Journal of Visualization, Vol. 5, No. 3 (2002) 301-307

Microfluidic Turn-down Valve

Tesař, V.*†

* The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK.
e-mail: v.tesar@sheffield.ac.uk

Received 20 May 1999.
Revised 24 January 2002.

***Abstract*:** Flow visualisation and numerical flowfield computations were used in the development of a microfluidic valve for control of reaction product in microreactors. The flow rate is modulated by head-on collision with an opposed flow of control fluid. This principle makes possible unique capability of turn-down (rather than diverting) control at very low operating Reynolds numbers (- design value Re = 75). The planar layout with shallow constant-depth cavities is suitable for microfabrication, especially by one-sided etching.

***Keywords*:** microfluidics, valves, colliding flows, colliding jets.

1. Introduction

Microchemistry, performing chemical reactions in micron-sized microreactors, is a fast developing area of present-day chemical engineering (e.g. Ehrfeld, 2000). In a typical "*lab-on-chip*" application, a large number of chemical analyses are made simultaneously using minimum amount of biological sample fluid. This makes possible e.g. DNA analysis for objective diagnosis of illnesses or for paternity tests. In other applications, fuel synthesis or similar large throughput reactions are performed by huge number of microreactors operating in parallel – the advantage being high yield achieved by precise individual controllability of processes taking place in the small volumes.

Taking advantage of the controllability requires having means for control actions. One of the essential controlled variables is the flow rate of reaction products. To vary it calls for having a micron-sized valve at the microreactor exit. Although microvalves with mechanical moving parts have been demonstrated, they tend to be unreliable: they are delicate and their lifetime is limited, especially in the high-temperature environment associated with exothermic reactions. A much more attractive alternative are no-moving-part fluidic valves, in which the control action is based upon hydrodynamic effects in fixed-geometry cavities. There are two basic problems. The first one is the inevitable contact of the reaction products with the control fluid. This is not very serious. Undesirable product dilution may be eliminated by separating the control fluid further downstream and this may be simplified by choosing suitable physical properties of control fluid (- e.g. using immiscible liquids). The contact may be in fact used to some advantage - such as e.g. for liquid-liquid extraction. More severe is the other problem: the typically low Reynolds numbers. Not only the size is small, but also the flow rates (and hence velocities) are often small due to the requirement of the reactor residence time. On the other hand, viscosity (of viscous biological fluids or high temperature gases in the fuel synthesis) is often high. As a result, flows tend to be viscous effects dominated and it is difficult or even impossible to use the usual inertial phenomena upon which large-scale no-moving-part fluidic devices (Tesař, 2001) are based. The microreactor control requires flow turning down

† on leave from ČVUT - Czech Technical University in Prague, Czech Republic

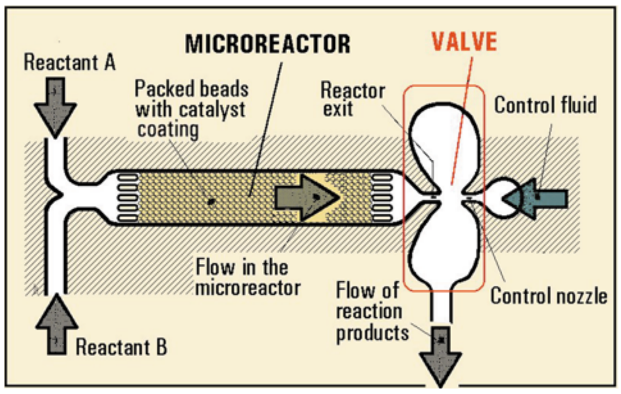

Fig. 1. An example of the microvalve at the exit of a packed-beads type microreactor. All cavities made simultaneously by etching (note the "grid" keeping the beads in place).

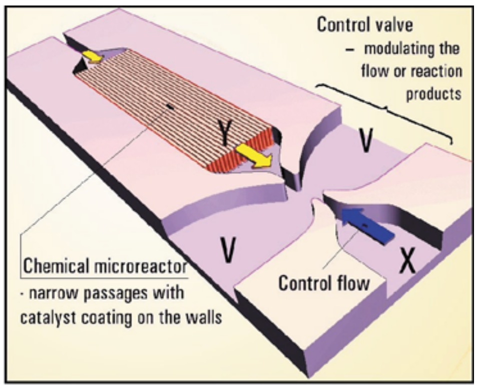

Fig. 2. Another example of the investigated colliding-jets valve,made integrally with a reactor (this time of a different, monolithic matrix type).

(Figs. 1 and 2). This is in large-scale fluidics achieved in vortex amplifiers - but these fail to work below Reynolds numbers of the order of 10^3 because of the fluid rotation being slowed down by friction.

2. Colliding Jets Valve

A suitable microfluidic valve capable of turning down flows at very low Reynolds numbers has been developed by this author. It is based upon the colliding jets idea: the flow of the reaction products, leaving the microreactor, is modulated by the head-on collision with oppositely directed flow of the control fluid. This, in effect, varies the available exit area (Tesař and Tippetts, 2000 - see Fig. 3). A similar principle has been known in an arrangement using axisymmetric nozzles (e.g. Katz and Reid, 1971). In the present case, however, the layout is planar - the cavities are of constant depth everywhere (Fig. 4). This makes the valve suitable for production by etching (e.g. Datta, 1998). Very little has been known about the planar case hydrodynamics, apart from the work of Nomoto et al. (1972), unfortunately covering Reynolds number range higher by several orders of magnitude. The present valve was designed for operation at reactor nozzle Reynolds number

$$Re = \frac{w_{e\,max}\, b}{\nu} = 75$$

where $w_{e\,max}$ [m/s] is the maximum velocity at the exit of the main nozzle, b = 0.35 mm is the exit channel width, and n [m^2/s] is fluid kinematic viscosity.

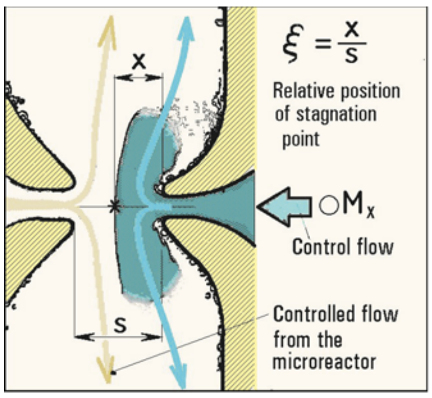

Fig. 3. Flow of the control fluid (blue) decreases the effective exit cross-section available at the microreactor outlet.

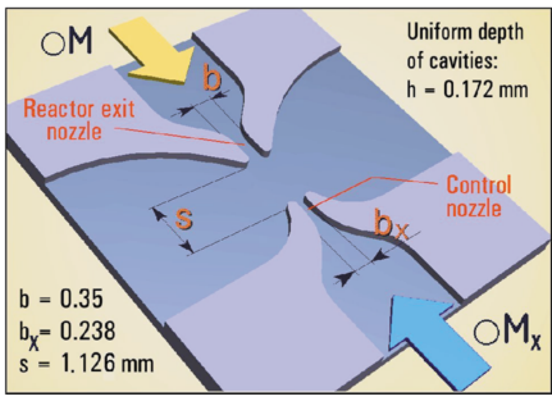

Fig. 4. The geometry of the microvalve. The flow from the reactor ○M (yellow) is varied by the action of the control flow ○M_X (blue) issuing from the (slightly narrower) control nozzle.

Another unusual feature that makes previous experience of little use, is the extremely small aspect ratio of the nozzles. This was dictated by the one-sided etching used to manufacture the present valve, as shown in Fig. 4. Both nozzles were designed with a large cross-sectional contraction, in an attempt to amplify whatever inertial effects are there at the low *Re*. The control nozzle exit was made slightly (0.68 times) narrower. The exit edges of both nozzles were all rounded by r = 0.1 mm radius, to avoid problems with manufacturing reproducibility and sensitivity to mechanical handling. The separation between the nozzles was $s = 3.22b$, a value small when compared with the usual nozzle separations in fluidic devices.

Classical large-scale fluidics aimed at developing fluidic amplifiers, with as large as possible flow gain. The colliding jets principle remained at the periphery of interest mainly because the achievable flow gains are rather small - control flow rate ○M_X [kg/s] required to turn down significantly the main flow ○M is relatively high. This, however, is no real problem in microfluidics as the absolute fluid flow rates are small and easily provided by even a small capacity source.

3. Computations

FLUENT solver version 5.5 was used, together with GAMBIT for grid generation. The friction on the flat bottom and top cover plate is quite important with the present low aspect ratio. Computations were therefore made for fully 3D geometry. The grid was tetrahedral unstructured, refined in high velocity gradient locations by adaptive cycles. A minimum of 8 cells per height were used, which made it impossible to use larger cells in low velocity areas - and this resulted in large total number of cells, 121 715 cells after last adaption. Computations were performed for laminar incompressible water flow at a constant reactor mass flow rate ○M corresponding to the nozzle Reynolds number Re = 75. In total, 16 computation runs were made at different control flows ○M_X. Six examples of the computed flowfields, characterised by the velocity ratio u (cf. Fig. 5), are presented in Fig. 6. They show the shift of the relative position χ of the stagnation point (cf. Fig. 3) towards the reactor exit with increasing magnitude of the control flow.

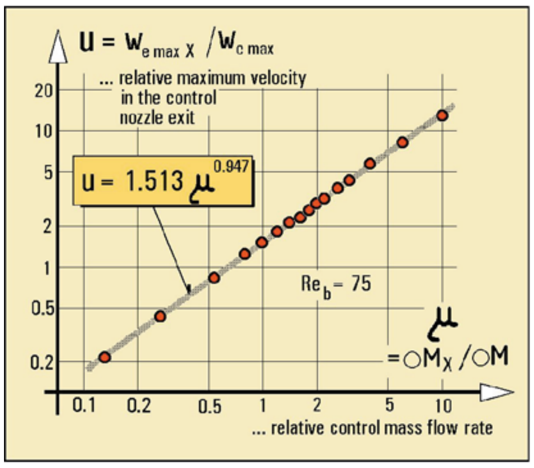

Fig. 5. Dependence between the velocity ratio u and the ratio of mass flow rates.

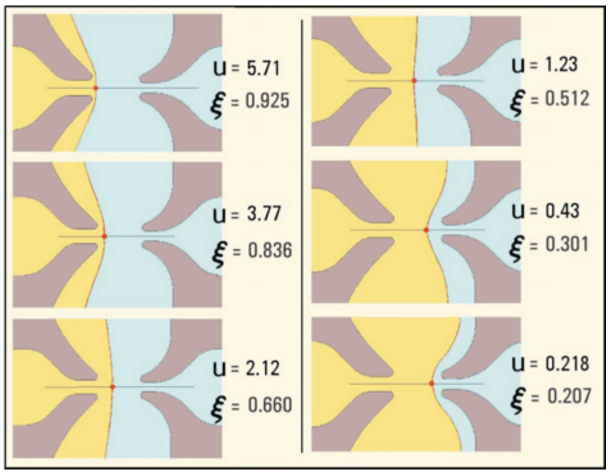

Fig. 6. Computed dividing streamlines passing through the stagnation point (red) at different velocity ratios u.

While the changing stagnation point location χ is instructive, what a designer of the device needs are the resultant changes in hydrodynamic properties of the reactor exit nozzle caused by the control action. A suitable quantity may be the resistance R. Its definition [†2] in Fig. 7, based upon a direct analogy to the Ohm's law of electric

†2 This definition was adopted after hesitation, as it is based on theoretically deficient system of state parameters, the mass flow rate ○M as the through variable and pressure drop DP as the across variable. This is not a consistent system as may be seen from their product being not power in proper units (watts). Specific energy drop would be a much better across parameter (Tesař, 1976a). It is, unfortunately, rather unusual - while pressure and mass flow rate are commonly used, directly measurable, and well understood.

circuits, assumes linear dependence between DP and $\circ M$. This would not be a good assumption in large-scale fluidics, where assuming quadratic dependence (Tesař, 1976b) leads to a much better characterisation. In the present case, the approach is applied to laminar flow where the assumption of linear behaviour is well substantiated.

Computed values of the effective nozzle resistances in Fig. 8 show the control by the colliding jet is highly nonlinear. This may be an advantage. It makes possible both small sensitivity at low x, which means a capability to adjust the flow very precisely - as well as, on the other hand, a very steep response (note the logarithmic scale in Fig. 8) at high x. With the constant flow boundary condition, of course, no complete closure of the flow was possible - nor in fact desirable for the chemical reactor flow control application.

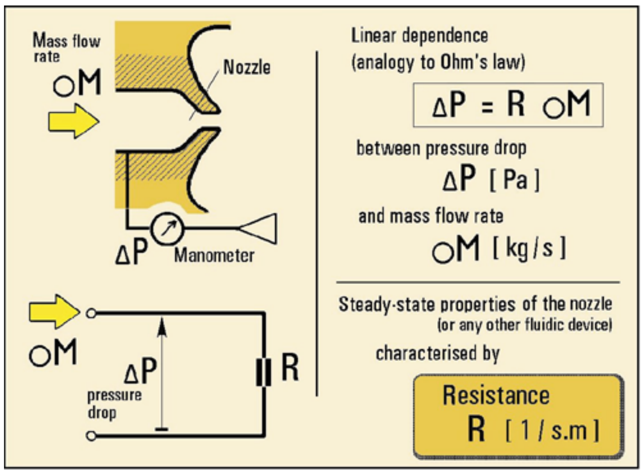

Fig. 7. The concept of the hydraulic (or pneumatic) resistance R applied to expressing the turning-down effect. The nozzle flow (top) is represented by an equivalent zero-dimensional restrictor model.

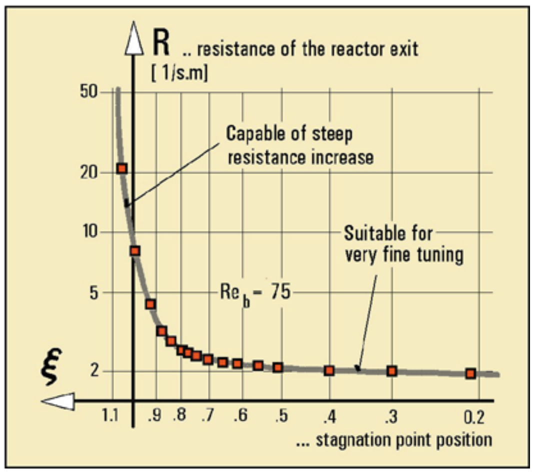

Fig. 8. Computed dependence of the effective resistance R of the main (= reactor exit) nozzle on the stagnation point position x. More than ten times increase in R is achievable. The reverse orientation of the horizontal co-ordinate was selected to agree with the actual movements of the stagnation point.

4. Experiments

The visualizations were used for two purposes. On one hand, because of extremely small and therefore hardly directly measurable water flow rates, the conditions were identified by velocity measured by particle tracking in the nozzle exits. On the other hand, features of the flowfield - in particular the relative positions of the stagnation point - were evaluated using flow visualisations by dye addition. The tests were run with water supplied to both nozzles.

4.1 Velocities

This part of the experiment was based upon a very simple version of particle image velocimetry. A steady state was adjusted while tiny polystyrene particles were added to water and carried with the flow. Their motion inside the nozzles was video recorded so that it was possible to evaluate the velocity (from frame recording frequency and measured travelled distances). The beads used for the distance measurements were those moving fastest so that they indicated the maximum velocity $w_{e\,\max}$ in the nozzle exit.

The flow regimes in the experiments were specified by $u = w_{e\,\max\,x} \,/\, w_{e\,\max}$ - the ratio of the maximum velocities in the two nozzles. This ratio differs from the ratio m of the mass flow rates (Fig. 5) due to the variations of the velocity profile shapes - especially in the control nozzle (Fig. 9), where the velocity is varied over a wide range of Reynolds numbers. The changes in the control nozzle velocity profiles are indicated in Fig. 10 by the ratio of the largest velocity in the profile to the bulk velocity. In the present case of rounded nozzle exit edges, the

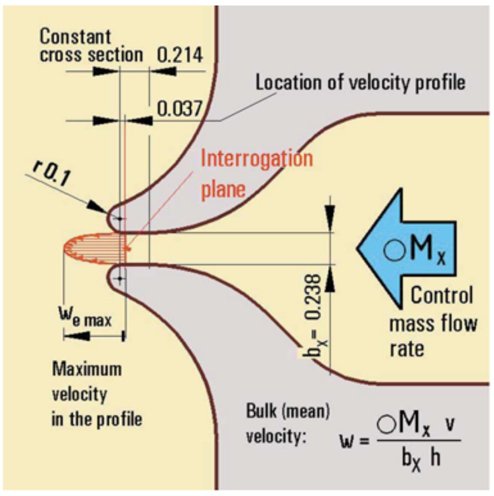

Fig. 9. Geometry of the control nozzle.

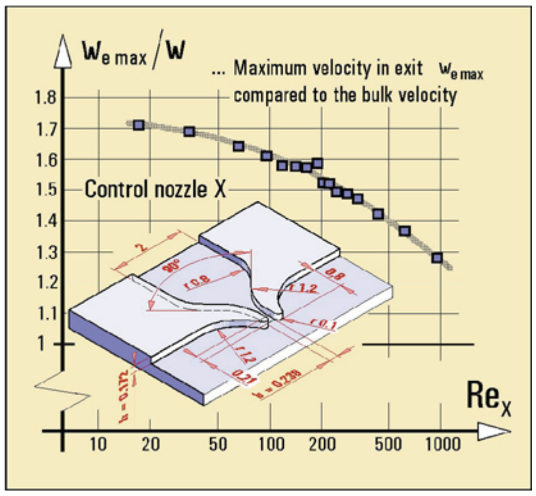

Fig. 10. Reynolds-number dependent variations of the velocity profile shape in the control nozzle.

precise location at which the exit velocity profiles are evaluated may be of importance. The "*interrogation planes*", were specified slightly upstream from the location in which the width of the channel begins to increase. This is shown in Fig. 9 for the control nozzle and in Fig. 12 for the main nozzle.

4.2 Flowfield Visualisation

The flowfield was made visible by dye addition into the control fluid. Prior to each run, a small amount of dyed water (using powerful *Victoria blue* dye) was inserted into the supply pipe upstream from the control nozzle. After starting the flow, clear water downstream from the dye passed through the control nozzle during the acceleration phase. The dyed column reached the nozzle when steady flow velocity was attained, causing a coloration change of control fluid from transparent to dyed - while flow velocities remained constant. It was this coloration change that was photographed.

Typical examples of the visualisation are presented in Fig. 11. Note that this is not a sequence of an unsteady increase in control flow. Instead, each picture shows a different steady-state experiment with independently adjusted velocity ratio u. The pictures were taken after the coloration change of control fluid reached to the stagnation point and then continued transversally along the dividing streamlines - but did not yet fill the whole domain occupied by control fluid in Fig. 6.

The measured stagnation point locations in Fig. 13 correspond well with the computation results. Over most of the range, the best fit to the computed values is quadratic (slope: 2.0) reflecting the quadratic relations between jet momentum flow rate and velocity. The dependence becomes much steeper once the stagnation point gets inside the nozzle exit channel. Experiments revealed a limitation as to the values of operational Reynolds numbers: above about Re = 100, the flowfield tends to become unstable and starts to oscillate (Tesař et al., 2000). This, however, is beyond the limit of operational conditions in the microreactor control applications.

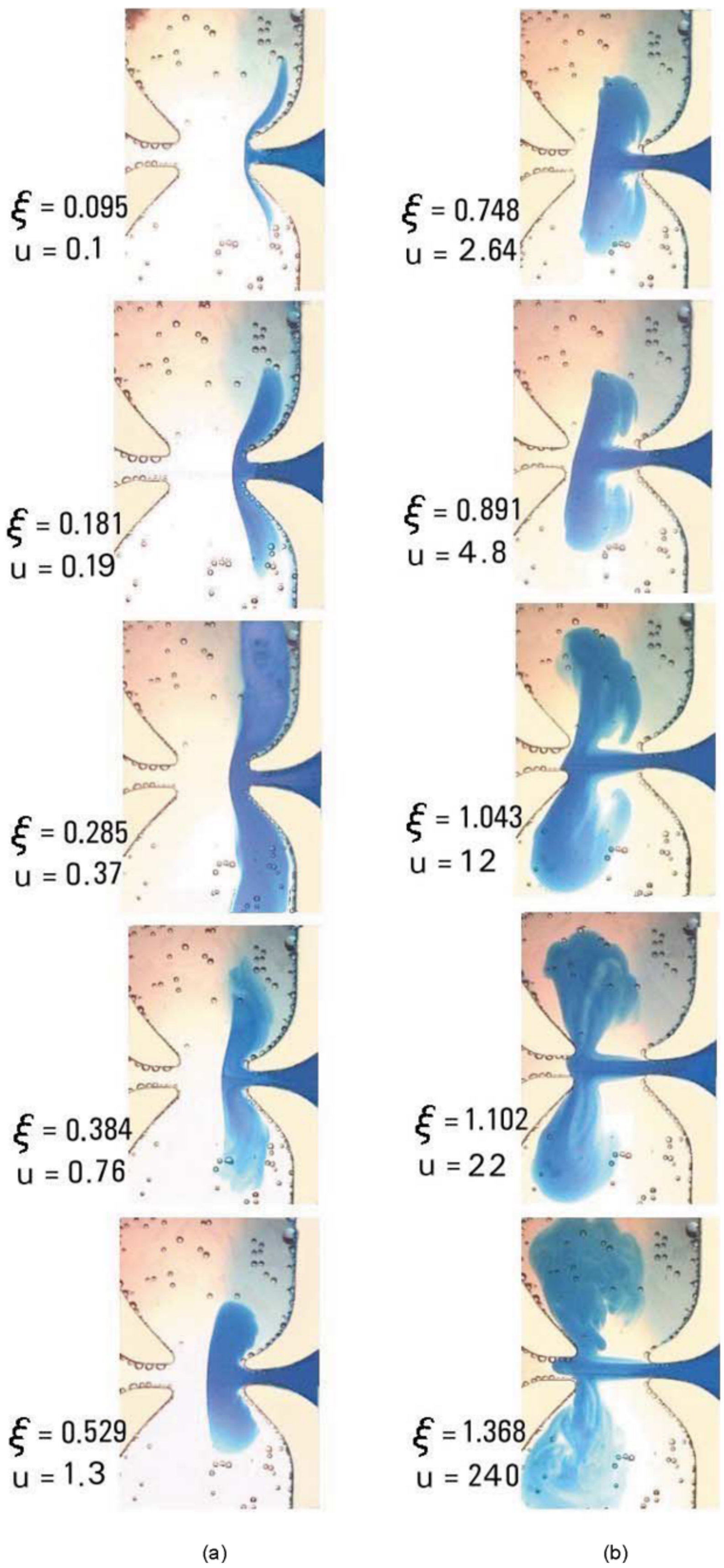

Fig. 11. Flow visualisation experiments at different ratios *u* of control fluid (blue) to reaction products (transparent) nozzle exit velocties.

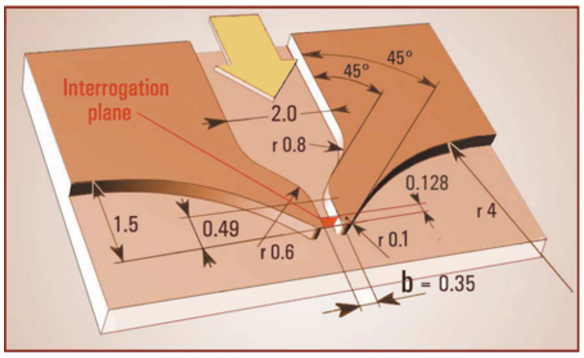

Fig. 12. Main nozzle: geometry and location of the interrogation plane.

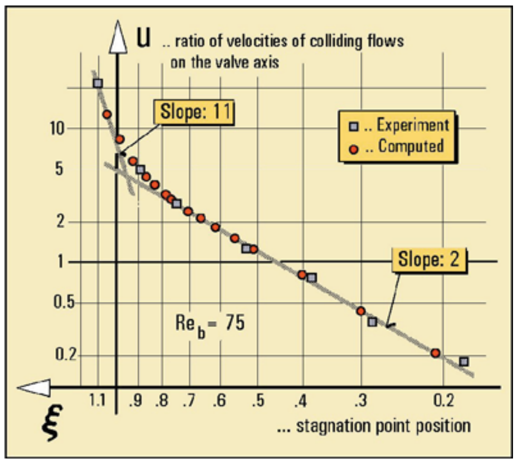

Fig. 13. Dependence between the ratio of collision velocities *u* and the position of the stagnation point.

5. Conclusions

Flow visualisation and numerical computations led to understanding of the flow interaction mechanism in the novel microfluidic valve without moving components - an ideal valve for microreactor flow control in cases where the added control fluid is unimportant or may be easily separated. This new valve offers at very low Reynolds numbers a unique flow turning-down capability. Depending upon the chosen location of the stagnation point (specified by the control flow at the basic operating point according to Fig. 13, using the dependence in Fig. 5) it can provide either fine flow adjustment (at low *R* in Fig. 8) or substantial variations of resistance (at high *R*).

Acknowledgments

The flow visualisation was set up in collaboration with Dr. J. R. Tippetts. The work was supported by $_iA_c$ - Institute of Applied Catalysis, United Kingdom.

References

Datta, M., Applications of Electrochemical Microfabrication: An Introduction, IBM Journal of Research and Development, 42-5 (1998), 563

Ehrfeld, W. (ed.), Microreaction Technology: Industrial Prospects, (2000), Springer, Berlin, ISBN 3-540-66964-7.

Katz, S. and Reid, K. N., A Generalized Static Model for Fluidic Impact Modulators, Trans. ASME, J. Basic Engng., (1971), 283.

Nomoto, A., Yamamoto, K. and Ohshio, Y., Axial Impingement of Two Bounded Jets, Proc. of 2nd Int. JSME Symp. on Fluid Machinery and Fluidics (Tokyo), (1972), 71.

Tesař, V., A System of Quantities for Description of States in Fluidic Circuits, Proc. of 6th Intern. "Jablonna" Conf. on Fluidics (Moscow, Soviet Union), (1976a).

Tesař, V., Some Basic Solutions of Fluidic Circuits Involving the Quadratic Dissipance, Proc. of 6th Intern. "Jablonna" Conf. on Fluidics (Moscow, Soviet Union), (1976b).

Tesař, V. and Tippetts, J. R., Fluidic Flow Control and Fluidic Device, British Patern Application No. PCT/GB00/03982, (2000).

Tesař, V., Tippetts, J. R. and Low, Y. Y., Oscillator Mixer for Chemical Microreactors, Proc. of 9th Intern. Symp. on Flow Visualization (Edinburgh), (2000), paper No. 298.

Tesař, V., Microfluidic Valves for Flow Control at Low Reynolds Numbers, Journal of Visualisation, 4-1 (2001), 51-60.

Author Profile

Václav Tesař: He received his Ing. degree in Mechanical Engineering fromČVUT - Czech Technical University, Praha, in 1963. From 1963 to 1999 he was employed at ČVUT Praha, Czech Republic as Assistant, then Docent, and finally Full Professor. He recived C.Sc. degree from ČVUT Praha in 1972. In 1985, he became Visiting Professor, Keio University, Yokohama, Japan and in 1992 Visiting Professor at Northern Illinois University, DeKalb, USA. From 1994 to 1998 he was Head of the Department of Fluid Mechanics and Thermodynamics, ČVUT Praha. He is currently Visiting Professor, Department of Chemical and Process Engineering, University of Sheffield, United Kingdom. His research interests are in shear flows, in particular jets and wall jets and their applications to fluidic no-moving-part flow control (named as inventor on 195 Czech Patents, mainly on fluidic devices, 9 British Patent Applications in microfluidics).