Microvalve Analysis: Wall Shear and Diffuser Effects

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ABSTRACT

This work deals with the analysis of silicon passive microvalves. The analysed microvalves consist of a circular central mass suspended by two flexible beams anchored on a pyrex substrate. The mechanical and fluidic analysis are first done by FEM (FLOTRAN) simulations, and afterwards the results are compared to an iterative analytical model, showing good agreement at low flow rates. In this model, we have taken into account viscous losses as well as inertial ones, usually neglected in model extraction and validation. A good fitting is achieved at high flow rates for a diminished inertial losses contribution. Measurements with air have been carried out in order to validate the proposed model.

Keywords : Microvalve, Finite Element Method, Analytical Modelling, Microfluidic Measurements.

INTRODUCTION

Microvalves play a key role in a great amount of microfluidic devices [1,2,3] like micropumps, microchemical analysis systems and microdosing. As a consequence, a good and reliable model for this component is needed for the analysis of the device performance. As high flow rates are achieved, the microvalve is forced to work in a non-linear operation mode and inertial effects can appear. Moreover, microvalves can be initially opened. All these effects influence the flow-pressure characteristic and, in this work, we will face these problems. It would be desirable to obtain a compact analytical model that also includes this last effect in order to avoid long time-consuming numerical calculations in FEM solvers[4]. Another point of interest is the evaluation of the geometric tolerances on the valve behaviour: high influence of thickness variations and misalignment can appear.

MICROVALVE MODEL

The analysed passive microvalve and its technological processes are described in detail in references [5] and [6]. It consists of a central circular mass attached to two flexible beams anchored on a pyrex substrate that define its stiffness. It is initially opened (about 5 μm) and the thickness of the beams is 10 μm. Radius of the central mass (r_t) is 400 μm and the radius of the input hole (r_w) is 250 μm. A SEM photograph of this kind of microvalve can be seen in Fig. 1.

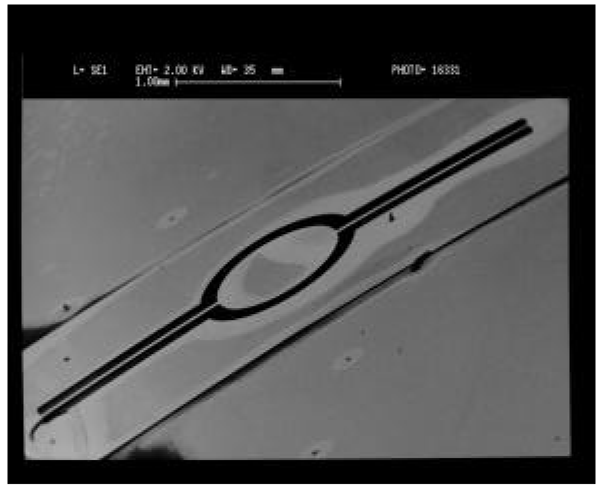

Figure1. SEM photograph of a two beam microvalve.

An iterative analytical model has been proposed, taking as initial point the behaviour of a diffuser[7]:

$$\frac{p(r)-p_2}{r\overline{U}^2/2} = 24\frac{r_w/d_b}{N_R}\cdot\ln\left(\frac{r_t}{r}\right) + b_{et}\left(\frac{r_w}{r_t}\right)^2 - b_e\left(\frac{r_w}{r}\right)^2$$

$$d_b = k(\overline{P})\cdot\Delta P$$

$$\frac{\Delta P}{r\overline{U}^2/2} = 24\frac{r_w/d_b}{N_R}\cdot\ln\left(\frac{r_t}{r_w}\right) + b_{et}\left(\frac{r_w}{r_t}\right)^2$$

The meaning of the geometrical parameters can be seen in Figure 2. p_1 is the pressure at the input, p_2 is the pressure at the output,)P = p_1-p_2, Δ is the density of the fluid (air in this case), r_w is the radius of the input hole, r_t is the radius of the central mass, 5 is the mean velocity at the entrance (r= r_w) d_b is the distance separation between the central mass and the pyrex substrate, N_R is the Reynolds number at

$r = r_w$, ∃ is the energy distribution factor (depends on the flow distribution) and k is the valve stiffness.

As the area of the channels grows as r increases, the flow will develop faster than for a constant section channel. So, ∃ = 1.543 (fully developed flow) is, generally, good for the whole channel. First equation gives us the pressure distribution over the central mass. The first right-hand side term of this equation is related to wall shear losses and the other two terms are related to the inviscid ideal diffusion (relevant for high pressure values). The coupling with the mechanical domain is given by the displacement of the valve in reaction to the mean pressure over the central mass (second equation, with k: valve stiffness), that, for large displacements, can depend on the pressure applied. This relation can be obtained by non-linear mechanical FEM simulations. Last equation gives the pressure difference between the inlet and outlet as function of the fluid flow. The model also shows that negative pressure values acting on the valve lid, can be reached and it is especially important for high flow rates[8].

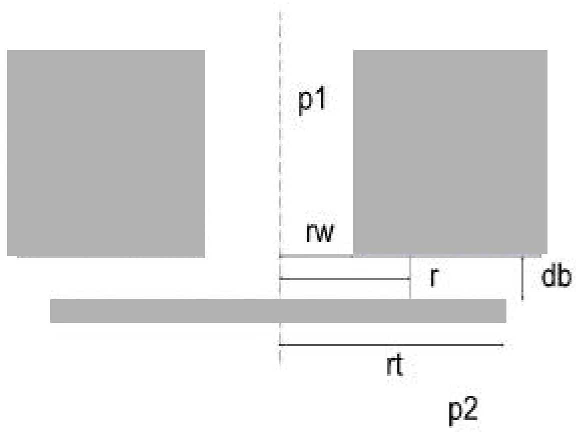

Figure 2. Cross section scheme of the microvalve model.

FEM ANALYSIS

FEM simulations have been performed in order to compare results with the previous analytical model. FLOTRAN has been used to simulate the fluidic domain with air with an axisymmetrical model (a centered inlet hole is assumed in simulations). The stiffness of the microvalve is taken constant (no non-linear behaviour is considered). Due to the fluidic-mechanic coupled problem, iterative FEM simulations were needed to obtain the flow(pressure) characteristic. Turbulent flow was considered at high pressures. In figure 3, it's shown the FEM axisimetric model used in FLOTRAN. As can be seen in Figure 4, FEM results agree quite well with analytical model data. The first slope (low pressures) is due to the initial opening of the microvalve (flow is proportional to pressure). Viscous losses term is the dominant process in this region. As the valve opens, the slope grows up to four times the initial one. At high pressure, we have assumed ∃=1 in the model. This value is used because of the non-developed flow regime (the microvalve has a high opening compared with the length channel) and a high N_R (greater than 100) in the channel in this particular case. However, results diverge from model predictions at high pressures. This can be explained by the additional non-reversible losses at high flow rates at the turbulent regime [9]. These losses are proportional to the square of the mean flow velocity (as the ideal diffusion losses). The proportional constant should be, in principle, empirically determined. The reason is that this constant depends on a series of dimensionless variables such as surface roughness, viscosity, velocity, density, etc. We have opted to implement it in the model by the addition of a proportional constant in the diffuser effect term of previous model equations. We have obtained a better agreement by reducing the initial inertial contribution to the model. In Figure 5 it's shown the results obtained by diminishing the inertial effects by a factor of 5. As it can be seen, simulations agree with model predictions also for high pressures.

Figure 3. Axisymmetric FEM model used in FLOTRAN.

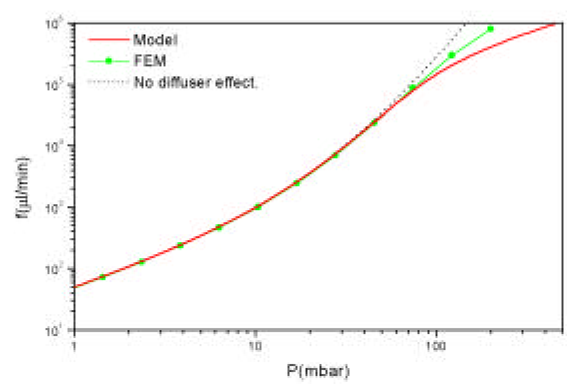

Figure 4. FEM (FLOTRAN) results compared to the analytical model

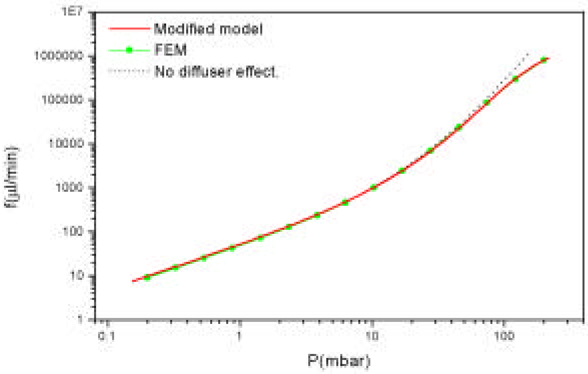

Figure 5. Comparison between FEM and modified model (relation factor=5).

MODEL PARAMETERS INFLUENCE OVER FLOW CHARACTERISTICS

We have used the analytical model in order to obtain the dependencies of the flow (pressure) characteristic with respect to the rigidity of the valve and the length of the channel. In figure 4 we can see four different cases, combining the following parameters: valves stiffness k_m^{-1} = 0.7 and 0.23 :m/mbar and channel length L_{ch} = 150 and 25 :m. They are compared with the pure wall shear effect (dashed lines), that is usually modelled [10,11]. The diffuser effect appears at high flow rates, showing a slope decrease of the characteristic f(P). As shown in the figure, this effect becomes more important for low channel lengths. Due to the high displacement of the valve at this level of pressure, the distance for fully developed flow should be taken into account.

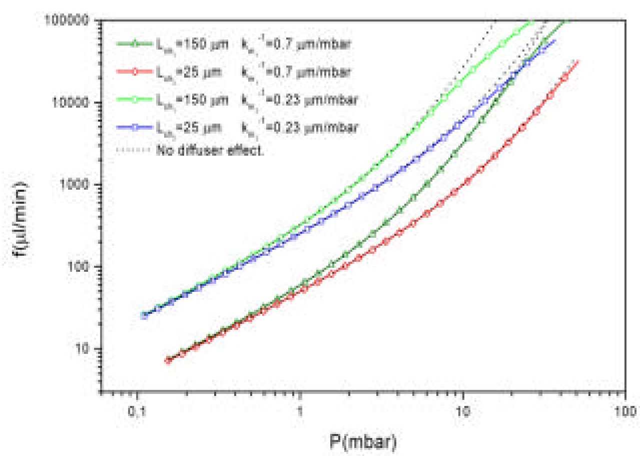

Figure 4. Parameter study of the analytical model obtained by changing L_{ch} and k_m.

EXPERIMENTAL RESULTS

The measurement set-up used for air flow measurements consists of a input chamber that is filled by a flux of air up to maximum pressure level. Then, this flux is stopped and it's left to flow through the output. Air flow can be obtained from the slope of the pressure against time evolution. To obtain the flow, ideal gas behaviour is considered. . As the level of pressure is quite low (with respect to atmospheric pressure), this assumption is supposed to be valid. Also, quasiestatic condition is supposed for valve operation and pressure uniformity of the input chamber.

In Figure 5, we can see the pressure evolution in time obtained with the mentioned setup. The extracted flow-pressure characteristic can be seen in figure 6. Variation of the valve parameters within the technological uncertainties allows a good agreement with the results extracted from the analytical model. Some differences could be explained by non-uniform structures, roughness of the pyrex surface (it was done to improve the bonding between pyrex and silicon) and also the entrance length effect for high flow rates.

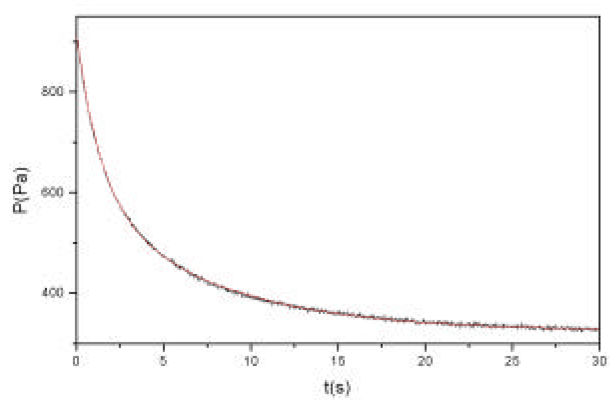

Figure 5. Pressure transient measurement for flow determination.

CONCLUSIONS

We have proposed an analytical model of a silicon passive microvalve that has been compared to FEM simulations, showing a good agreement at low pressures, where viscous losses are predominant. The model was improved by means of an addition of a proportional constant in the diffuser effect term. It shows a better agreement at high pressures, while having a good one at low pressures. Therefore, diffuser effect can not be neglected at high pressures and high valve openings. Moreover, the presence of non-developed flow over the channel must be considered.

aplicación a la fabricación de componentes para microfluídica", PhD Thesis, 1998.
[7] L.A. Zalmanzon, “Components for Pneumatic Control Instruments”, Pergamon, Oxford, 1965.
[8] F. Yang, I. Kao, “Analysis of pressure balanced MEMS valves”, Proceedings of the 1998 International Conference on modelling and Simulation of Microsystems Semiconductors ,Sensors and Actuators pp.534-539.
[9] V. L. Streeter, E. B. Wylie, "Mecánica de los fluidos", Mc Graw Hill, eight edition (1993).
[10] R.E. Oosterbroek, S. Schlautmann, J.W. Berenschot, T.S.J. Lammerink, A. van den Berg, M.C. Elwenspoek, “Modelling and validation of flow-structure interactions in passive micro valves”, Proceedings of the 1998 International Conference on modelling and Simulation of Microsystems Semiconductors, Sensors and Actuators pp. 528-533.
[11] Hal Jerman, “Electrically-activated, normally closed diaphragm valves”, Journal of Micromechanics and Microengineering 4, 1994, pp. 210-216.