant number of the valves at any time is in the "CLOSED" or "ON" state diverting the supplied fluid flow into the vent, while all the rest of valves are in their "OPEN" or "OFF" state. This is, e.g., the case of the fluidic multiplexer sampling unit to be discussed below. In this case, the pressure control circuit, of course, suffices with a simple passive throttling in the common vent outlet, as shown in Fig. 9. The throttling valve may be adjustable (perhaps manually), but this serves only for setting up the desirable operating conditions and eliminating the influence of inevitable manufacturing tolerances.

The problem of the required high control power needed to control the valves in these regimes is a serious one. In most cases, it is simply necessary to accept the strong control flows as necessary. In the present author's experience, it has been often inevitable to operate with the so called „fractional" gain, i.e. instead of the usual amplifier properties of the control valve the output signal in these cases is a mere fraction of the input control signal. If the operating Reynolds number is not very small so that the assisting pressure difference is not high (precise meaning of what is "high" in this context will be given below in association with the introduced parameter Te), the problem with the required high control power may be made easier – or perhaps solved - by just optimising the control action: increasing the efficiency of the deflecting action of the control flow. Decreasing the width of the control nozzle may help, but the opportunities in this direction are limited, in particular by the maximum aspect ratio (depth/width) of channels that may be produced by the currently stan-

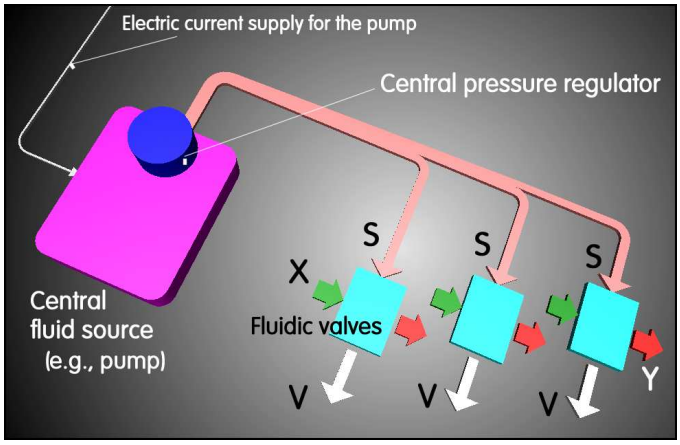
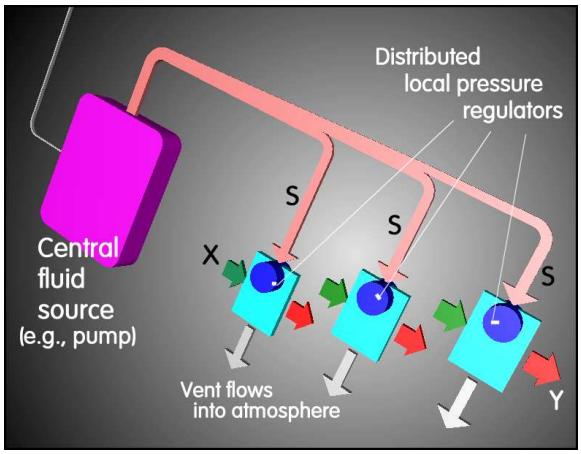


Fig. 10 Typical configuration of a fluidic circuit: the fluid into the devices is supplied by a central common source. Here the vent flows are dumped into atmosphere — alternatively (especially if the working fluid is a liquid) they may be recirculated into the source.

dard isotropic etching manufacturing method. If plates containing the valves are etched through, they may be stacked to obtain quite high aspect ratio, but this complicates the manufacturing and assembly by another unwelcome (expensive) step. Some helpful effect is obtained by inclining the control nozzle towards the main nozzle, as is seen e.g. in Fig. 9.

The usual layout of obtaining the driving pressure difference by throttling the total vent flow is shown in Fig. 13. Sometimes fluidic circuits do not operate predictably and there is no easy way of predicting at the design stage the total of vent flow rates. Then the pressure driving may require a different approach, perhaps with distributed pressure regulators – Fig. 11, provided theregulators can be made small and inexpensive. Yet at another possibility is generating the fluid flow directly at each fluidic device, as shown schematically in Fig. 12. Of course, this requires rather simple and inexpensive pumps – perhaps of the sort currently



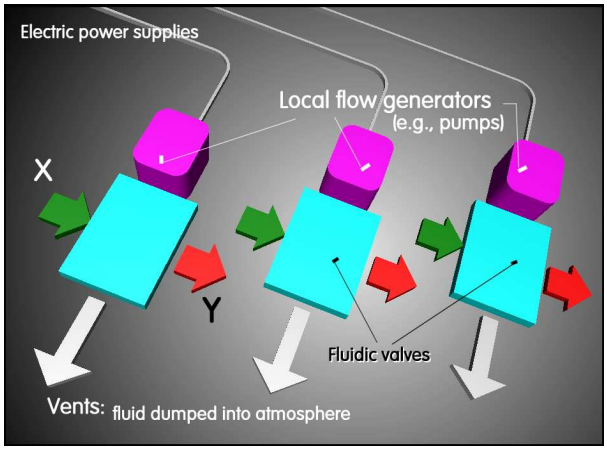


Fig. 11 (Left) Alternative to the configuration from Fig. 10: the fluid pressure is adjusted separately at each driven fluidic device. Because of the typical coexistence of microfluidic and electronic circuits on the same chip, the needed large number of regulators (most of them, after all, rather simple) may represent no problem. **Fig. 12** (Right) Yet another alternative configuration: each fluidic device has its own flow generator.

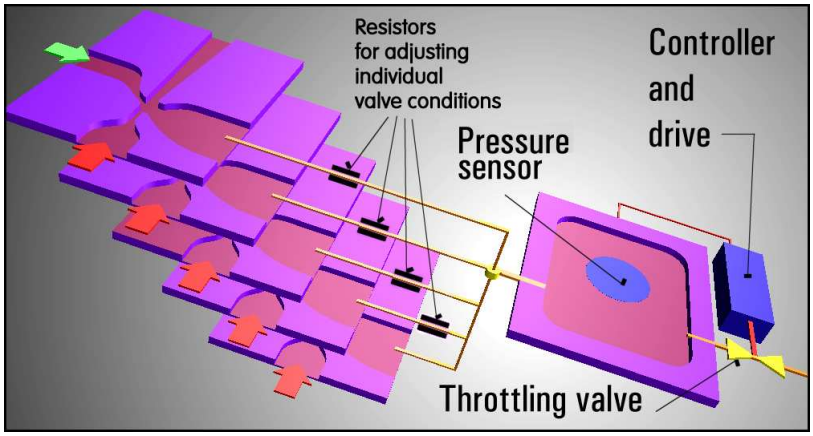


Fig. 13 Usual configuration of driving pressure keeping circuits: essentially a combination of the layouts from Figs. 8 and 9. The pressure is maintained by throttling the total vent flow. Individual pressure requirements of various valves are taken into account by the restrictors.

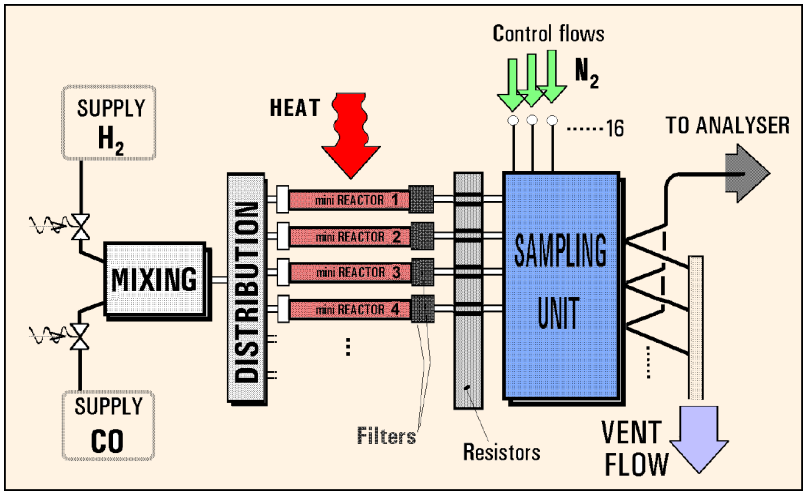
developed for control of flow past bodies by a large number of small synthetic jets. At any case, the design of the fluidic circuits involving the generation of suitable driving pressure differences complicates the fluidic circuit design – the more so, that at the same time the no-moving-part fluidic devices require proper matching of sources and loads to achieve effective power transfer.

3. An Example: Microfluidic Sampling Unit

It may be useful to describe the practical aspects of these problems on a practical example from the present author's experience with valves operating at low Reynolds numbers. Because of the special demand for purity of the handled fluids, the particular design task was admittedly slightly more difficult to solve than it is in typical cases. The essential experimental investigations, typically for present-day microfluidics, were performed on scaled-up laboratory models. The higher than usual demands on the pressure adjustment led to more fundamental investigations involving numerical flowfield computations, which showed the importance of the dimensionless pressure parameter.

3.1. The Task

The small size of microreactors and other microfluidic devices makes it possible to perform a large number of chemical tests in parallel under nominally identical pressure and temperature conditions and this is particularly useful for discovering new materials and drugs (Tesař, 2008). In particular, one of the very attractive uses of microfluidics (and the associated microchemistry) was discovery of new and more effective catalysts. This was the aim of an interdisciplinary collaborative research project *"High Throughput Parallel Catalyst Testing"* supported by the Institute of Applied Catalysis ¿**A**c, involving a development of a suitable microfluidic catalyst testing system. The system was specifically intended for identifying advanced heterogeneous catalysts for the Fischer-Tropsch process. This is a chemical reaction of immense importance, its drawback being a high required temperature and pressure level at which the reaction takes place. The reaction is a catalysed one, strongly



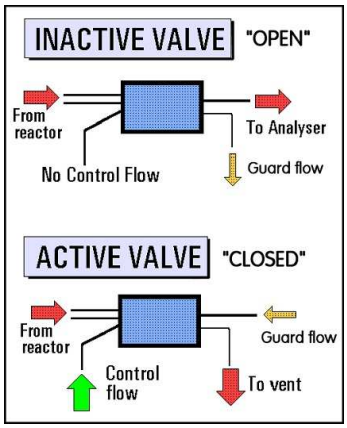


Fig. 14 (Left) Schematic representation of the microfluidic catalyst testing facility. **Fig. 15** (Right) Schematic representation of the operation of the microfluidic valve – switching between the "OPEN" and "CLOSED" states. The sampling unit essentially consists of a large number such valves.

dependent on use of catalysts, which are usually based on mixtures of iron and cobalt. The process converts carbon monoxide gas and hydrogen gas into liquid hydrocarbon fuels, lubrication oils, or ethanol. Recently, a combination of gasification of biomass (and household refuse) and the Fischer-Tropsch synthesis is considered to be a very promising route to produce renewable transportation fuels. Also, there are investigations underway to reduce the otherwise seemingly unavoidable CO_2 emissions generated by combustion engines by using solar power to convert the emissions into the suitable CO reactant for Fischer-Tropsch production of hydrocarbons.

New catalysts are still being sought[α] to decrease the present inconveniently high required pressure and temperature and improve the selectivity and yield of the reaction. The efficiency of the catalysts is measured by composition analysis of the reaction products (Wilkin et al., 2002). In the *i*Ac system the instrument used is an IR analyser. As it is very singular and expensive and the reaction kinetics is not high, it was decided to use a single analyser supplied by samples in a cyclic manner from individual reactors. The task of selecting a particular sample is performed by the sampling unit, Fig. 14. This is essentially (Tesař 2002b) a multiplexer containing a large number of sequentially opened valves, each operating in the two-position (OPEN – CLOSED) regimes as shown in Fig. 15.

The sampled and analysed fluids are gases, typically hydrogen, carbon monoxide, methane, and Syngas, which is a mixture of hydrogen and carbon monoxide. The conditions inside the reactor are severe: temperatures typically in the range from 200 - 400 ^{o}C and absolute pressures up to 1 MPa. The pressure inside the sampling unit may be decreased by passing the exit flow of reactants through a bank of flow restrictors, but it nevertheless remains at a considerable level and together with the unavoidable high temperature (the system operates inside an oven) were among the factors that led to the decision to design the system as consisting of no-moving-part microfluidic units.

[α] In August 2008, Louisiana State University announced they had received $2.9 million funding from the US Department of Energy for development of new catalysts for Fischer-Tropsch reaction.

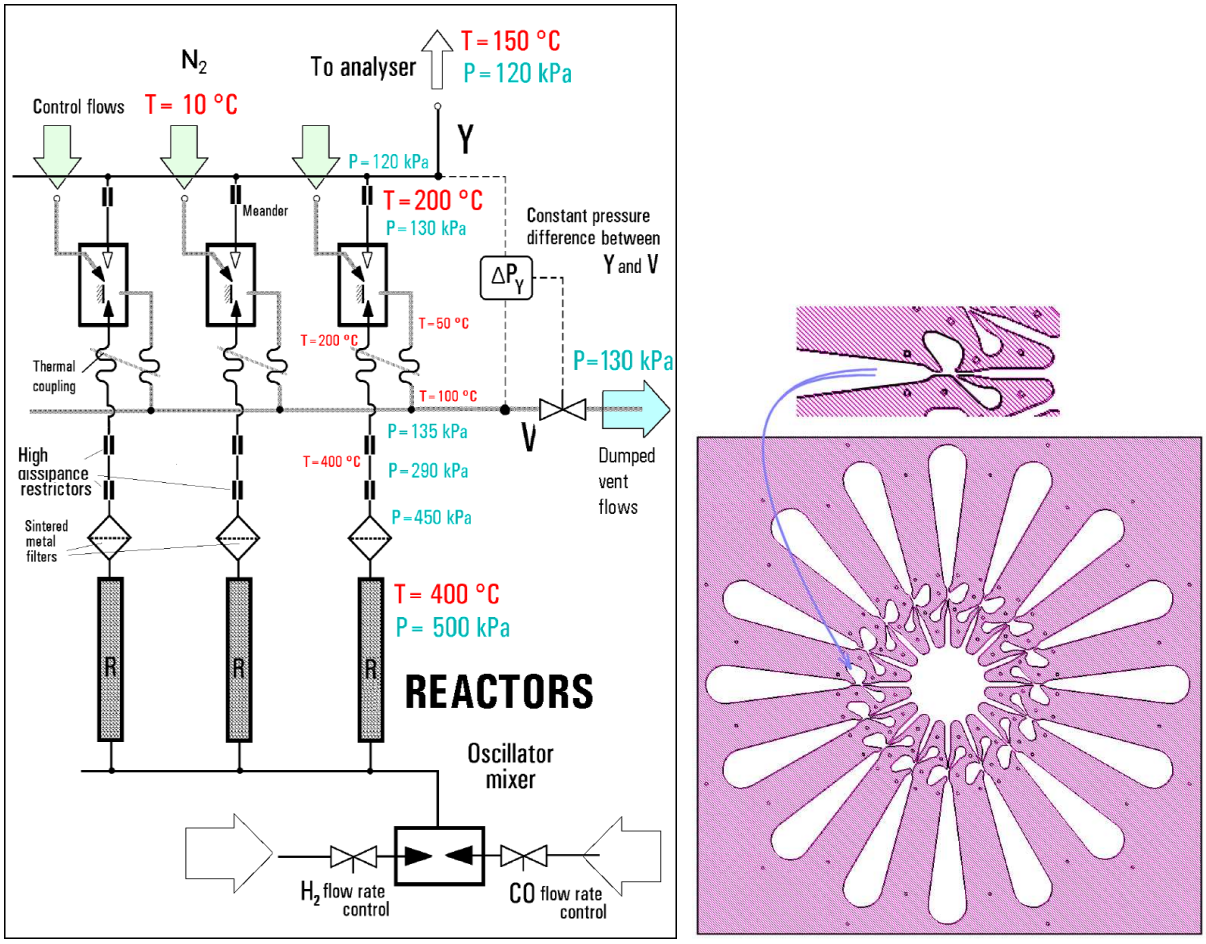


Fig. 16 (Left) Typical temperature and pressure levels in some locations in the catalyst testing facility. **Fig. 17** (Right) The basic parts of the sampling unit are thin stainless steel plates, each containing a circular pattern of 16 etched diverter valves surrounding the central output outlet.

The valves in the sampling unit operate in the "ON-OFF" regimes. Only one of them at any time in the "OPEN" state, allowing the sample to pass into the analyser. The control flow was to be nitrogen (chemically neutral with respect to the tested reactants), supplied from an external source.

The factor severely limiting the sampling unit design was the small handled gas flow rate. The chemical engineers who designed the reactors demanded the output flow rate to be only 600 ml/hour. Combined with the high viscosity of the gas at the high temperature levels, the resultant Reynolds numbers in a reasonably sized valve in the sampling units were typically as low as $Re \sim 90$. The pressure driven operation was therefore a necessity. Since the valve operation in parallel in the "ON-OFF" manner, the total vent flow rates are quite predictable. Together with the constancy of the total supply flow (passing through the main nozzles) and of the total control flow (only one valve active) this makes the task of designing the pressure driven microfluidic system in principle relatively simple: according to Fig. 9 it suffices to place the constant cross-section restrictor (as opposed to the regulated one in Fig. 13) into the common outlet from all vent terminals.

3.2. Operating principle and Guard Flows

Due to very little previous experience with the operation at the very small Reynolds number (although still above the sub-dynamic limit), the choice of the operating principle vas based on preliminary tests with several operational principles considered suitable for the task. The tests were performed in laboratory using scaled-up transparent laboratory models with cavities made by laser cutting. The working fluid was water. The main method in these tests was flow visualisation, for which different water flows were dyed by different dyes – Fig. 18. Results of these tests are described in more detail in the references Tesař 2001, Tesař 2002a, and Tesař 2003.

Initially, the principles that seemed to be most promising were those based on blocking the flowpath by the control fluid – 1 and 2 in Fig. 18. They can work reliably in very low Re creeping flows. Unfortunately, they were to be later discarded because of the increasing emphasis placed by the chemists and chemical engineers involved in the project on two aspects of the valve operation.

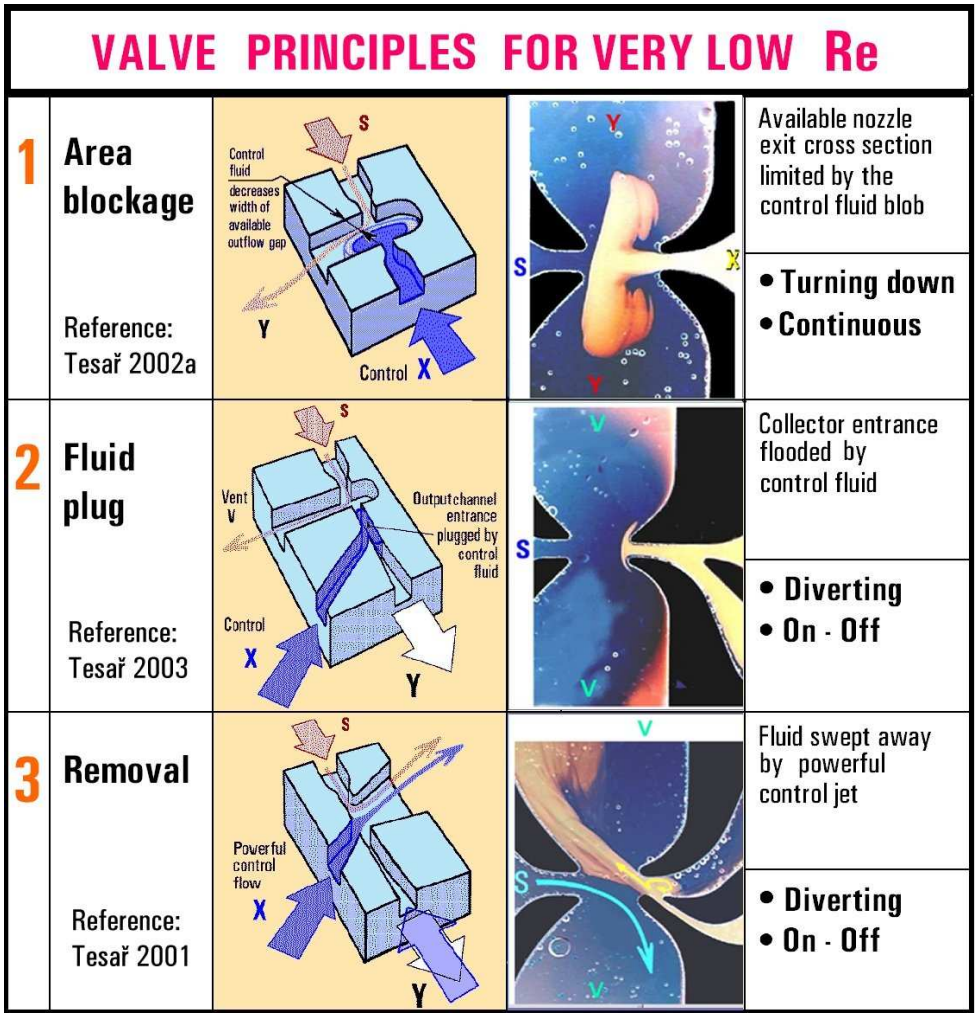
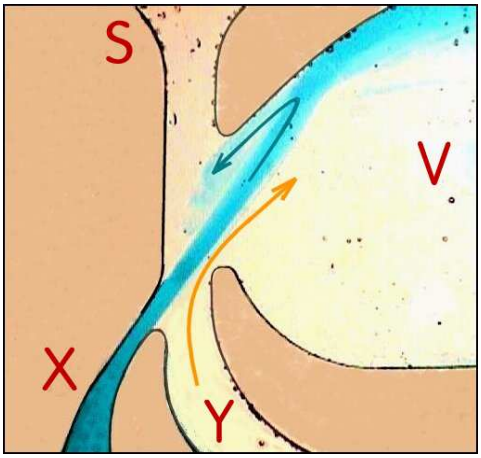


Fig. 18 Three operating principles of microfluidic no-moving-part flow control valves considered for the microfluidic catalyst testing facility. The requirement of "guard flows" has led to selecting the removal principle #3.



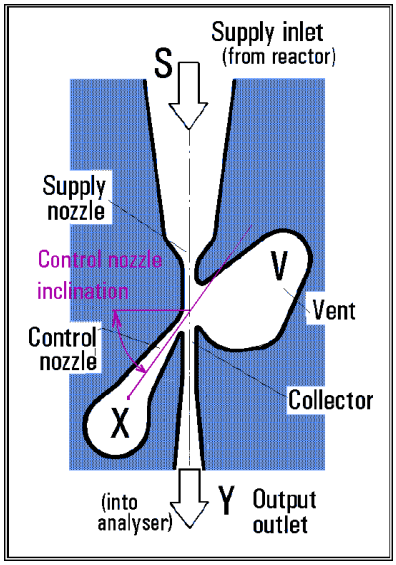


Fig. 19 (Left) One of the water flow visualisation studies on scaled-up model. The control flow from X generates by jet-pumping action the return "guard" flow (orange colour arrow). Unfortunately the supply flow from the reactor is blocked (the blue arrow shows returning part of the control flow). **Fig. 20** (Right) Basic features of the final valve design base of the idea of very powerful control flow.

The first aspect that gradually came into the focus of attention was called ***sameness*** of the operating conditions inside all the reactors - including the reactor the output flow from which was allowed at a particular time the sample to pass into the analyser. Obviously, the area blockage principle 1 in Fig. 18 has from this point of view the disadvantage as it caused large variations in the flow rate and pressure level upstream from the valve, where there is the reactor (cf. Fig. 14). In principle, the reactor flow could be maintained constant by arranging two blockage valves side-by-side operated in antiparallel (opening the blockage into the analyzer is simultaneous with closing the flow into the vent). This, however, was seen as substantially complicating the fluidic circuitry.

Then came another aspect considered to be increasingly important: the ***sample purity***. The composition of the reaction products are under some conditions only rather weakly influenced by the properties of the tested catalysts. The analysis has to be very sensitive. Reliable evaluation could be put into jeopardy even by slightest cross-contamination between the individual samples. It should be said that perfect mutual isolation of the samples is not an easy problem in a system in which the samples are not separated by a material wall. There are, in fact, two possible causes of the contamination – and bith have to be eliminated by judicious design of the flow switching microfluidic valves.

The first possibility for cotamination arises in the vents which, as discussed above, were to be all connected according to Fig. 9 to the common equalisation volume. In this volume exists an uncontrollable mixture of various samples brought there from all the "CLOSED" valves. Although not very likely to happen, a possibility cannot be excluded altogether that due to some unexpected operating conditions this mixture can flow or creep into the sample passing through the single "OPEN" valve into the analyser. A solution to this problem (Tesař 2002b and also Tesař et al. 2004) was sought and found in sacrificing a small proportion of the sample from the "OPEN" valve and let this "guard" flow permanently move into the vent – Fig. 22. The dangerous uncontrolled mixture cannot get from the vent V into the output Y.

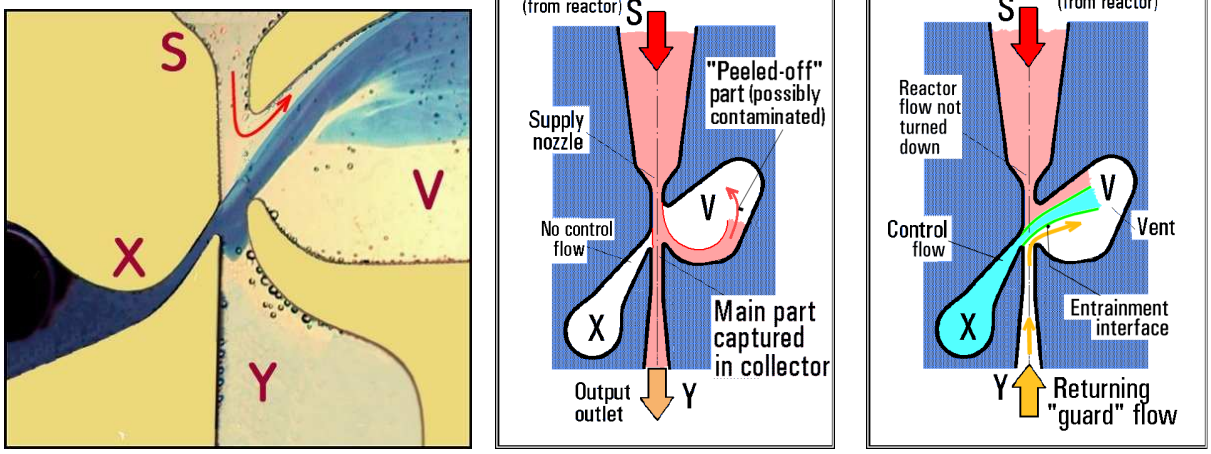


Fig. 21 (Left) Another alternative of the interaction region in flow visualisation tests. The blockage of the reactor flow is removed, but there is no jet-pumping driven "guard" flow. **Fig. 22** (Centre) The desirable operation of the valve in the "OPEN" states. **Fig. 23** (Right) The desirable operation of the valve in the "CLOSED" state.

The second contamination possibility is associated with the remains of the previous sample which fills the volume between the valves and the analyser. This can be, in principle, removed by flushing this "dead" space with some neutral fluid, but such solution was found again to lead to unpleasant complexity. Some measure of relieving the problem was obtained by arranging the valves into groups (each containing 16 valves, Fig. 17) around the common central exit outlet to the analyzer – this minimises the "dead" volume. Nevertheless, an active cleaning action was necessary and a solution (much simpler than with the flushing – Tesař 2002b) was found in the removal of the previous samples from the "dead" volume by reversing the direction of the fluid flow downstream from the valve in the "CLOSED" valves – Fig. 23. This reversal "guard" flow would again remove and sacrifice some small amount from the currently analysed sample.

3.3. Deflection Control Valve

The two flow blocking principles of valve operation – the first and second one in Fig. 18 – were unable to generate this reversed "guard" flow. As a result, the winning solution selected for the final valve design was the last, third principle in Fig. 18. To generate the flow reversal in the output terminal Y, it uses the jet-pumping, entrainment effect of the control jet. This is made possible by the inclination of the control nozzle, Fig. 20 (of course, the best jet pumping action would be achieved with the control nozzle and the output collector being parallel, but this cannot generated the desirable deflection effect). As already mentioned in connection with Figs. 9 and 13, the properly inclined control jet possesses a higher efficiency of the flow deflection of the supplied flow from S into the vent. Nevertheless, at the small Reynolds numbers the necessary control flow is quite high – this results in the "fractional" flow gain in the valve, a paradoxical feature, the very opposite to the usual reasonably high gain of standard large-scale fluidic valves, most of which can operate as fluidic amplifiers.

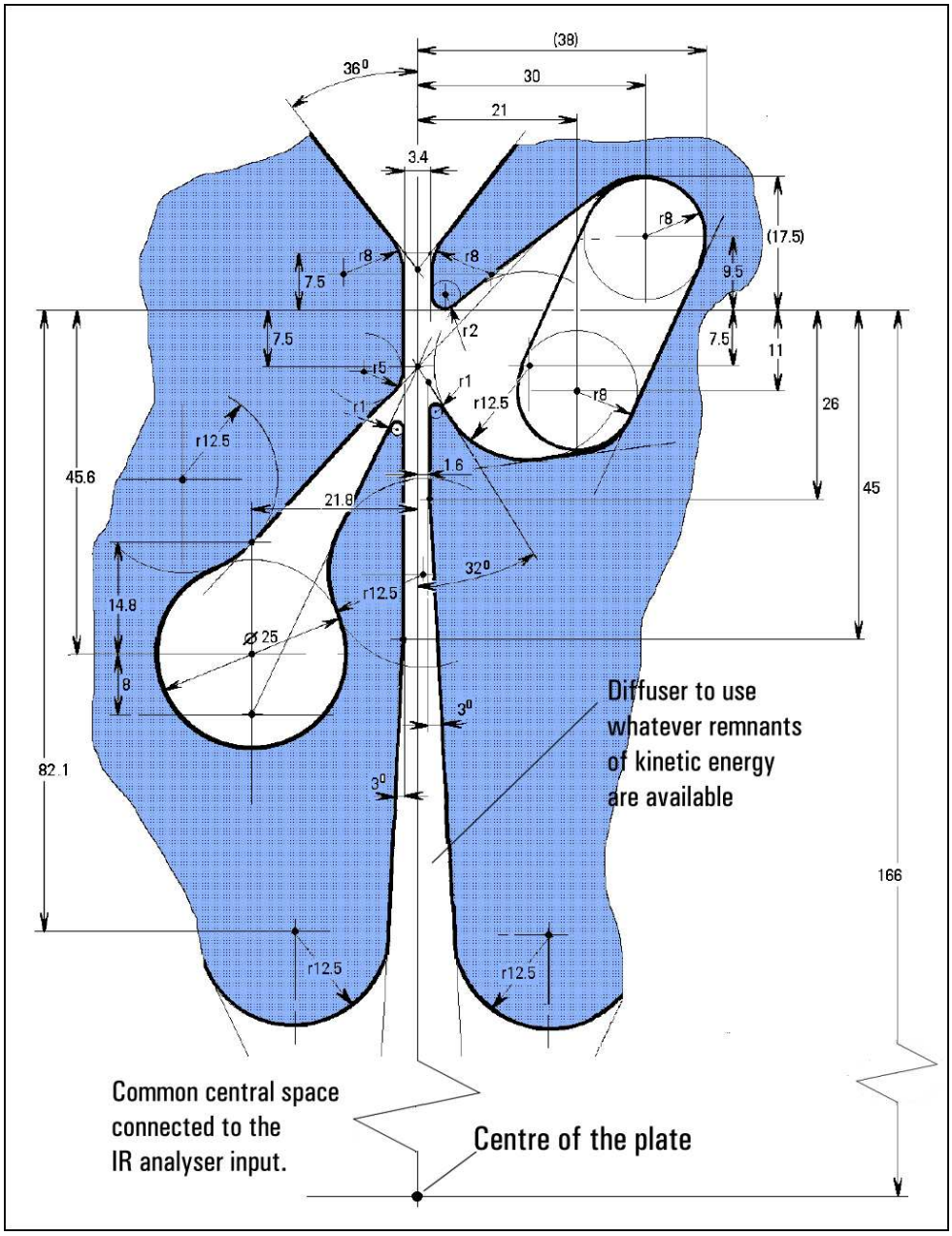


Fig. 24 Geometry of the valve in the tested 10-times scaled-up model of the sampling unit.

The required return flow from the output Y must be very small – it comes from the only flow through the "OPEN" state valve and if the jet pumping were very effective, the very existence of the analysed sample at the exit of the single would be endangered by too much being taken from it by all those "CLOSED" valves. Thus a rather primitive, not very efficient "jet pump" design in Figs. 19 and 22 does suffice when it is driven by the rather powerful control flow. Development of the proper geometry, involving the several contradictory requirements, was rather difficult. Apart from numerical flowfield computations of chosen possible alternatives it involved also experimental verification of the central core interaction region of the valves using water flow visualisations in scaled-up laboratory models, Figs. 19 and 29.

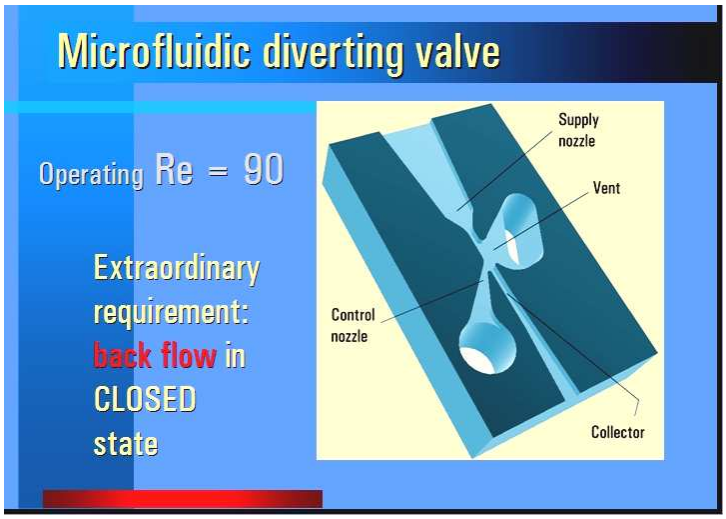


Fig. 25 (Left) The fluidic diverter valve. The rather shallow constant-depth cavities are made by etching in stainless steel plate, according to Fig. 17. **Fig. 26** (Right) Flow visualisation of the "CLOSED" state in the scaled-up model operated with dyed water.

At the final development stage, there were laboratory tests of the complete 10:1 scaled-up plate containing 16 valves. These were made in transparent material (polymethylmetacrylate - Perspex) and the flows were mainly investigated Again using mainly the flow visualisation (Figs. 26, 27, 28 and 29). Th interest in these final tests concentrated on two aspects: the studies of mutual flow interactions between the valves in the plate and proper adjustment if the driving pressure diffferences. In the example photograph presented in Fig. 27 the valve at left is in the "CLOSED" state, its orange-dyed flow prevented from reaching the central exit (on top of the picture) by the action of the transparent control flow. p The neighbouring valve at right in Fig. 27 is in the "OPEN" state.

In its mechanical design, the sampling unit was essentially a stack of thin stainless steel plates. The geometry of the valves is presented in the workshop drawing of the scaled-up model in Fig. 24. The total number of the valves was divided into groups, each group comprising 16 valves. These were arranged in a circular pattern surrounding the central common vent space, as shown in Fig. 17. The plates were clamped between solid stainless steel pieces, the sealing of the valve cavities relied upon the rather large clamping force.

The isotropic etching of the final design of the small microvalves for the actual catalyst testing system — of 0.34 mm diameter of the main (supply) nozzle — in the stainless steel plates was performed by an external supplier.

Fig. 27 (Left) Photograph of the tests made with the scaled up laboratory model, with cavities laser-cut in perspex plates. The flow visualisation tests test were run using water; individual flows were discriminated by various dissolved dyes.

3.4. *Similarity Parameter: the* Te *Number*

The main problem of the pressure-driven microfluidics, the proper adjustment of the driving pressure differences, is demonstrated in Figs. 28 and 29. Both show side-by-side results of the flow visualisation and numerical flowfield computation – the latter displaying the computed pathlines.

In both examples, the valve is in the "OPEN" state, without any action of the control flow. The fluid – the sample to be analysed – coming from the reactor through the supply inlet S has in this state to pass through the valve with only a very small proportion being spilled over into the vent V — this sacrificed small proportion is the "guard" flow protecting the sample from an accidental contact with the mixture of fluids inside the common vent space. At the small Reynolds numbers, shown in the pictures, the inertia of a jet formed in the nozzle cannot compete successfully with the slowing-down action of the viscous friction. It has to be supplemented – or even substituted by the driving pressure difference. In the example presented in Fig. 28, the assisting pressure is obviously not sufficient. Most of the fluid (two thirds) leaving the main nozzle prefers the easier way out from the valve through the vent V and does not progress to the output Y and from there to the analyzer. The amount of the loss is shown in the picture in terms of the relative output mass flow rate

$$\mu_Y = \frac{\dot{M}_Y}{\dot{M}_S} \tag{1}$$

— where $\dot{M}_S$ [kg/s] is the mass flow rate of the sample fed into the supply terminal S of the valve, while $\dot{M}_Y$ [kg/s] is the mass flow rate of the sample actually reaching the output terminal Y.

Obviously, the insufficient driving pressure in the regime shown in Fig. 28 must be increased to get proper valve operation. This is done in the second example, shown in Fig. 29. There, only 13 % of the available sample fluid is lost by being spilled over into the vent — in spite of the fact that the Reynolds number Re in this case is very small indeed.

For the proper adjustment of the driving pressure, it is very useful to have a complete dependence of the relative output flow μ_Y on the acting pressure difference. Such dependences were evaluated by the present author. Of course, as could be expected, with so many variables in the problem, even for geometrically similar valves this is not a simple function. It was, however, discovered, that a much simple dependence is found if instead of the acting pressure one uses the dimensionless parameter Te, as presented in Fig. 30 (or its

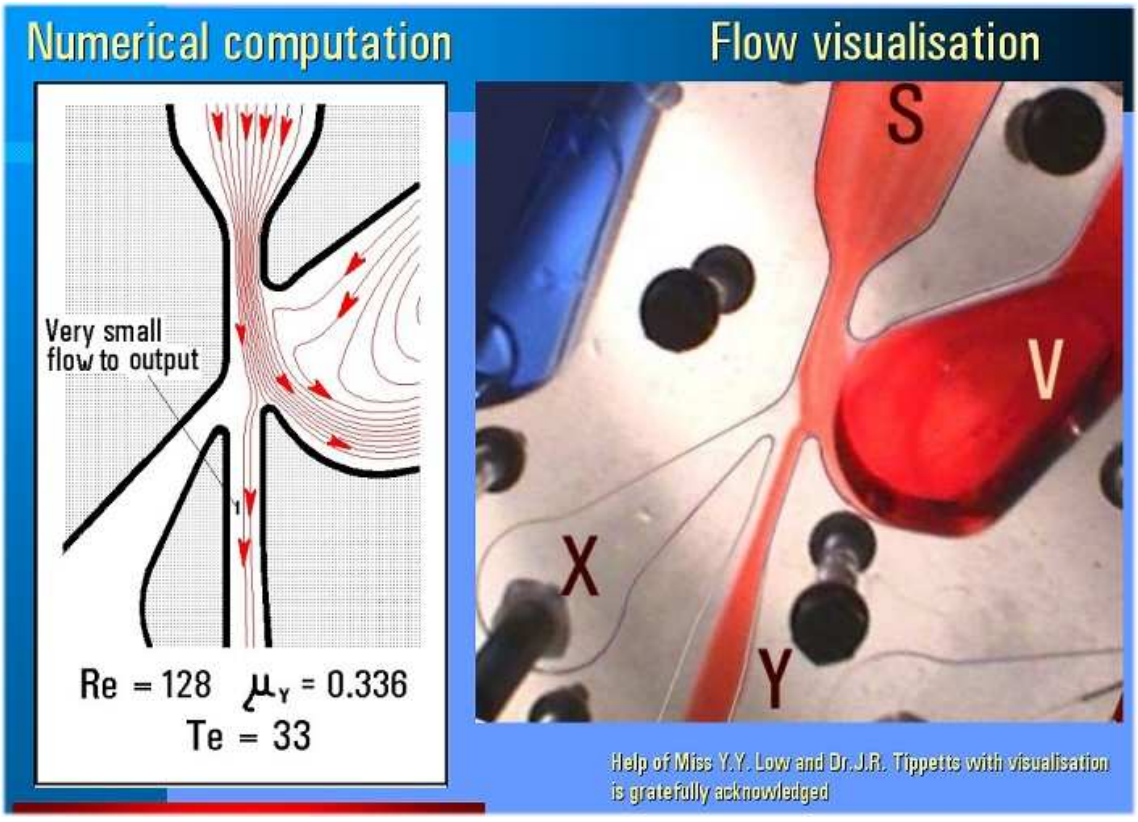


Fig. 28 Computed (at left) and visualised (at right) flow in the "OPEN" state in the microvalve operated at a typical low Reynolds number. In spite of the open flowpaths from S to Y (there is no control flow in X), an unacceptably large proportion (66.4 %) of the sample fluid escapes into the vent V.

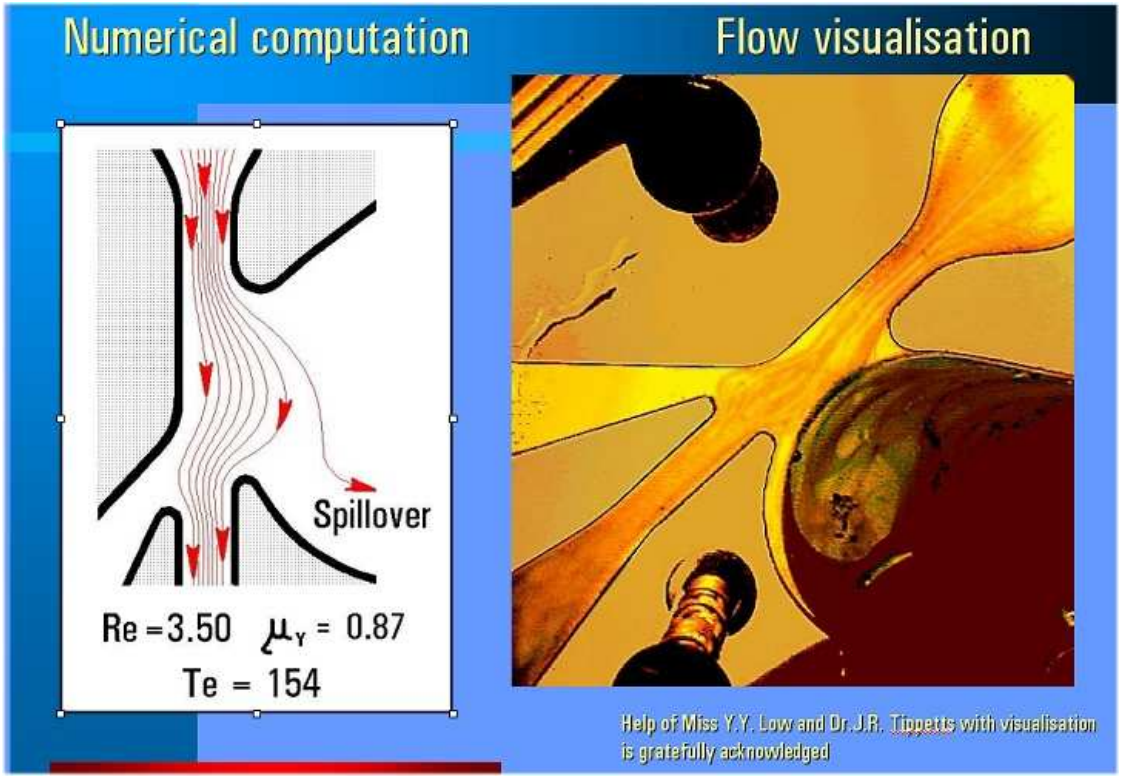


Fig. 29 The pressure driven flow through the same valve as in Fig. 28. Despite the Reynolds number here being much lower, the pressure effects (characterised by the large value of the dimensionless parameter Te) can force most (87%) of the sample fluid to pass through Y.

alternative variants - Tesař 2004, also Tesař et al., 2005). An example of such simplified dependence for the valves discussed above is presented in the left-hand part of Fig. 30. In this case, what remains of the complex multi-parameter dependence is just a dependence of μ_Y on two dimensionless parameters, on Te and on Reynolds number Re. Moreover, all these all curves – some of them found experimentally, others by numerical computations – approach the same common asymptotic straight line. The lower is Reynolds number Re, the better the behaviour is approaching the asymptote valid for the limit of sub-dynamic flows. This is an important finding, of immense importance for low Reynolds number pressure driven microfluidics in general (Tesař et al., 2005).

4. Summary

Despite the seemingly proliferated use of unusual and sometimes downright exotic operating principles in present-day microfluidics, the use of the more or less classical mechanism of pushing the fluid through the device cavities by an applied pressure difference is not losing its importance. There are applications – such as when handling a high-temperature gas – where it is simply indispensable. The presented example has shown how the pressure levels in the fluidic circuits is to be adjusted to obtain the proper operating conditions. In this presented application example, where there were unusually strict

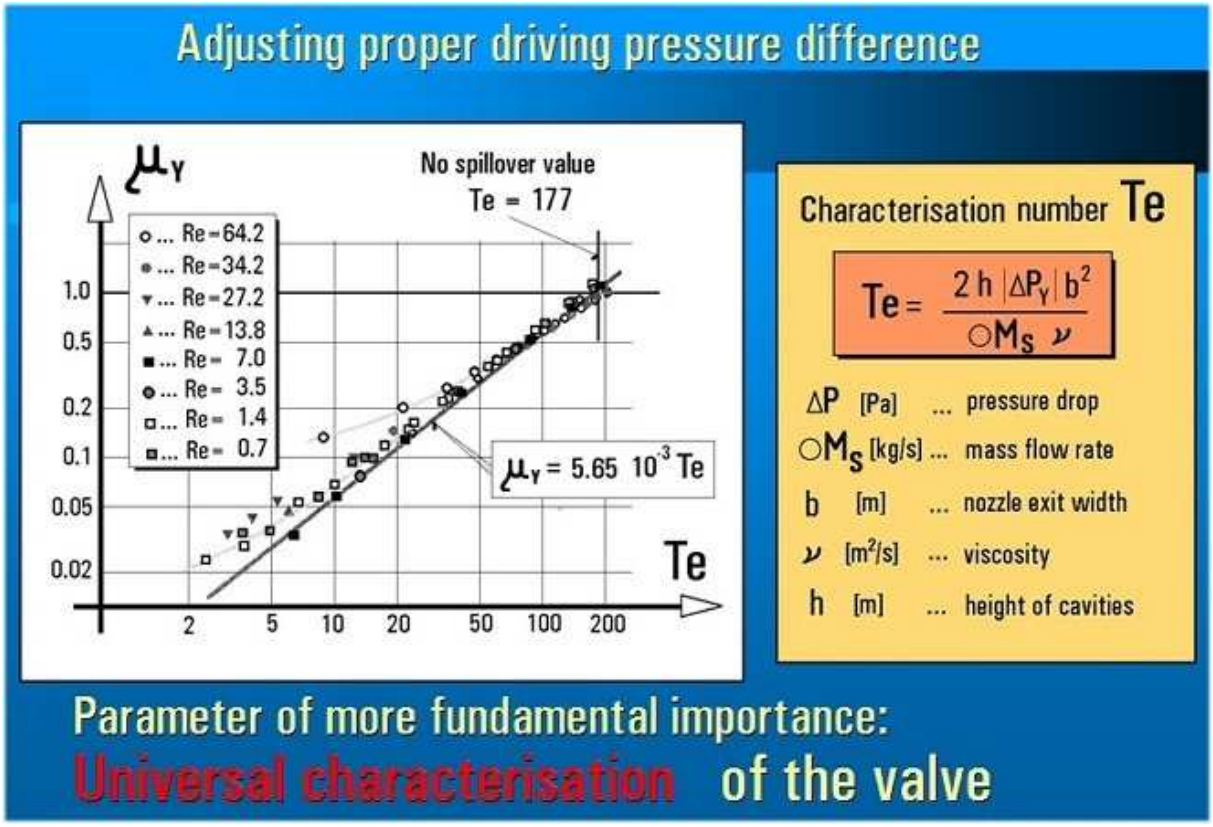


Fig. 30 A useful parameter for characterization of the pressure-driving effects (and design of the corresponding pressure regulation circuits) was found to be the dimensionless number Te.

requirements on securing protective "guard" flows, the task of adjusting the proper pressure levels at various locations became rather difficult.

It was found extremely useful to employ for solving the task the dimensionless characterisation number Te as defined in Fig. 30 (or in its alternative variants - Tesař 2004). At very low Re *"subdynamic regime "* (Tesař et al., 2005) Reynolds number ceases to be the similarity parameter and no more provides the proper characterisation of operating conditions, it is this parameter Te that takes over the role of the decisive factor.

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