Analytical study and characterisation of micro-channel and passive micro-diode

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Abstract

This paper presents a general approach to the problem of modeling rectangular channel or passive valve. The study is divided into three sections. The first describes the analytic modelisation of a channel versus its shape factor and describes a normalisation of its fluidic comportment. The second is dedicated to numerical simulation of a Tesla diode and purpose an optimisation of its efficiency versus the tesla geometry. The last part exposes the realisation and characterisation of prototypes. The characterisation is applied to the rectangular channel which showed good agreement with the analytic modelisation.

1. Introduction :

As interest in microfluidic systems grows, technique for pumping and dosing particle suspensions are required for many new applications in industrial production as well as in the fields of biotechnology, environmental testing, and instrumentation for analytically chemistry [1]. Here, we are interested in developing a global data base of micro-channel and passive microvalve to be implemented is future development around the study of micropumps or bio-devices.

2. Study of micro-channel

For many devices the flow-pressure characteristic can be described using a simple analytical formula well known from macroscopic fluid mechanics as for micro-channel [2] or nozzle diffuser [3]. This is the application of the Navier-Stokes equations. But for other devices such as vortex [4] or Tesla [5], no analytical solution can be calculated. One solution is to use the CFD software Computational Fluid Dynamics (ANSYS®/FLOTRAN) or FlumeCAD {Microcosm}. From the numeric simulation results, an analytic formula can be extracted.

2.1. Case of rectangular channel

Most of micro-channel obtain by micro-technology, etch on the wafer surface, have a rectangular section. The microchannel can be described by its wide d, height h and length L (Fig. 1). Due to the low Reynolds number, the flow behaviour is supposed to be laminar.

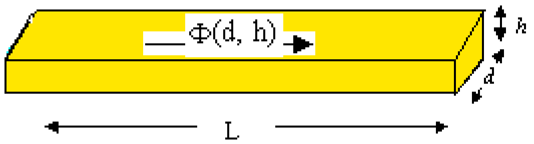

Fig. 1 : Schematic representation of the rectangular channel

In this case, two behaviours can be obtained and depends on the shape factor (λ) of the channel. Where λ is the width-height ratio : $(\lambda = d/h \geq 1)$.

<u>* If λ is close to one</u> :

the rectangular microchannel is similar to a circular channel with an hydraulic diameter D_h : $D_h = 4\dfrac{d*h}{2(d+h)}$. the flow characteristic is then calculate from the Hagen-Poiseuille law :

$$\boxed{\Phi_{Ps} = \frac{S.P}{32\eta L} D_h^2}$$

Where P, η are the hydrostatic pressure difference and the dynamic viscosity and S is the channel cross section $S = d \cdot h$.

<u>* If λ is far from one</u> :

In this case, h is very small compared to d, damping effect due to viscosity near the section width is negligible. The volume flow characteristic $\Phi(P, d, h)$ is than given by the law of Navier–Stokes :

$$\boxed{\Phi_{St} = \frac{1}{12}\frac{d \cdot h^3}{L}\frac{P}{\eta}}$$

This two behaviors can be expressed from λ (the shape factor) with the normalized parameter T :

$$T = \left(4 \cdot \frac{\Phi\eta \cdot L}{P \cdot h^4}\right)$$

By this way, the relation between the volume flow rate in the channel and geometry parameters (h and d) shown in equations 1 & 2 can be expressed as:

Hagen Poiseuille : $T_{Ps} = \dfrac{1}{2}\dfrac{\lambda^3}{(1+\lambda)^2}$

Navier Stokes : $T_{St} = \dfrac{1}{3} \cdot \lambda$

The use of Hagen Poiseuille relation or Navier Stokes is determinate by the value of λ. The limit is when the two models gives the same behavior (T_{Ps} equal to T_{St}). This is for λ=4.45.

In order to validate the theory, prototypes of rectangular microchannel have been achieved (fig. 2) and characterised (Fig.3).

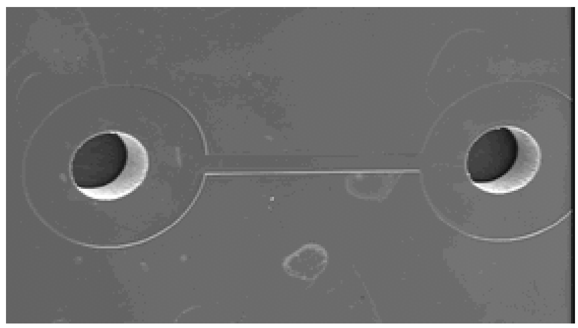

Fig. 2 : channel fabricated

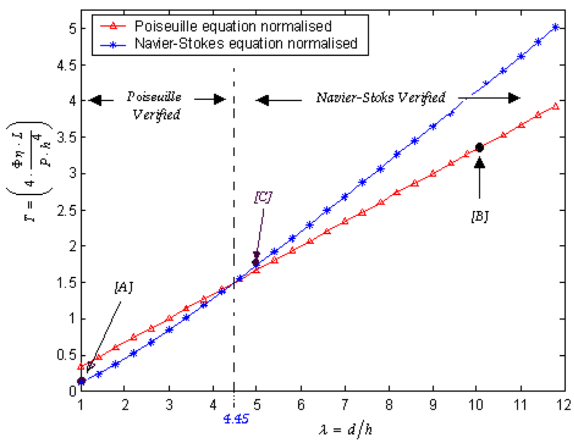

Fig. 3 : The relationship between the ratio λ and T

Results are depicted in figure (3).

- When $\lambda \leq 4{,}5$, we have to use Hagen-Poiseuille models (Point A), deduced from [3].
- When $\lambda \approx 4{,}5$, similar behaviour (Point C), deduced from [4].
- When $\lambda \geq 4{,}5$, then Navier-Stokes is more convenient see Point B from measurements obtain on our prototype (Fig. 2) by a collaboration with ENS Paris.

2.2. Study of Tesla diode

A Tesla diode [5] is similar to a valvular conduit. Its profile is presented in Figure 4).

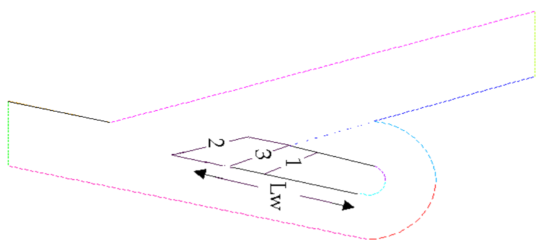

Fig 4 : Tesla channel structures{1_2_3}

The flow profiles are given by numerical solution (ANSYS®) for a 650µm long, valve of 85µm hydraulic diameter with an interner wall [5]. The valvular conduit allows the fluid (water) to pass in the forward direction, and prevents it from the backward direction by geometric turbulence (Figs. 5 (a, b)) :

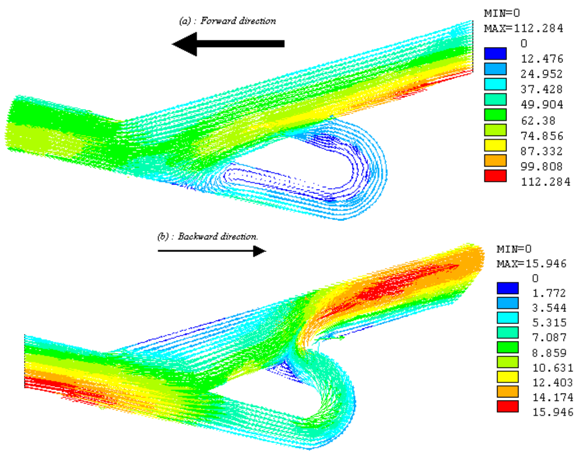

Fig. 5 : Velocity distribution of the valve at a pressure of 60000Pa.
(a) : Forward direction.
(b) : backward direction.

In order to study the influence of the internal wall length (L_W) , simulations of a Tesla channel, for three L_w varied from 1 to 3 (Fig. 4), have been achieved and are shown in Fig. 4. It is interesting to see that forward flow Φ_F, backward flow Φ_B. varies differently with L_w in Fig. 6.

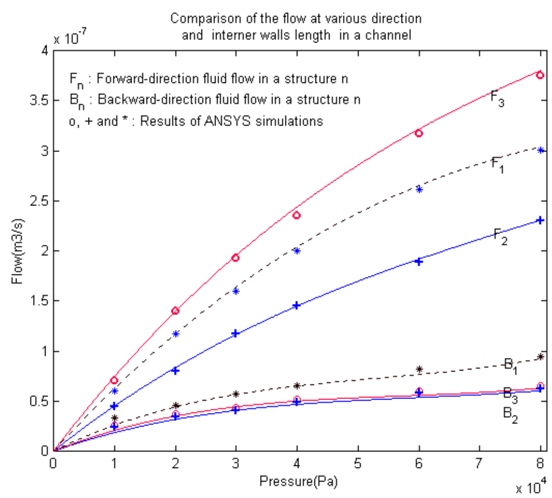

Fig. 6 : Flow-pressure characteristic in a Tesla Channel.

It's important to notice that the optimal structure, denoted by (3), corresponds to a linear prolongation of the entry channel. From numerical results, an analytical equation has been extracted using the least square method (table1). For the pressure of 10kPa (corresponding in this case of a Reynolds number of 1000), the efficiency $E = (\Phi_F - \Phi_B)/\Phi_F$ of the Tesla diode is 0,65.

	Structure 3
Forward direction	$\Phi = 1.62e-22\, P^3 - 5.31\, e-17\, P^2 + 7.96\, e-12\, P - 4.89\, e-9$
Backward direction	$\Phi = 2.24e-22\, P^3 - 3.84\, e-17\, P^2 + 2.42\, e-12\, P + 2.53\, e-9$

As for the micro-channel, we have achieved some prototypes which are under test.

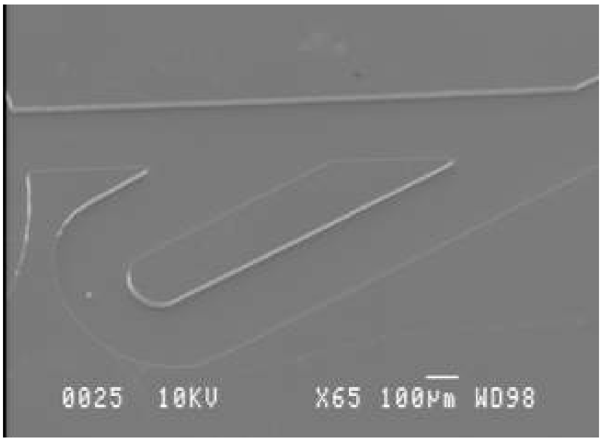

Fig 7 : valvular conduit fabricated using micro-machining technology

Finally, there are two main advantages of using this optimised valve. First, an important efficiency $(E \geq .5)$, second the valvular conduit contains no moving parts.

3. Fabrication and characterisation

Fig. 2 and 7 illustrate the photographs of channels fabricated in silicon wafers. These channels were obtained by etching a silicon wafer by Deep Reactive Ion Etching (DRIE) technique from 1μm to 200μm. The channel access are realised by a complete etching of the bottom side of the silicon wafer. An anodic bonding is done to close the channel with a Pyrex wafer.

The measurements were done by forcing the flow in the channel with a syringe pump and measuring the loss pressure between the input and output channel with a differential pressure sensor. The measure were done by controlling the temperature of the global system.

4. Conclusion

In this paper, a global modelisation of a rectangular micro-channel has been purposed in order to normalised its behavior. From the value of the micro-channel shape factor, the flow characteristic can be rapidly deduced. Prototype have been achieved and tested in order to validate the influence of the shape factor on the model used. The study is than extended to a more complex structure : the tesla diode. Numeric simulation presented enable to optimise the valve efficiency regarding to its geometry, an analytic formula is extracted from the simulation. In the same way of micro-channel, prototype has been achieved.

The direct application of these results is the possibility to integrate the analytic formula in a global simulator of a microfluidic devices using these structures.

5. Acknowledgements :

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6. References :

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