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"Fluid Plug" Microfluidic Valve for Low Reynolds Number Fluid Flow Selector Units

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Abstract : A novel no-moving-part valve was developed mainly for applications in microchemistry, where Reynolds numbers tend to be extremely low. The valve of very small size and working with viscous biological fluids was designed for operating at Re values between 10 and 100 . In this range, the inertial jet flow effects used in standard fluidics could not be relied upon and a qualitatively new operating principle was introduced: the control fluid forms a "plug" at the entrance of the collector, precluding an entry of the main fluid flow. In particular, an array of new valves was used in a selector unit to allow a single reagent flow into a reactor from several available sources. The flow visualization validated the assumptions on which the design is based and compared well with numerical flowfield computations.

Keywords : Fluid flow control, Fluidics, Microfluidics, Valves, Low Reynolds number

1. Introduction

Flow visualisation was used as a valuable tool in the development of a no-moving-part fluidic valve, based upon a novel operating principle. The valve is suitable for functioning at very low Reynolds numbers, where fluid flows are dominated by viscous effects. This low Re operating regime is encountered nowadays increasingly often in microfluidics - the new field of fluidics, characterised by extremely small size of the fluid flow control devices. The application for which the new valve was developed is a selective switching of reagent flows in microchemistry. The reagents are sequentially added to the analysed fluid sample so as to perform a number of analytic reactions. There is a large number of practical situations where such identification of the sample is currently performed by manual handling, using standard analytical laboratory methods. An example may be the analysis of biological fluid samples for laboratory proof of paternity (e.g. Katsumata et. al., 2001). The demand for such analyses has recently increased to unexpected proportions. Tedious repetition of the standard procedures is a nuisance, takes considerable time, and makes the tests quite expensive. The idea is to perform the tests automatically in a dedicated microanalytical system which is to be extremely small, with all its components (reagent inlets, flowpath channels, detection sensors) on a

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single chip. Extremely small amount of samples suffice for such a system. and if the chip is made by modern microfabrication technique, it may be so cheap as to be discardable after use, eliminating a possibility of contamination between the tests.

2. Requirements

An essential part of many such "*lab-on-chip*" systems is a selector unit handling the dosage of reagent fluids, which are added to the sample fluid in a pre-determined sequence. In principle, this unit consists of a number of parallel valves, each controlling the flow of one reagent. Only one of the valves is open at any instant of time to admit the corresponding reagent into the downstream passages. Mechanical microvalves with moving components are known and may be used for this task (e.g. Koch et al., 1996), but they are rather delicate and their manufacture is too expensive for a device to be discarded after the one-time use. A better solution is offered by no-moving-part fluidic valves (Tesař, 1998). These are basically constant-geometry cavities, which may be easily manufactured at effectively zero cost during a single etching operation together with the interconnecting channels. The reagent fluid flow is controlled by the control fluid admitted into a control nozzle.

A disadvantage of the absence of mechanical separation of the fluids in the fluidic valves is the possibility of unwanted mixing of the fluids. The presence of an admixture of the control fluid in the output reagent flow need not be a problem - if the chemical composition of the control fluid is chosen to be inert in the performed analytic reaction. The other potential problem, cross-contamination of the reagent fluids, requires careful hydraulic design of pressure levels at individual locations of the selector unit. It may be necessary to create protective “guard” flows (similar to the fluidic sampling units described by Tesař, 2002).

The basic problem encountered at the very beginning of the present development was the fact that the required extremely small valve size together with small flow rates of rather viscous reagents lead to very small operating Reynolds number

$$Re = w_{e\,max}\, b / \nu \tag{1}$$

where $w_{e\,max}$ [m/s] is the maximum velocity at the exit of the main nozzle; b [m] is the nozzle exit channel width, and ν [m^2/s] is fluid kinematic viscosity. Depending upon detailed operating conditions, the design value was to be between Re = 10 and Re = 100.

This is very small indeed, smaller by more than two decimal orders of magnitude, than the values at which standard fluidic devices usually operate Reynolds number indicates the relative magnitude of inertial and viscous forces acting on the fluid. In the operating range of present interest the flows are dominated by viscous friction. The usual principles of fluidic valves based upon inertial effects, such as the deflection of a fluid jet by interaction with the control flow (as described e.g. by Tesař, 1998), are hopelessly ineffective. New operating principles are required.

The present author has already designed microfluidic valves for these challenging sub-dynamic operating conditions. An example may be the valve described by Tesař (2001). Instead of relying upon the inertial effects, the flow in that valve is caused by a pressure difference applied between the valve vent and its outlet. The operation may be described as *pressure-assisted* operation (Tesař , 2000) at the higher end of the Reynolds number range (when *Re* is near to 100) and as *pressure-driven* operation at and near to the lower end (near to *Re* = 10).

This basic idea was adopted also in the present application, where, however, the valve as described by Tesař (2001) could not be used because its design was based upon a special control

mode, using very powerful control jet. The control flow rate there was larger than the controlled flow by more than a decimal order. This was dictated by the very special requirement of generating a reverse flow in the cavities downstream from the closed valve. This flow reversal was achieved at the price of extremely high control fluid consumption (Tesař, 2002). In the present case, on the contrary, it was desirable to keep the consumption of the control fluid small, which called for a different design.

3. New Operating Principle

The new valve is shown in Fig.1 and Fig.2.. The flow control action takes place in the relatively shallow cavities, of the same depth everywhere, made by one-sided etching. They are closed by covering the valve by a flat cover plate, not shown in these figures. Although the valves may be useful in other applications, they were designed for the operation in the selector unit for microchemical analysis, shown in Fig.3. In the unit, an array of identical valves is placed in parallel, between the inlets of the reagent fluids (at the top in Fig.3) and the single outlet of the selected reagent (at the bottom of Fig.3). Their vents are connected into the common vent space, with a single exit. The output from the valve array leads the selected reagent into the reactor (not shown) in which the analytical chemical reaction takes place between the reagent and the sample fluid. The valves are operated in two states – either OPEN or CLOSED. Only one valve in the array is in the OPEN state at any instant of time, the rest of them are CLOSED. The reagents entering the CLOSED valve are dumped into the common vent. This control mode, with loss of most reagent flows, is admittedly somewhat uneconomical. However, considering the extremely small absolute amounts of the handled reagents, the loss is usually acceptable. Besides, some bioreagents actually do not admit a turning-down control and require to be kept in permanent flow(some of them may have very short useful lifetime after being synthesized immediately upstream, some may tend to coagulate when they are stationary.)

The reagent fluid is supplied into the main nozzle of the valve, from which it issues as a jet (the flow path is shown in red in Fig.1.) Opposite to the nozzle exit, separated from it by the wide gap open on both sides to the common vent space, is the collector entrance. This is connected with the reactor by the downstream passages. The valve is in its OPEN state (Fig.1), allowing the reagent flow into the reactor, if no control action takes place(no control fluid is admitted.) Admission of the control fluid through the control inlet switches the valve into the CLOSED state (Fig.2). The control fluid prevents the reagent from passing through the valve downstream into the reactor and diverts it into the vent.

Fig. 1. The valve in the OPEN state: reagent fluid (red) passes unopposed through the cavities.

Fig. 2. The CLOSED state: control fluid (blue) forms a “plug”, reagent fluid (red) is diverted in to the vent.

The novel feature of the present valve concept is that the viscous effect at the low Reynolds numbers – which would be otherwise a nuisance – is here used as an advantage in the control action. The control fluid (blue in Fig.2) inserted through the control inlet into the collector entrance forms a "fluid plug" there. This blocks the entrance so that the reagent has to use an easier way out through the vent. The viscous friction acting on the control fluid makes it reluctant to move and keeps it in its flow blocking position. This may be particularly effective in the extreme case of very low control flow Reynolds numbers (very viscous control fluid) or in the case of using liquid for the control flow of a gas, where the liquid "plug" resistance to displacement may be assisted by surface tension. In this case, the control fluid "plug" would tend to remain in its position almost permanently. Switching the valve into the OPEN state would then call for a reverse, suction control flow.

At a higher control flow *Re* in the present application, with liquids both as the controlled as well as the control fluid, the control fluid is gradually removed from the collector entrance under the action of the driving pressure. On one hand, this makes the control circuits simpler. It is not necessary to reverse the control flow direction. Bringing the valve into the OPEN state is simply achieved by turning down the control flow. On the other hand, the control fluid then escapes into the outlet. Even though it is inert, its presence in the reactor is usually not welcome as it dilutes the reagents. At the high end of the Reynolds number spectrum the dilution could be quite strong. To oppose it, it may be useful to generate a reverse "guard" flow (Tesař, 2002) at the exit of the CLOSED valve. In the example of the valve shown in the accompanying illustrations, this effect is achieved by the control nozzle exit orientated upstream, towards the collector entrance. At higher Reynolds numbers of the control flow issuing from this nozzle, the fluid in the collector is pushed back, towards the vent. The control flow may even entrain the fluid from the outlet cavities due to a jet pumping effect .

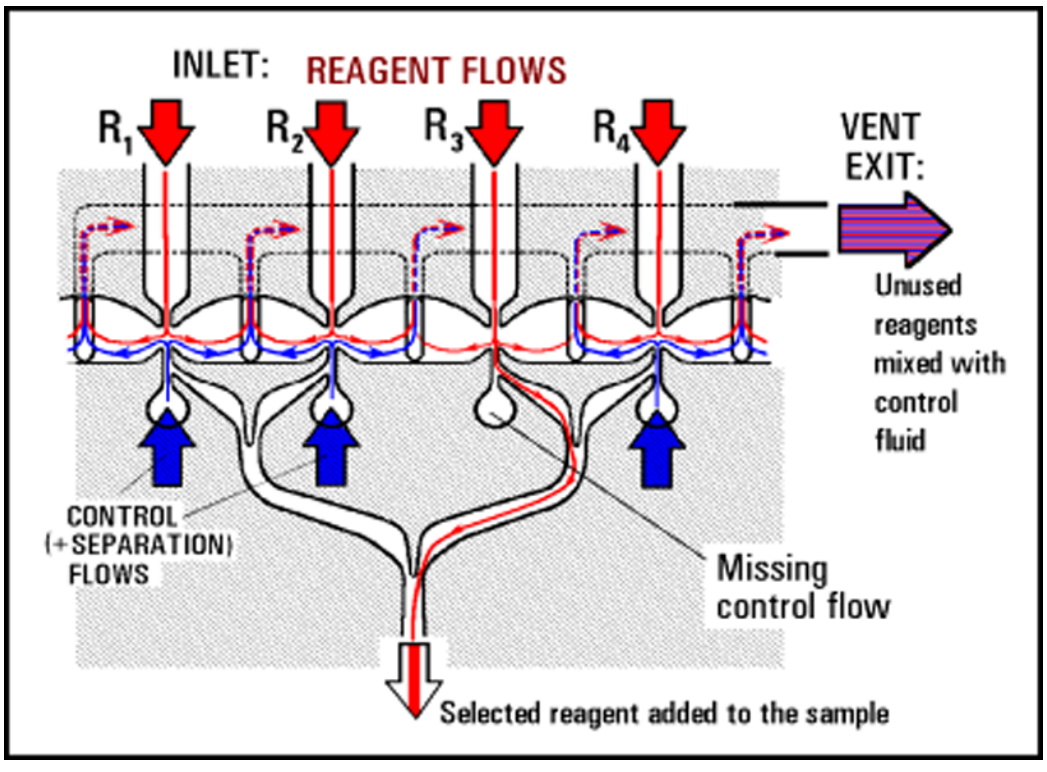


Fig. 3. The selector unit consisting of an array of the new microfluidics valves. Only one valve (third from the left) is in the OPEN state (note its missing control flow), allowing flow of the reagent R_3 into the reactor. Other valves are in their CLOSED state, diverting the flow into the vent exit.

4. Flow Visualisation Experiments

To verify the feasibility of the new valve concept, the operation of the valve was investigated by using a scaled-up laboratory model of the selector unit. The unit contained an array of only four valves. (A much larger valve number is needed in the actual application.) The width of main nozzle in the model was 3.5 mm and the depth of the cavities was 1.72 mm. The model was made of transparent material (Perspex). The test fluid was water. The flowfield was made visible by addition of dyes: *Victoria blue* dye added to the water simulating the control fluid, and *Saffron red* added to the simulated reagents. The advantage of the scaled-up model with low-viscosity fluid is the favourable time scaling. The fast switching processes in the actual valve are modeled at the same Reynolds number by slow, creeping motions. This makes the transitions – such as between the OPEN and the CLOSED states – conveniently observable and available for easy video recording.

The typical examples of the visualized flow in the basic valve states are in the still video frames of Fig.4 and Fig.5, showing one of the valves in the array: Fig.4 shows it in the OPEN state and Fig.5 in the CLOSED state. They prove the feasibility of the concept at low Reynolds numbers. The basic task in setting up proper operation of the selector unit is the adjustment of the proper driving pressure and the corresponding magnitude of the control flow rate for the CLOSED state. This is facilitated by the procedure involving the nondimensional plotting using the Te number, as described in Tesař (2001).

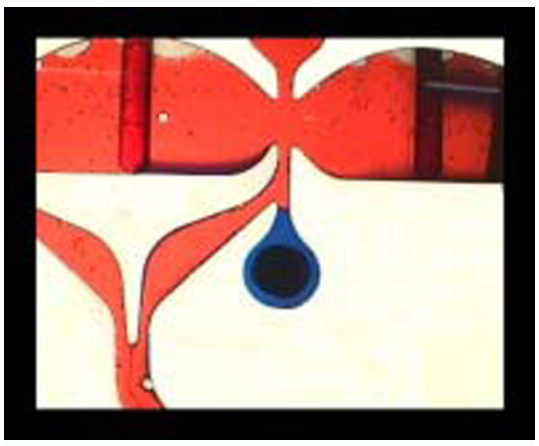


Fig. 4. Flowfield in the valve visualised by addition of red dye (reagent) and blue dye (control fluid). OPEN state after a prolonged absence of control action.

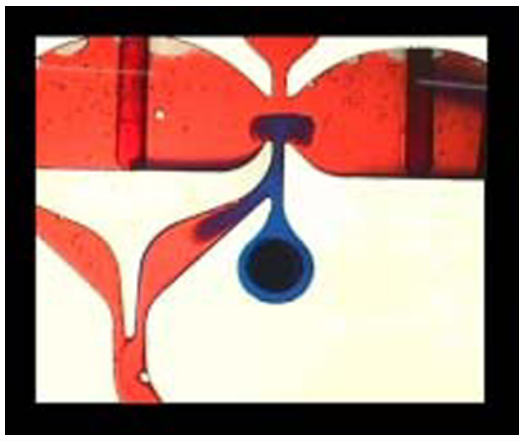
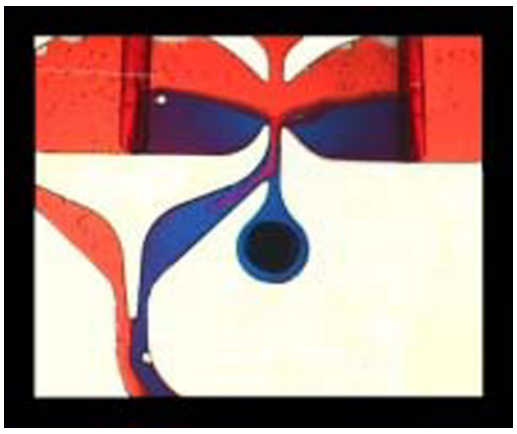


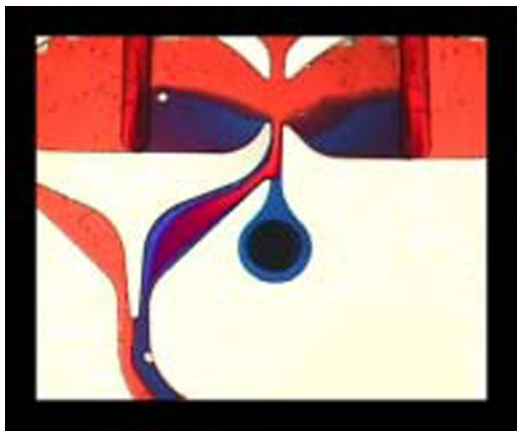
Fig. 5. Visualised flowfield in the CLOSED valve at a proper control Reynolds number.

Fig. 6. Visualised CLOSED state with too high control Reynolds number: reagent (red) at the exit (bottom) becomes diluted by the overspilling control fluid (blue).

If the driving pressure is too high, it is no longer possible to keep the control fluid "blob" safely in its blocking position at the collector entrance in the CLOSED state. As shown in Fig.6, the control fluid is then carried away towards the outlet. Additional control fluid to make up for the loss is to be supplied through the control inlet. A problem may arise due to the (red) reagent, passing through the neighbouring OPEN valve on the right(this valve is not visible in Fig.6, but may be seen in Fig.11.) being diluted by the control fluid. A small dilution may be acceptable (provided the control fluid is inert), but if spillover of the control fluid takes place in many valves (see Fig.11), the analytical reaction in the downstream reactor may be influenced. The diluting flow may be opposed by generating a reverse jet pumping flow. This, however, works only at the upper end of the Reynolds number range. At low control flow Re, as the case in Fig.6, there is no effective entrainment into the laminar control flow and no jet pumping effect. This documents the requirement of particularly careful adjustment of the operating conditions at low Reynolds numbers.

A useful method for obtaining quantitative information from dye visualization results is evaluation of isophot lines. This was used in the present research for evaluation of one particular problem of valve dynamics. The spillover of the control flow, as shown in Fig.6, apart from the dilution effect, also slows admission of the reagent into the reactor after valve switching. While valve opening from a properly adjusted state (Fig.5) is quite fast, the reagent penetration through the spillover of the control fluid after switching from the CLOSED state into the OPEN state may be beset by a significant lag. This is shown in the two video record frames of Figs.7 and 8 in a sequence taken during an opening process after a prolonged valve closure in which (like in Fig.6) the spillover of the control fluid (blue) has filled the downstream cavities.





Figs. 7 and 8. Visualised transition from the CLOSED to the OPEN state after a prolonged valve closure with too large control flow. The reagent (red) only slowly finds its way through the cavities filled by the control fluid (blue).

The isophot lines for this low Reynolds number penetration of the reagent, slowed down by viscosity, are shown in Fig.9. The elapsed time Δt, after the control flow is switched off is shown as the relative value

$$\tau = \Delta t / t_c \qquad (2)$$

related to the characteristic time $t_c = s / w_{e\,max}$. The distance s = 12.3 mm in the scaled-up model is indicated in Fig.9 and $w_{e\,max}$ is the main nozzle velocity as in Eq.(1). The experiment shown in Fig.9 was performed at $Re = 16$, where the model nozzle exit velocity was $w_{e\,max}$ = 0.0046 m/s, so that the

characteristic time, analogous to the characteristic nozzle-to-collector "flight time" of standard fluidic jet-type amplifiers, was t_c = 2.68 s. Obviously, the "cleansing" of the cavities from the unwanted fluid held by the relatively strong viscous effects on the walls takes a long time - longer than the typical switching process in high-*Re* jet-deflection fluidic valve (usually commensurable with t_c) at least by a decimal order of magnitude. Fortunately (because of the time scales roughly proportional to the square of the size) even these slow processes correspond to acceptably short time in the actual microvalve.

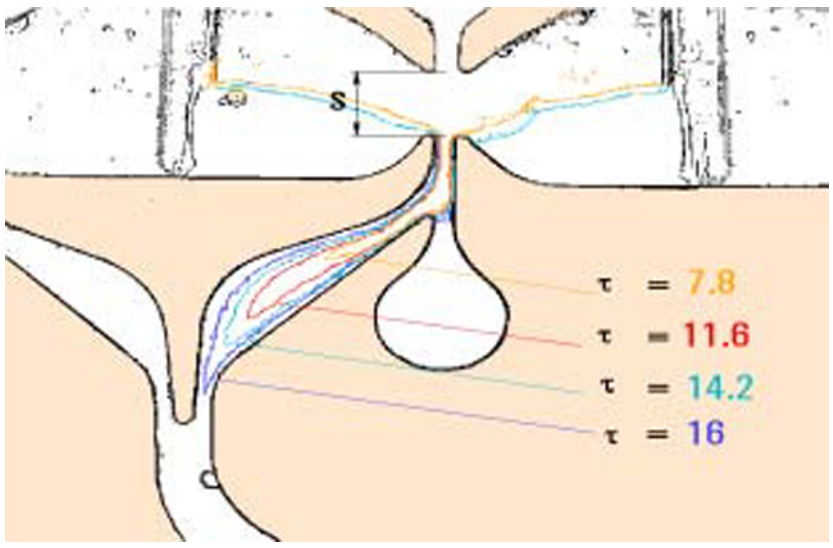


Fig. 9. Processing the flow visualisation pictures to obtain quantitative data: isophot lines mark the progress of the valve opening at different nondimensional times τ

5. Computations

FLUENT solver version 5.5 was used, employing a tetrahedral unstructured grid generated by GAMBIT. The grid was fully three-dimensional, in spite of the apparent two-dimensionality of the cavity shapes, because the friction on the flat bottom and top cover plate plays an essential role. The grid was refined in high velocity gradient locations by adaption procedure. One advantage of microfluidics is the flows being almost always laminar, so that the computation avoids the problems associated with turbulence modeling. Perhaps because of this simplification, the numerical results were often – but unfortunately not always – found to be in good agreement with the experiments. The exceptions were observed at the higher end of the *Re* range in those cases where there was a substantial influence of large stationary vortices. The experiments in these cases have shown that the vortices shed away instead of remaining in their predicted positions. Somewhat surprisingly, the steady vortices without shedding were predicted even when using the time-dependent version of FLUENT and it is this aspect of the computations that requires exceptional attention.

In situations where this shedding problem was absent, the numerical predictions were excellent. An example of the agreement is in Fig.10, showing only a part of the flowfield. The computation and flow visualization runs, of which Fig.10 is an example, were aimed at investigation of another aspect of the valve operation that calls for close attention. It was found in the initial

stages of the transition into the CLOSED state when using a low-viscosity control fluid. While the control flow rate is still small, as the case in Fig.10, the control "plug" action is missing. The "streamlines" (actually flowpaths) shown there are computed for the midplane so that they in the left part of Fig.10 avoid the remains of the slightly blue regions of previously present control fluid, the remnants of which are held at the wall by its viscosity. The control fluid (blue) is carried into the output terminal by the driving pressure difference. The control action is established by applying the sufficiently powerful control flow rate. This is reliably predicted by the computations, which are also seen in Fig.10 to predict well the shape of the blue fluid region in the exit channel.

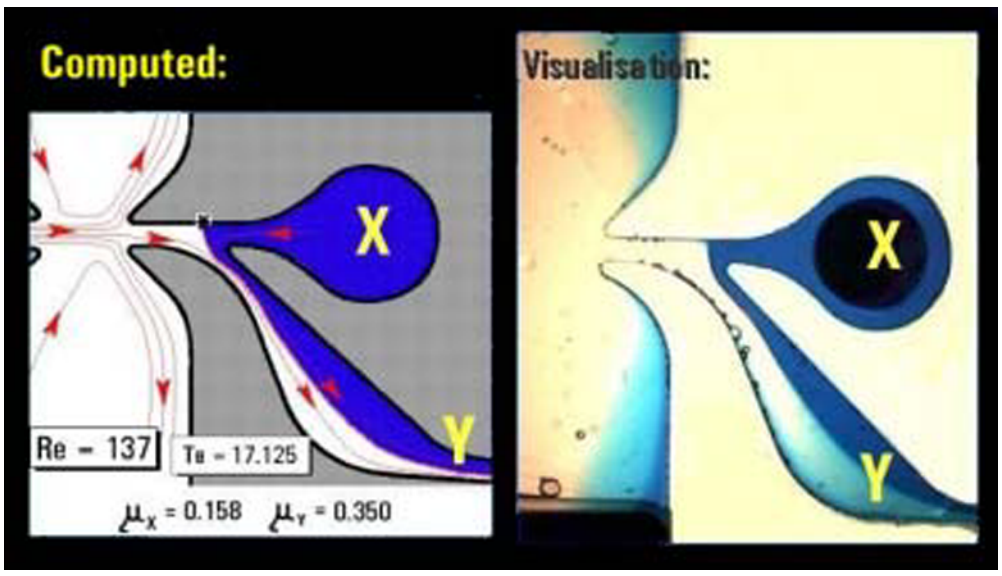


Fig.10 Computed streamlines (at left) in the initial stage of valve closing sequence (with too small control fluid viscosity) confronted (at right) with flow visualisation (here with only control fluid dyed).

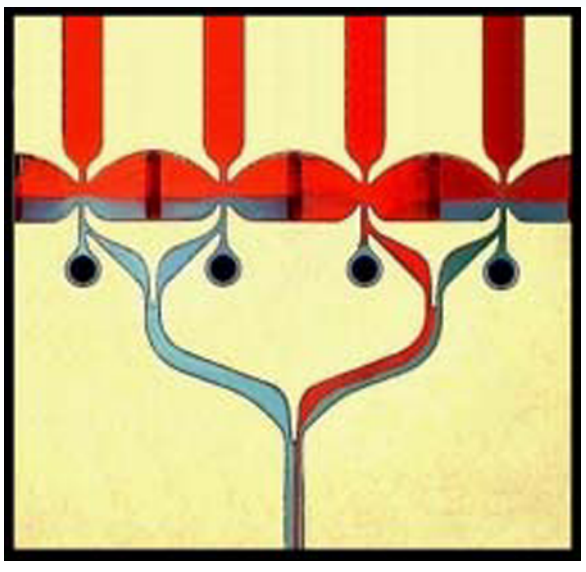


Fig. 11. Flow visualisation of the flows in the complete model of the selector unit (corresponding to Fig.3). Too small viscosity of the control fluid (blue) results in dilution of the reagent in the exit.

6. Conclusions

The flow visualizations were used for the verification of the predicted operation of the new microfluidic valve. Figure 11 shows the example of visualized flow in the whole model of the selector unit. This was developed for little explored conditions of extremely low Reynolds numbers. The valve was intended for dosage of reagents in microchemistry, but may find use in other situations where it is not necessary (or even not desirable) to turn down the controlled flow. Visualisation experiments in collaboration with numerical flowfield solutions identified several extreme operating conditions which require special attention to avoid possible problems.

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