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Microfluidic Valves for Flow Control at Low Reynolds Numbers

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***Abstract*:** Fluidics is a technology of generating and controlling fluid flows - preferably without the action of mechanical moving components. Microfluidics perform these tasks in small, typically micron-sized structures. Essential part of almost all microfluidic systems are flow control valves. The basic problem is the low Reynolds number *Re*: inertial effects used in large-scale fluidics are too small relative to viscous dissipation. New approaches, such as pressure or electrokinetic driving are required. In the subdynamic, viscosity dominated flow regime, *Re* ceases to be of importance and for pressure-driven valves a new characterisation number was to be introduced. An example of a diverter valve, developed by the author, is described and the meaning of the new dimensionless parameter is demonstrated.

***Keywords*:** flow control, valves, fluidics, microfluidics, microvalves, Reynolds number.

Nomenclature:

b	[m]	nozzle exit width (Fig.4)
h	[m]	height (or depth) of cavities
$\circ M_S$	[kg/s]	supply mass flow rate (Fig.1)
$\circ M_X$	[kg/s]	control mass flow rate
$\circ M_Y$	[kg/s]	output mass flow rate (Fig.1)
DP_Y	[Pa]	driving pressure difference
Re	[-]	nozzle exit Reynolds number
Te	[-]	Tesař number (Fig.8)
s	[m]	splitter distance (Fig.4)
Dt	[s]	jet travel time (Fig.4)
n	[m³/kg]	fluid specific volume
w	[m/s]	nozzle exit velocity (Fig.4)
m_S	[-]	relative supply mass flow rate
m_X	[-]	relative control mass flow rate
m_Y	[-]	relative output mass flow rate (Fig.1)
v	[m²/s]	fluid viscosity

1. Introduction

The last decade saw a fast growth of a new technological field of microdevices, manufactured by methods originally developed for semiconductor electronics. Microchips have been demonstrated containing mechanical components such as gears, electric motors, and even turbines and complete miniature combustion engines. The prospects are promising: an expectation of 40 billion US dollar microdevice business in year 2002 was recently published (Ehrfeld, 2000). Many microdevices work with fluid flows in micron-sized channels in applications ranging from adsorber heat pumps (cooling), fluid sample chemical analysis (DNA identification for disease diagnostics), to chemical microreactors. Particularly encouraging is their use e.g. for compact fuel processing for fuel cell powered automobiles. Flow control by some sort of valves is, of course, essential. Microvalves with moving components were successfully demonstrated, but much more promising is application of the concepts of no-moving-part fluidics (e.g. Tesař, 1998).

2. Fluidic Diverter Valves

The fundamental problem is that due to the small channel cross-sections and small flow velocities (in microreactor applications dictated by reactor residence time requirements), the usual fundamental characterisation parameter of fluid flows, the Reynolds number *Re*, tends to be very small, often very near to 1.0. This results in totally different operating conditions from those in large-scale fluidics, where flow control action without moving components usually depends upon dynamic effects in accelerated fluids. Instead of simply replicating the more conventional ("millimetre size") fluidic devices on the "micron size" (in itself a not trivial task, because of the restrictions imposed by quite different manufacturing methods), microfluidics calls for the more challenging task of inventing new operating principles.

Although real fluidic valves and circuits in which they are used are often more complex, the simple generic example in Fig.1 may be useful for clarifying some basic facts. The valve is there shown placed between the source (which may be a pump), and the load-device in which the flow is to be varied. The source delivers a constant supply flow (mass flow rate $\dot{M}_S$ in Fig.1) supplied into the nozzle where it forms a jet. Its inertia at high *Re* carries it into the collector opposite the nozzle. The load receives the variable output flow (output mass flow rate $\dot{M}_Y$ in Fig.1) captured by the collector, which re-converts the jet into a closed cavity flow.

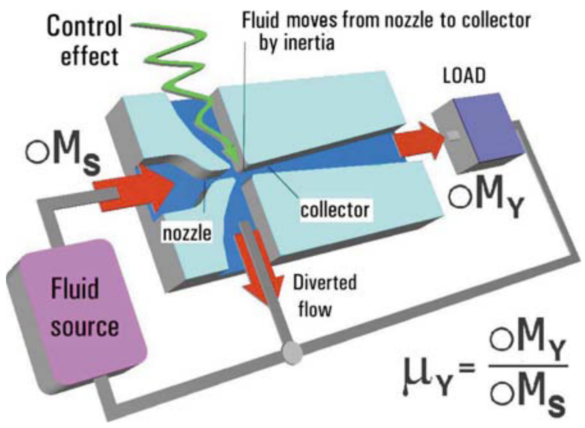

Fig. 1. A generic example of a no-moving-part fluidic valve flow control by an effect acting in the gap between the supply nozzle and the collector. It diverts a controllable amount of fluid, preventing it from reaching the load.

The constancy of the supply conditions is commonly maintained by a supply regulator. Because of the usually invariant properties of the supply circuit, a pressure regulator is commonly used, as shown in Fig.2 even if it is actually constant flow that is desired. Note that the pressure difference maintained constant in Fig.2 is that across the source. Usual applications often involve many valves supplied from a common source so that the presence of the regulator is not a large complication, as just a single one usually suffices for the whole fluidic system.

The output flow variation is achieved by the action of a control effect. This may be acoustic, electric, but in a typical fluidic valve it is usually the action of another fluid flow. Depending upon the intensity of this control flow, some part of the supplied flow is diverted into the vent outlet and thus prevented from reaching the output. The relative output flow

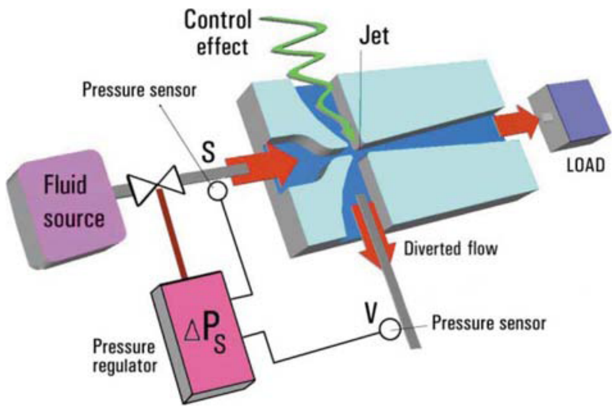

Fig. 2. Standard use of a supply regulator: To avoid changes in output flow not caused by the control action, the valve is usually operated with pressure regulator which keeps constant pressure difference between supply *S* and vent *V*.

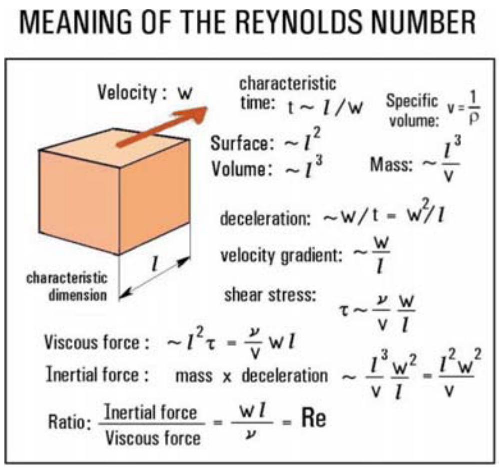

Fig. 3. Derivation of Reynolds number *Re* by comparison of inertial and viscous forces on an elementary fluid volume.

$$m_y = \frac{\dot{M}_y}{\dot{M}_s}$$

(see also Fig.1) is decreased. Without the control action the valve must provide a reasonably high value of m_Y (in other words, a reasonable percentage of supplied fluid must reach the load) so that there is something the control action can decrease. This is achieved in fluidic devices at high *Re* by ***dynamic effects***. To overcome the viscous loss occurring in the gap between the nozzle and the collector, the flow is accelerated in the nozzle so that it reaches the collector still with considerable kinetic energy to be converted into pressure rise. Selecting proper dimensions of the gap is the key task of the valve designer. A wide gap leads to more effective jet deflection control, but leads to large loss of jet momentum. The interplay between inertial and viscous forces acting on the jet is determined by the value of the Reynolds number *Re*. In Fig.3 it is expressed in terms of a characteristic length *l*, characteristic flow velocity and fluid viscosity.

3. Microfluidics and Limits of Fluid Dynamics

In fluidics, it is common to use Reynolds number evaluated from nozzle exit conditions - Fig.4.

$$Re = \frac{wb}{v}$$

determines the character of fluid flow in a fluidic valve. It is the basic parameter of the scaling law: if two fluidic devices, mutually similar but of different size, are to exhibit the same properties, their ***Re must be equal***. To get a microfluidic valve by scaling down ten times a successful design of a large scale fluidic valve (Fig.4) requires ten times higher velocity *w* in the resultant small device, if using the same working fluid. In fact, in many microfluidic applications (viscous liquids in DNA tests, high viscosity hot gas in energetic conversions) fluid viscosity n is high requiring even higher *w*. But already ten times higher velocity is usually out of question as it means absurdly high supersonic or even hypersonic values, for which there is usually not the required hundred (or more) times higher pressure source anyway. Moreover, in many applications there is a requirement of very low velocity (e.g. due to the required residence time in a chemical microreactor or a composition analyser). As a result, aerodynamically similar scaling down is usually impossible and we must accept much lower Reynolds numbers.

This, of course, means increased viscous retardation of the jet relative to its inertia and deteriorating valve efficiency. We may use the magnitude of the relative output flow m_Y in the no control flow regime as a measure of the hydrodynamic efficiency of a fluidic diverter-type valve. In good large-scale designs operating at the usual high *Re*, typically of the order 10×10^3 - the efficiency may be as high as $m_Y = 0.80$. The example in Fig.6 (evaluated for the valve shown in Fig.12) indicates the fast decrease of achievable m_Y with decreasing *Re* in the laminar flow

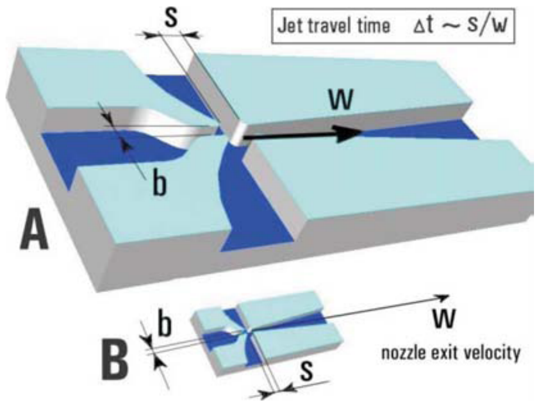

Fig. 4. Device miniaturisation as the way towards microfluidics. Basic problems are the scaling law relations between the properties of the microfluidic valve *B* and large device *A* from which it is scaled down.

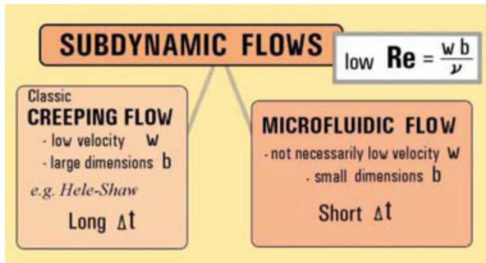

Fig. 5. Subdynamic flows at low *Re* need not be creeping flows. A subdynamic flow in a microdevice may cover the small travelled distances extremely fast - so that characteristic times of the order of milliseconds or less are no exception.

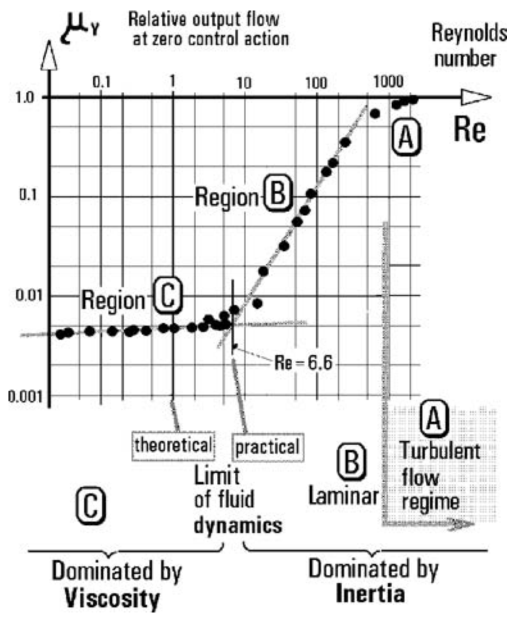

Fig. 6. The typical decrease of a diverter valve efficiency with decreasing Reynolds number *Re*. In the subdynamic regime C the behaviour ceases to be dependent upon *Re*.

region *B*. As long as *Re* is not very low, some compensation is possible by decreasing the distance *s* between the nozzle and the collector. This calls for much larger control flows, but this is usually no problem with the small absolute flow magnitudes - some microfluidic valves are known to work successfully with control flow much larger than the controlled flow, which would be an unacceptable paradox in large scale fluidics.

In other applications the Reynolds number is so low that operating conditions correspond to the region *C* in Fig.6. This is below the theoretical limit *Re* = 1 (Figure 6 shows that practical limit value may be slightly different) below which, in region *C*, the flow becomes fully dominated by viscosity and inertial effects become negligible. An interesting fact is that the transition into this ***subdynamic regime*** (at *Re* = 6.6 in case of Fig.6) is so distinct and sharp. Another important fact is that in the subdynamic regime *C* the Reynolds number ceases to be the governing parameter. In this regime the typical example shown in Fig.6 demonstrates that the efficiency becomes nearly the same even if Reynolds number is varied by several decimal orders.

Low *Re* flows are sometimes described as creeping flows. This would lead to a wrong impression about microfluidic valve operation. These valves should not be imagined as working with slow creeping flow. Since the distances *s* (proportional to the nozzle width *b*, Fig.4) to be travelled by the jet are very short, perhaps of the order of microns, the Strouhal number *Sh* may be quite large. The characteristic time (proportional to the jet travel time $Dt = s/w$) may be very short. This means that flow switching in a microfluidic valve may actually be very fast, especially if the circumstances (and available supply pressure difference) permit working with high nozzle exit velocity *w*.

4. Pressure Driven Devices and the Relevant Characterisation Number

In the frequently encountered microfluidic applications that demand operating at *Re* near to and even below the subdynamic regime limit, m_Y achievable by inertial effects (Fig.6) is too small to be of practical interest. The inertial mode of fluidic valve operation is out of the question. The remedy is to force the fluid towards the load using another effect. It is possible to use the electroosmosis - the micro flow injection analysis (*mFIA*) based on this effect is becoming quite successful in microanalytical systems (Fletcher et al., 1999). The present author remained in the safe realm of purely mechanical effects, forcing the fluid towards the load by pressure difference DP_Y between the vent *V* and output terminal *Y*. What is needed, as shown in Fig.7, is just a second regulator (similar to the supply regulator from Fig.2) to keep a constant pressure difference between the two terminals. Of course, an additional regulator is no problem with the electronics available on the "***intelligent***" chip. Note (cf. Fig.1) that this second regulator basically keeps a constant pressure across the load. Again a single regulator may be used for a large number of parallel valves (e.g. one regulator is used for all 16 valves shown in the example in Fig.11). Such a parallel circuit also places less demand upon the regulator frequency range, especially if opening some of the valves takes place simultaneously with closing other ones.

With proper adjustment of the pressure drop, the relative flow rate m_Y in the "fully open," no control flow state may be made as high as we may wish - even higher than $m_Y = 1.0$ (- which is, of course, not achievable with fluidic diverters based upon dynamic effects). To simplify the adjustment, a diagram like Fig.10 may be used. Initially as just a convenient nondimensional representation of the required pressure drop, useful as an aid for its adjustment, a dimensionless number *Te*, as defined in Fig.8 was introduced. Several alternative definitions are possible, the one in Fig.8 is a practically convenient one, basically using the (bulk) velocity $w = \circ M\ v/(bh)$ in the nozzle exit. However, a deeper meaning of the new parameter became soon obvious. We may note in Fig.9 that it is completely analogous to the Reynolds number (as presented in Fig.3) and replaces it in situations where it is pressure force instead of the inertia acting on an elementary fluid volume. In the subdynamic range (Fig.5) where the Reynolds number ceases to be a meaningful characterisation of operating conditions, it is *Te* which is the really meaningful parameter completely characterising fluid flow in a pressure driven subdynamic microfluidic valve. This may be seen in the example in Fig.10, where the relative output flow was evaluated both experimentally and

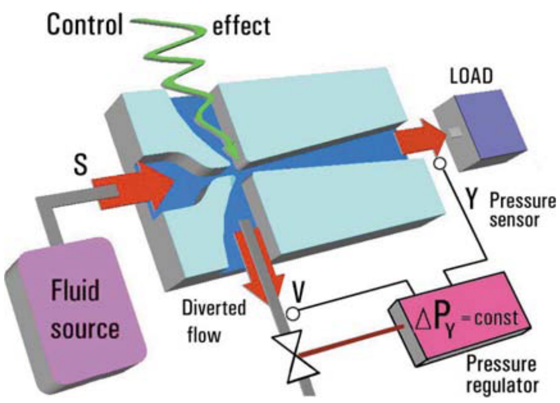

Fig. 7. Operation of the pressure driven microfluidic diverter at very low *Re* requires an additional pressure regulator maintaining a constant pressure difference DP_Y between the vent *V* and the output *Y*.

by numerical flowfield computations for a particular fluidic valve, shown in Fig.11. The character of the dependence is, in fact, quite generic and typical for many similar diverter devices. The lower is Reynolds number, the nearer the values are to the asymptotic linear dependences $m_Y = K\,Te$ (K .. a constant characteristic for a given valve). In the subdynamic range, where the properties are determined solely by Te, this line becomes the universal relationship for the valve behaviour in the OPEN (- no control action) state.

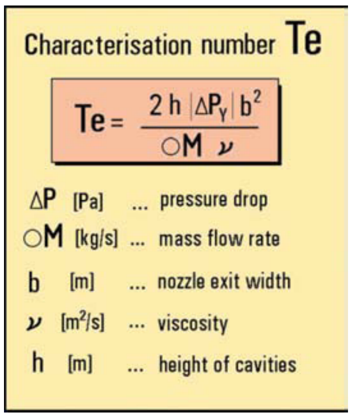

Fig. 8. Definition of the new dimensionless parameter *Te* characterizing behaviour of the pressure-driven valves in the subdynamic regime.

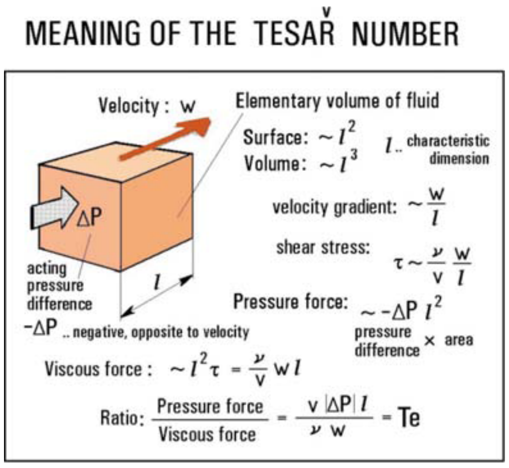

Fig. 9. Derivation of *Te* by comparing the pressure and viscous forces acting of a cube-shaped elementary volume of fluid - showing meaning of *Te* analogous to the Reynolds number *Re* in Fig.3.

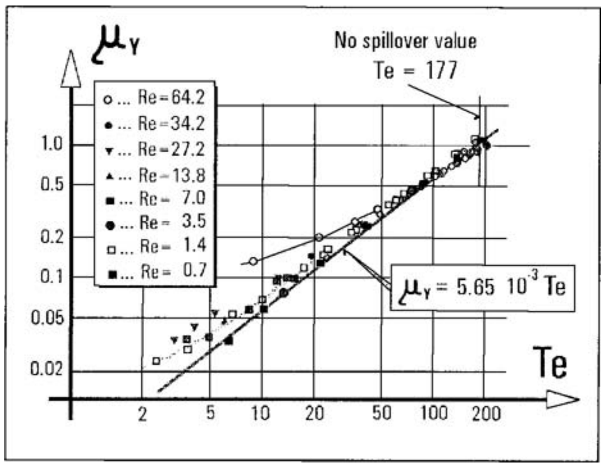

Fig. 10. An example of the dependence of the relative output flow m_Y the pressure difference DP_Y between the vent *V* and the output *Y* in the microfluidic valve shown in Fig.12. DP_Y is expressed nondimensionally in *Te* , which leads to universal characterization in the subdynamic range (*Re* < 1) - all data points for all *Re* are on the single universal straight line. For higher Reynolds numbers this line is just an asymptote.

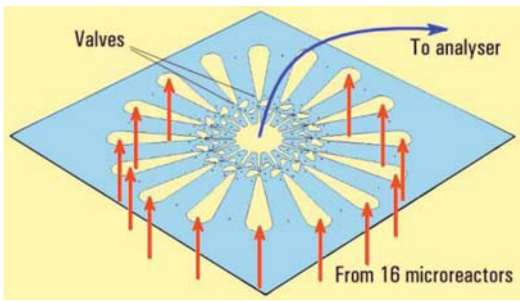

Fig. 11. An example of a microfluidic sampling selector (Tesař, 2000). It is a concentric array of 16 valves (Fig.12). Only one of them is in OPEN state admitting only 1 reactant sample from parallel 16 microreactors at any particular time to enter the central outlet into a composition analyser.

5. An Example of a Pressure Driven Diverter Valve

The theoretical predictions based upon the characterisation by the newly introduced *Te* number were tested on a microfluidic valve (Tesař, 2000) developed by the present author for an application in high-temperature chemical microreactor technology. It is the key element in the sampling unit admitting sequentially a gas sample flow from one of 16 microreactors into a gas composition analyser. The sampling unit (Fig.11) is manufactured by etching in stainless steel. The performance requirements involve

a) 10% spillover flow (i.e. $m_Y = 0.9$) in the OPEN state to eliminate possible sample contamination by mixing with fluid from the common vent, and

b) a jet pumping effect (backwards output flow $m_Y < 0$) in the CLOSED state to remove the previous sample from the analyser cavities.

The jet-pumping requirement resulted in the unusual inclination of the control nozzle - Fig.12. Another unusual feature is the small depth of the cavities, equal to only 0.44*b*. The smooth downwards sloping shape of the flow transfer characteristic - Fig.17 - at large control flows ○M_X (Figure 17 uses the relative value m_X = ○M_X /○M_S) assures that the conditions in the CLOSED state can be always met, even though at the price of using a control flow more than 20-times the controlled flow. This is no problem since the absolute magnitude of ○M_X is small and the control fluid consumption is easily met. Of key importance for proper operation is therefore the adjustment of the OPEN state conditions. The high temperature and very small sample flow rate lead to Reynolds number around $Re = 30$, very near to the transition into the subdynamic range, so that without the applied pressure according to Fig.7 the output flow in the OPEN state would be almost zero. Computed (Fig.13) and visualized (Fig.14) flows show that even with some applied pressure forcing the sample flow into the output terminal, the sample flow still tends to prefer leaving through the vent - in spite of the not really very low *Re* (note the formation of a jet, which does not take place in the ***subdynamic regime***). With increased pressure difference DP_Y as shown in Fig.15 and Fig.16, the tendency of the streamlines to spread after leaving the supply nozzle exit and to head into the vent, the pressure action is seen to force them to enter the collector. The diagram corresponding to Fig.10 was essential in finding the proper *Te* value and the corresponding proper pressure. An interesting aspect is that by contrast with common situations in aerodynamic, where laboratory models are usually scaled down, here the water flow models are larger than the final valves - and the Strouhal number scaling results in much slower processes in the model, making their video recording an easier task.

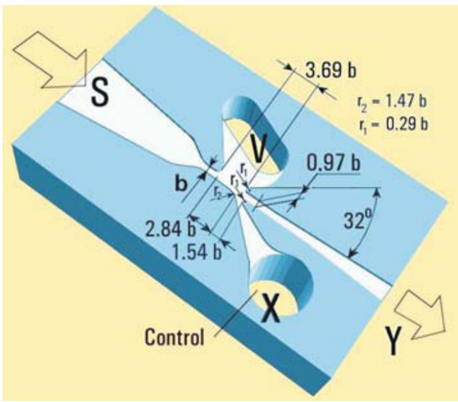

Fig. 12. Geometry of the microfluidic switching valve (Tesař, 2000) developed for operation in the pressure driven subdynamic regime. Flow of reactant sample from *S* to *Y* is deflected into the vent *V* by a powerful flow from the control terminal *X*. It differs from the general example Fig.1 by the inclination of the control nozzle, required for removal of the sample fluid from downstream cavities in the CLOSED state.

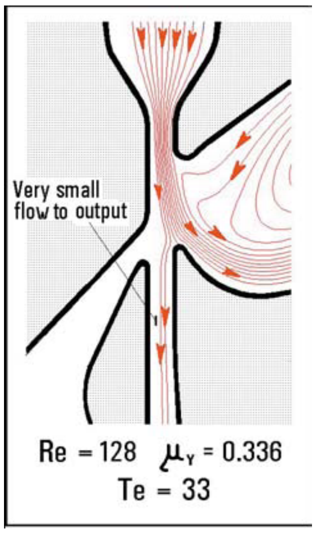

Fig. 13. Computed streamlines for the valve from Fig.12 in the OPEN state. Only 33.6% of the supplied flow here reaches the output *Y* - the applied pressure difference DP_Y (note the nonzero *Te*) is insufficient.

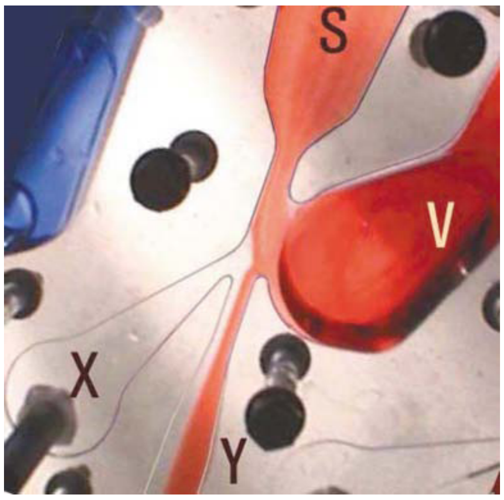

Fig. 14. Photograph of dyed water flow in scaled-up valve model at conditions corresponding to Fig.13 indicates good predictive capability of the numerical model. *Te* is below the no-spillover value.

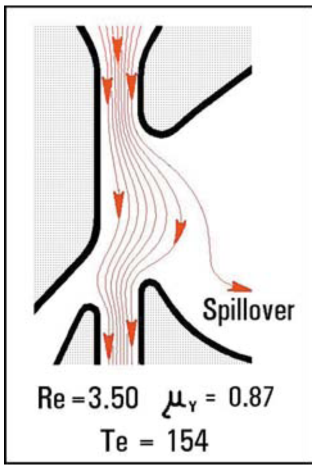

Fig. 15. The correctly adjusted pressure difference DP_Y - although at a too large *Re*. The fluid leaving the nozzle does not have sufficient inertia, but is driven into the collector by DP_Y. A small spill-over flow (here 13%) in this OPEN state is required to guarantee no cross contamination between the samples through the interconnected vents.

Fig. 16. Detailed photograph of water model flow in the OPEN state at an extremely low *Re* and properly adjusted DP_Y.

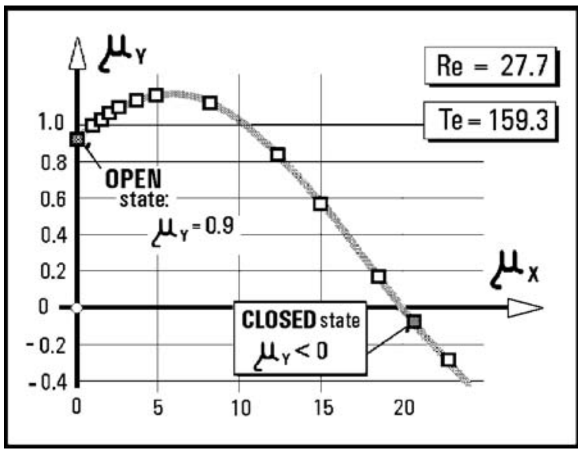

Fig. 17. Flow transfer characteristic of the valve from Fig.12 in relative co-ordinates (control flow: horizontal co-ordinate, output flow: vertical co-ordinate - both related to the supply flow). Note that extremely powerful (> 20-times the sample flow) control flow is required for closing the valve and generating the jet pumping effect.

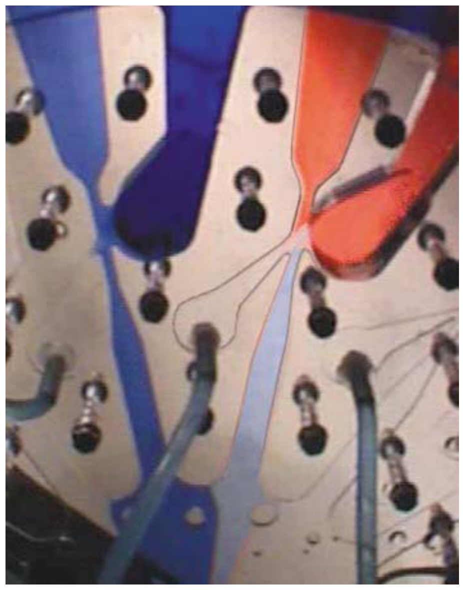

Fig. 18. Visualisation of water flow in the scaled-up model of two neighbouring valves. Left valve: OPEN state, blue dyed water passes to the analyser. Right valve: CLOSED state, red dyed water diverted to vent while blue dyed-water from the output terminal is jet-pumped backwards.

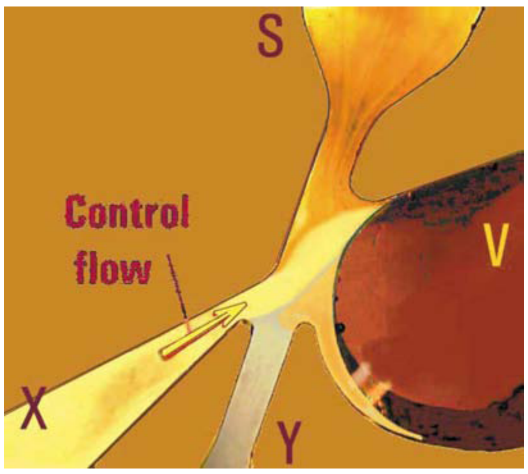

Fig. 19. Detail of the visualized CLOSED state flow.

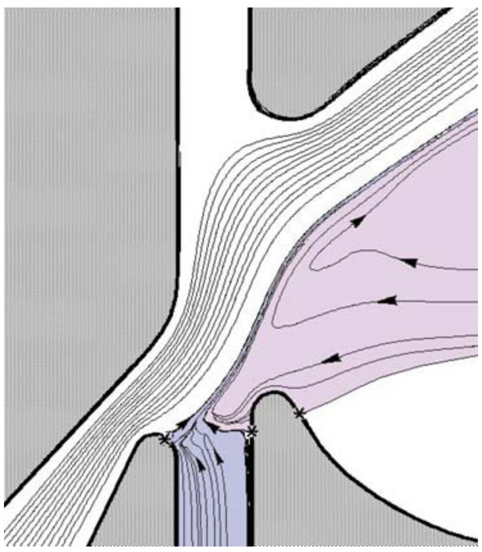

Fig. 20. Computed streamlines explain why the jet-pumping effect in the CLOSED state is not strong: most of the entrainment is used by the fluid penetrating from the vent.

6. Conclusions

The basic problem encountered in microfluidics is the low Reynolds number which represents the ratio of dynamic effects to viscous dissipation. As a consequence, the inertial transport of fluid between nozzle and collector, the basis of operation of jet-type valves as used in large-scale fluidics, cannot be employed and new approaches are required. The diverter valves, as demonstrated on a practical example, which were developed by the author can operate in the extremely low *Re* subdynamic regime. All that is required is an additional pressure regulator. This creates a favourable pressure difference across the load which forces the fluid to move into the collector of the valve and further downstream into the device in which the flow is to be controlled. A new characterisation number *Te* (Fig.8) was introduced replacing the Reynolds number, which ceases to be of importance in this regime. The required pressure drop for proper operation in the OPEN state can be evaluated from a relationship (Fig.10) between the relative output flow rate and *Te*. An important feature of this relationship is the asymptotic straight line, which represents the subdynamic behaviour limit.

Acknowledgments

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