

VALVELESS FLUID ACTUATION: LIEBAU'S PRINCIPLE FULLY INTEGRATED ON THE MICROFLUIDIC SCALE

L. Bogunovic^{1*}, S. Gerken¹, M. Viefhues¹, J. Regtmeier¹, R. Eichhorn², and D. Anselmetti¹

¹*Biophysics and applied Nanoscience, Bielefeld University, GERMANY*

²*NORDITA, KTH Royal Institute of Technology and Stockholm University, SWEDEN*

ABSTRACT

In this contribution, we present the integration of valveless impedance pumping on the microfluidic scale. When a fluidic channel is periodically compressed at a point located asymmetrically with respect to an impedance mismatch in the system, an effective fluid flow is the result although no further moving parts such as valves are involved. Such an impedance mismatch could be e.g. a sudden reduction of the channel cross section. Four different types of impedance mismatches are being investigated concerning their response to different applied pressures and compression frequencies. A maximum fluid velocity of 25 $\mu\text{m/s}$ and even a frequency dependent overall inversion of the flow direction could be observed.

KEYWORDS: Valveless fluid actuation, impedance pumping

INTRODUCTION

We demonstrate fully integrated valveless pumping in a linear microfluidic channel using only a single actuated membrane and thus avoiding many constraints of common miniaturized pumping mechanisms. This pumping effect is based on the Liebau phenomenon or so called impedance pumping [1,2,3]. If a fluidic tube is pressed together by a periodic force at a position located asymmetrically with respect to an impedance mismatch in the fluidic system, a net transport of the fluid therein without any valves or further moving parts is observable. Such an impedance mismatch could be for example a sudden constriction, a reduction of the channel cross section, curves or microstructures integrated into the channel surface. It is meanwhile widely accepted, that this effects is the result of pressure wave reflection and interference at this point of impedance mismatch [2,3]. Such an approach is ideally suited for lab-on-a-chip systems, that are designed to perform multiple laboratory functions in a single miniaturized chip because no critical valves, blades, internal moving parts, nozzle/diffuser components or external electric or magnetic fields are required. In the present contribution, we focus on the fabrication of such chip integrated valveless pumps and characterize their performance depending on the applied pressure, its frequency and the exact shape of the impedance mismatch.

EXPERIMENTAL

Our valveless pumping device consists of three parts, fabricated with soft lithography, which are assembled one after each other (see Fig. 1). On top of a glass substrate, a first layer of PDMS containing the primary channel structure is bonded with oxygen plasma. In the next step, the 20 μm thick PDMS actuation membrane is oxidized and installed on top of the first layer. On this membrane, a second PDMS layer is deposited, containing the actuation channel, which is oriented perpendicular to the main channel (drawn in green). The structured PDMS parts were fabricated before with standard soft lithography using SU-8 photo resist and a standard 4 inch silicon wafer coated with tridecafluoro-1,1,2,2-tetrahydrooctyl trichlorosilane. The result are two crossing channels on top of each other, separated by a thin and flexible membrane, that can be pressed down by filling nitrogen with pressure p into the upper actuation channel.

The nitrogen flow is controlled with digital high speed valves (transient time: 2 ms) which either inject nitrogen with a desired externally chosen pressure or dump the nitrogen in the channel to the normal atmosphere. The main channel that is filled with water as working fluid is constructed in four different geometries (I-IV), illustrated in the insets of Fig. 1. Their main criterion is, that the channel symmetry with respect to the actuation channel is broken, resulting in the desired impedance mismatches. While this is done with different sudden cross section changes (I –III), design IV features an array of integrated microstructures in the channel. The fluid velocity is measured via particle image velocimetry.

RESULTS

Our main results are shown in Fig. 2. Using channel design I, the effect of the actuation frequency for different nitrogen pressures on the effective fluid velocity was investigated (Fig. 2a) and generally reveals non-monotonic behavior. Additionally, the application of higher pumping pressures leads to higher fluid speeds. In all cases, a velocity maximum around $f = 20$ Hz was observed with a highest value of 25 $\mu\text{m/s}$ for $p = 0.7$ bar, where a positive velocity means, that fluid flows from the larger to the smaller part of the channels. However, a flow reversal is observable at $f = 80$ Hz for 0.5 and 0.7 bar. For even higher frequencies, the granted relaxation time of the membrane is too short so that no effective pumping was observed.

The influence of the geometry of the impedance mismatch was studied in fig. 2b), where the resulting fluid velocities for a constant pressure of $p = 0.7$ bar for the channel designs I, II and III are compared. Again, a strong dependence of the fluid velocity on the actuation frequency is notable. There is, however, no strong correlation between the relation of channel diameters and the overall archived fluid velocity. In this case the position of the flow maximum seems to correlate with

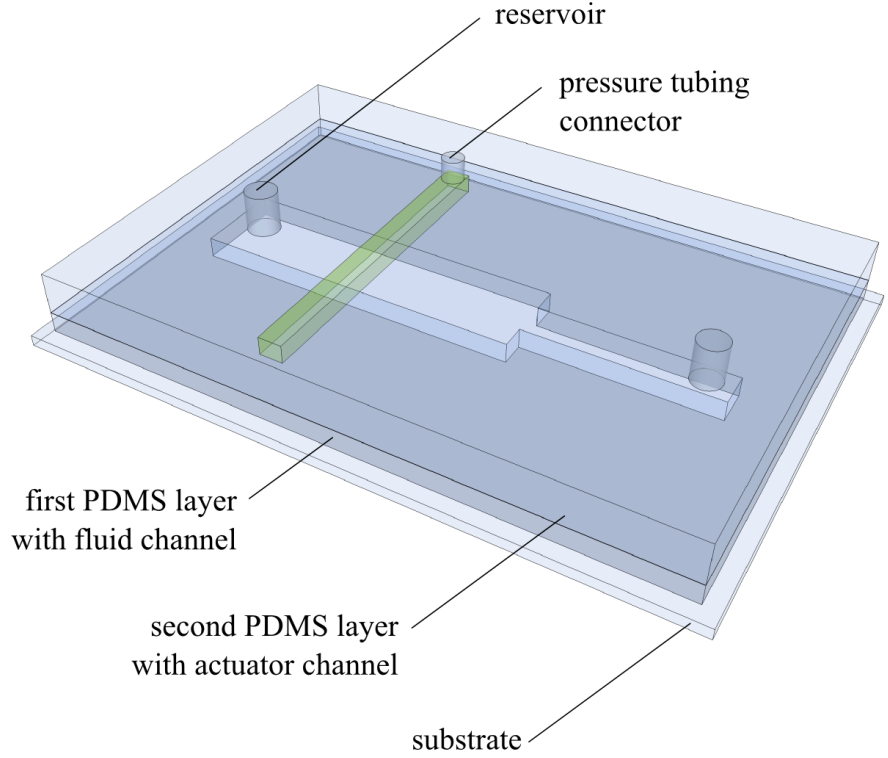
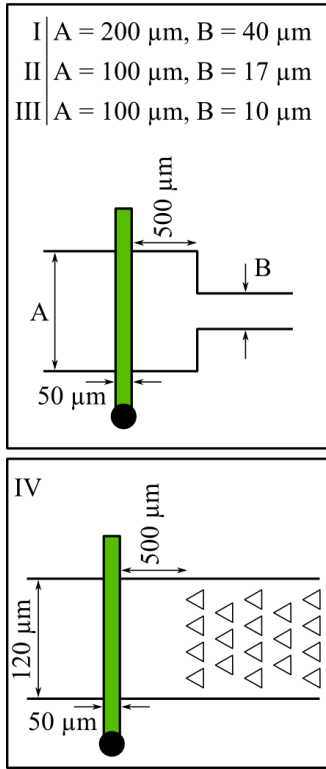


Figure 1: Schematic of the impedance pumping device integrated into a microfluidic chip. Two PDMS layers containing the fluid channel and the actuation channel (green) are bonded together, separated only by a $20\ \mu\text{m}$ thin PDMS membrane. This membrane is actuated by nitrogen pressure connected to the actuation channel. The device was realized in four different designs (I – IV). I, II and III introduce the required impedance mismatch with a simple constriction at one side of the actuation channel. Design IV breaks the symmetry with an array of structured triangular posts reaching from the channel top to the bottom.

the maximum fluid velocities. A flow reversal is notable for the 5:1 mismatch (design I), while in the other two cases, the velocity sign remains unchanged. To demonstrate, that the required impedance pumping for the Liebau effect can not only be introduced by different channel cross sections (as originally proposed [1]), the channel has been structured with rectangular posts reaching over the full height of the fluid channel (design IV). All together, these posts block 28% of the channel cross section. For different actuation pressures (0.4 – 0.7 bar), the observable maximum fluid velocity shifted to approximately 50 Hz while the non-monotonic character of the frequency response remains. During operation the device itself turned out to be very robust as the flexible PDMS membrane did not suffer any defects or ruptures. Moreover, no membrane adherence to the channel walls was observed.

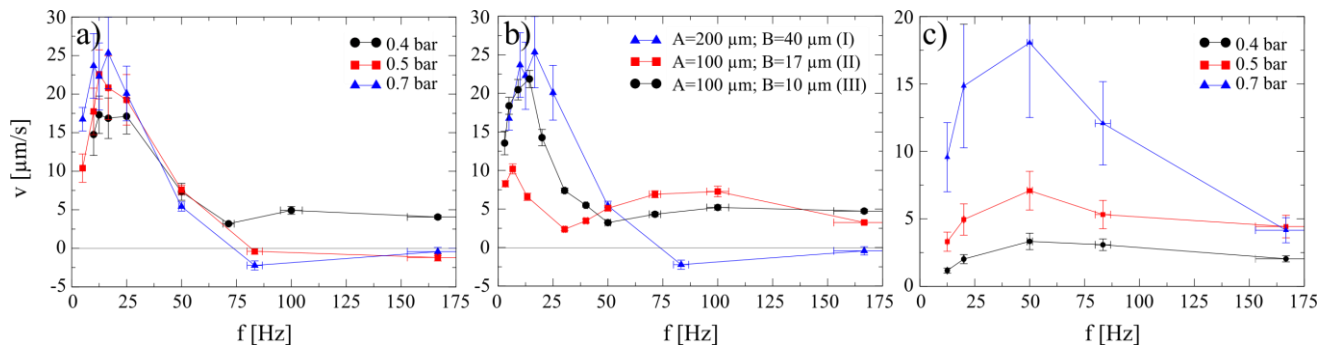


Figure 2: Fluid velocities achieved with the constructed impedance pumps. a) Principle I has been characterized with three different nitrogen pressures for several actuation frequencies. A clear non-monotonic behavior with a flow maximum around 20 Hz is observable. For the highest pressure, even a flow reversal around 80 Hz can be discerned. b) The pumping velocity of principle I, II and III was evaluated with 0.7 bar for different actuation frequencies. The optimal pumping frequency as well as the fluid throughput shifts to higher values, when larger channel diameters are considered. Finally, it is demonstrated in c), that the required impedance mismatch can not only be generated with different channel diameters (as Liebau originally suspected) but also with a structured triangle array. However, the best performing actuation frequencies are shifted to approximately 50 Hz.

DISCUSSION

The exact quantitative interpretation of the physical basics behind Liebau's phenomenon are still under debate, although a general agreement that the fluid motion is a consequence of wave reflections at the impedance mismatch, exists [2,3]. So far such mechanisms can exist on large scales with significant Reynolds numbers. In our case, the Reynolds number is smaller than $5 \cdot 10^{-3}$ and thus inertial effects are strongly dominated by viscous forces. This is the case even during transient actuations near the membrane, which can be concluded by quantifying the Womersley number, being here $\alpha = \sqrt{\omega L^2/\nu} \ll 1$, where $\omega/2\pi$ is the actuation frequency, L is a typical channel length scale and ν is the kinematic viscosity of water. This consideration reveals, that the explanation of the observed pumping with fluid waves alone is not sufficient on the microfluidic scale, although it holds well for large fluidic systems. However, there is still the possibility, that the required wave propagation to the impedance mismatch occurs in the channel bulk material near its fluid interface, which is well compressible [3]. Using a Young's modulus of 750 kPa for PDMS and an applied pressure of 0.5 bar one can roughly estimate, that the PDMS channel surface will be deformed by a few micrometers upon pressing the membrane down. Significant changes in the channel geometry as shown in the sketches of design I – IV might thus indeed be sufficient as wave reflection sites for Liebau pumping. The claim is supported by the typical characteristics of impedance pumps, we observed experimentally [1,2,4], being the increase of pumping velocity with increasing actuation pressure and especially the non-monotonic frequency characteristics. A deep quantitative numerical analysis of the wave propagation process in our microfluidic devices is carried out in an ongoing study.

CONCLUSION

We presented a realization of Liebau's principle fully integrated into a microfluidic channel for valveless pumping of fluids. Besides an oscillating membrane that periodically compresses the microchannel, no moving parts are required. Depending on the compression frequency and amplitude, different fluid velocities and even overall flow reversal for certain frequencies and pressures were observed. The strong dependence on the actual channel geometry underlines the need for future optimization to design efficient microfluidic Liebau pumps tailored to specific problems.

ACKNOWLEDGEMENTS

Financial support from the German Research Foundation (DFG) within the collaborative research center SFB 613 (TP D2) is greatly acknowledged.

REFERENCES

- [1] G. Liebau, "Ueber ein ventilloes Pumpprinzip", *Naturwissenschaften*, vol. 41, p 327, 1954
- [2] A. I. Hickerson and M. Gharib, "On the resonance of a pliant tube as a mechanism for valveless pumping", *J. Fluid Mech.*, vol. 555, pp 141-148, 2006
- [3] A. I. Hickerson, D. Rinderknecht, M. Gharib, "Experimental study of the behavior of a valveless impedance pump", *Exp. Fluids*, vol. 38, pp 534-540, 2005
- [4] M. Utz, M. R. Begley, H. Haj-Hariri, "Microfluidic waves", *Lab Chip*, vol. 11, pp 3846-3854, 2011

CONTACT

*L. Bogunovic, tel: +49-521-106 5388; bogunovic@physik.uni-bielefeld.de