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Micro-Venturi injector: design, experimental and simulative examination

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Abstract. This paper reports the first factorial design of a micro Venturi injector completed by a simulative investigation of the device. For the first time, a comprehensive correlation between the point of the maximum vacuum pressure generated by the Venturi nozzle and the variation of the inlet pressure is shown. The device reported in this contribution enables a new solution for robust low-pressure generation in parallel fluidic channels.

1. Introduction

The integration of microfluidic functionalities into conventional silicon MEMS devices has yielded growing interest especially with new technologies and products in biology and life sciences. Due to increasing complexity of devices, the parallel operation of several flow generators is required in some cases. Standard microfluidic components can be parallelized easily but miniaturization of effective pumps for flow or pressure generation remains difficult. Mostly, fluidic microsystems consist of miniaturized subsystems that are connected to a macroscopic pump. By using simple channels in parallel, the flow in each device depends on the flow in the parallel devices, i.e. if one channel blocks, the flow in the other channels will increase. For many applications this behavior is not desired. A complex solution to make systems more robust against failure of single channels might be the integration flow-regulated pumps or throttle valves. However, these solutions require additional sensors and active elements. In contrast, the integration of Venturi injectors offers a robust and easy solution to generate a flow in parallel microchannels without the need of any additional components.

The working principle of a Venturi injector is based on a fluid flow that causes low pressure at an inlet port. Thus, low pressure can be generated from a high pressure flow. A Venturi injector consists of pressure inlet, suction inlet, outlet and a convergent-divergent constriction. Low pressure is generated as air flows through the converging passage that gradually widens. The constriction causes a high velocity by which a low pressure at the suction inlet is caused. Thus, the fluid at the suction inlet is drawn into the nozzle and mixes with the inlet fluid.

Venturi injectors on a microscale have been reported as air-flow based tactile display [1], as a device for precise liquid aspiration [2] or as part of an optofluidic flow sensor [3].

The injector reported in this contribution is designed as integrated flow generator supplying an airflow to a particle detector. The low pressure generated at the suction inlet is utilized to produce a flow which transports particle-loaded air into a detection channel where the particles are counted and/or material and size are determined (see Figure 1). The Venturi injector has advantages over the use of a flow-regulated suction pump since multiple injectors can be operated in parallel using a constant inlet pressure, i.e. the flow of the single injectors depends only on the geometrical dimensions of the injector and the inlet pressure and not on the total number of injectors.

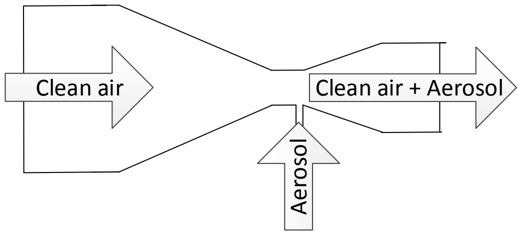

Figure 1. Working principle of the Venturi injector as part of a particle detector. Clean air flows through a constriction and thus aerosol from the suction inlet is soaked into the flow and mixes with the clean air.

2. Design and fabrication

The dependence of the vacuum pressure on the geometric dimensions at the suction inlet was investigated by using a design of experiments (DoE) approach. Aim of this approach is to observe the effect of design variables on the system response. In this case, the DoE was used to examine the impact of geometrical changes of the constriction on the low pressure generated at the suction inlet in order to find an optimum design of the Venturi injector.

For this purpose, a full factorial design with three factors was created. The variables considered to have the largest impact on the vacuum pressure are constriction width W, length L and the divergent angle Θ_{Div}. Table 1 lists the variable design parameters, the level of the single factors and the values of each level. According to the factorial design a total number of 16 devices with different geometries was fabricated. The depth of the constriction and the entire Venturi injector was 40 µm and the convergent angle was 30°. Both parameters were fixed for all designs. The design of the Venturi injector and in particular of the constriction section can be found in Figure 2.

Table 1: Design parameters of the design of experiments (DoE)

Factor	Level	Values
Length L	2	1500 µm; 3000 µm
Width W	2	100 µm; 250 µm
Divergent angle Θ_{Div}	4	20°; 30°; 40°; 50°

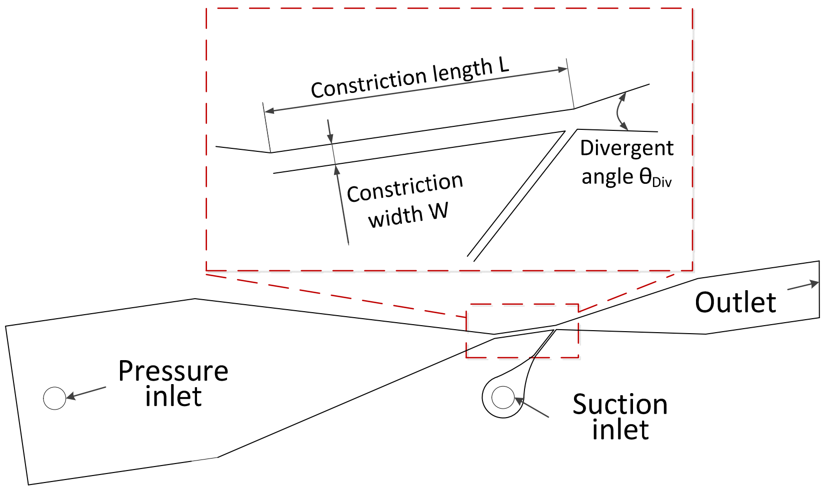

Figure 2. Dimensions of the micro-Venturi injector: The constriction length L, width W and the divergent angle are varied in the factorial design while the remaining geometrical parameters remain fixed.

The fabrication made use of standard microfabrication processes: The channels were etched in a DRIE process into silicon wafers and the openings for the fluid connection were also etched from the back side of the wafers. The outlet is on the edge of the chip (see Figure 3). The fluidic channels were covered by anodic bonding of a Borofloat® glass substrate. This manufacturing process enables simple integration of the Venturi structures into a large number of sensors, actuators and lab-on-chip devices.

To realize a connection to the experimental setup, NanoPort™ assemblies were used. These assemblies are specifically designed to provide a consistent fluidic connection for chip-based analysis. The NanoPort™ assemblies were bonded to the chips using an epoxy-based adhesive ring. They enable a stable and pressure tight connection up to pressures of >100 bar. Pictures of a fabricated chip device with attached NanoPorts™ can be found in Figure 3.

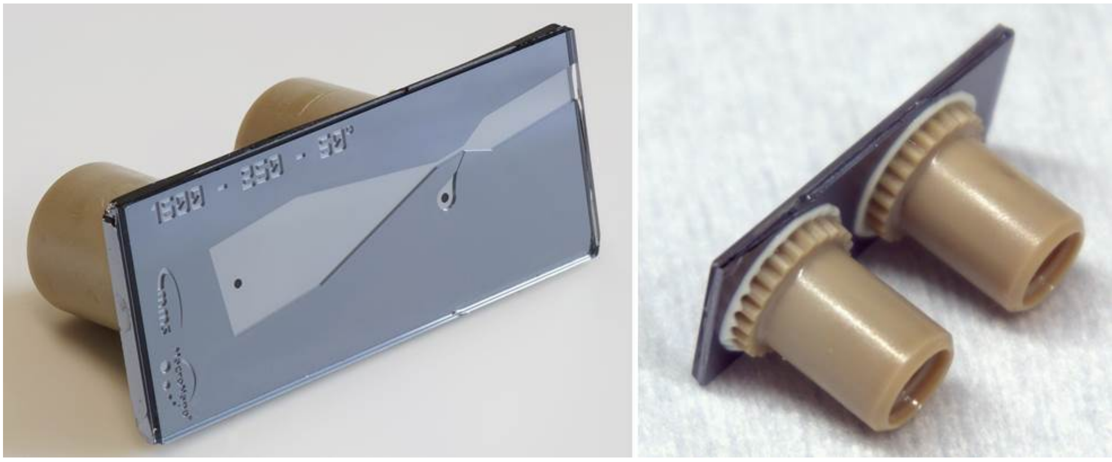

Figure 3. Photographs of the fabricated micro-Venturi injector. The microfluidic channels are etched into silicon and enclosed by a cover glass plate. The fluid connection to the chip is realized by NanoPort™ assemblies.

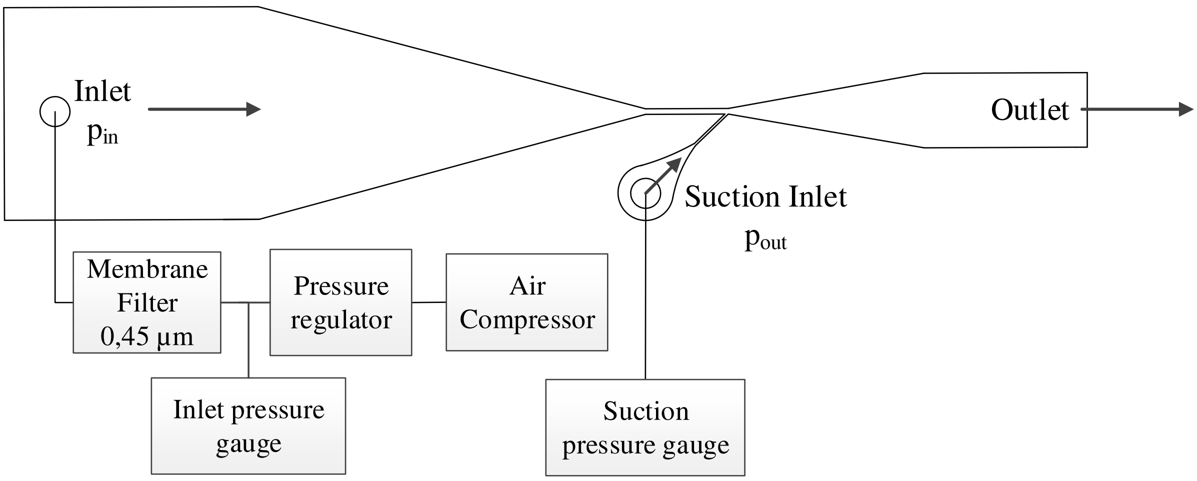

Figure 4. Experimental setup to measure the low pressure p_{out} at the suction inlet in dependence of the pressure at the pressure inlet p_{in}.

3. Experimental

The devices were connected to a compressor with an intermediate pressure regulator and were tested with air at a pressure range from 200 mbar to 3000 mbar at the pressure inlet. The pressure at the suction inlet was measured with a pressure gauge. A schematic of the complete experimental setup can be found in Figure 4.

Figure 5 shows the measured outlet pressure p_{out} at the suction inlet vs. the inlet pressure at the pressure inlet p_{in} for 3 exemplary design variations. The designs depicted in the graph all have a constriction width of 100 µm, a constriction length of 3000 µm and the divergent angle varies from 20° to 40°. During the measurements it was found that the relative suction pressure decreases with rising inlet pressure, reaches a minimum and then increases. These results are comprehended by the simulation as shown in Figure 7. The location of the minimum pressure is not fixed as expected but it depends on the inlet pressure. This insight provides an explanation for the nonlinear behaviour of the Venturi injectors.

For the statistical evaluation of the measurement data the statistical analysis software Minitab was used. The maximum respective vacuum pressure $p_{vac,max}$ for each device served as the base for the evaluation. Figure 6 shows the main effect plot for $p_{vac,max}$. In this graph, the means for each value of the variables are plotted. The results show that the divergent angle has the greatest influence on the suction pressure, followed by the constriction width whilst the constriction length has the smallest impact.

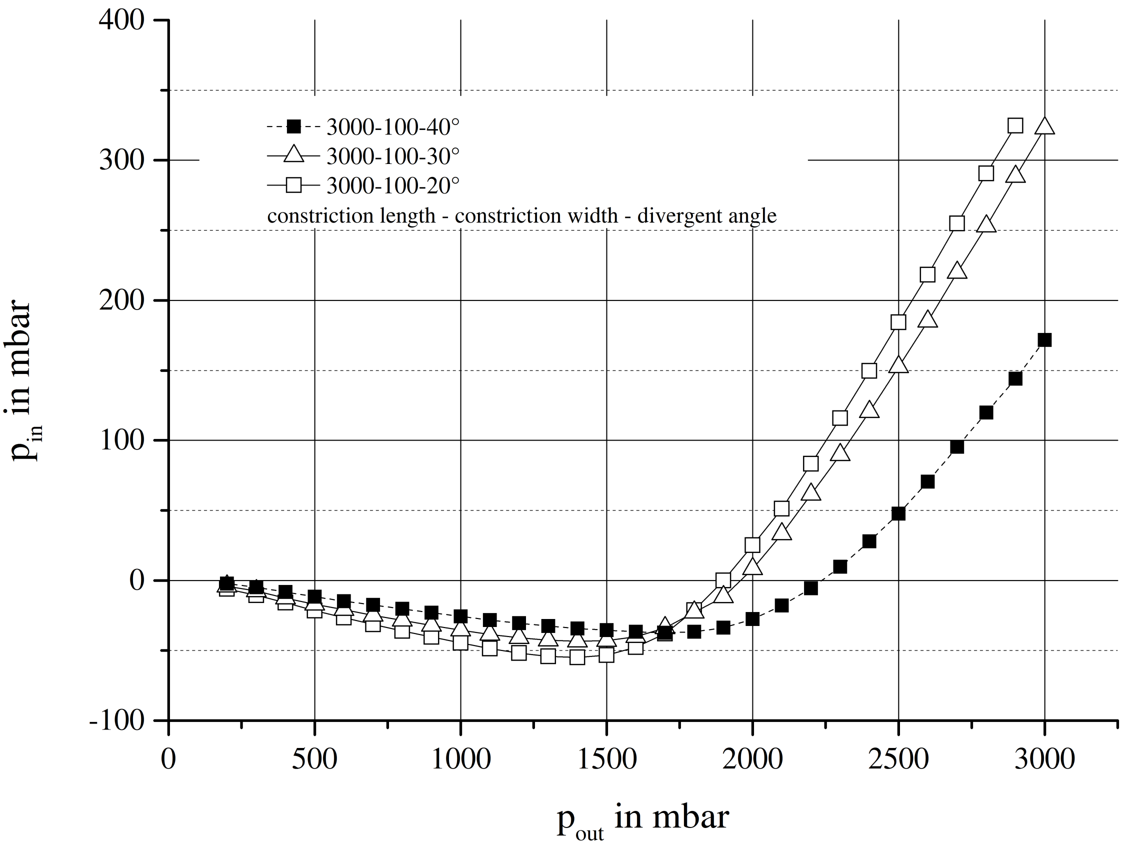

Figure 5. Measurement results of exemplary Venturi injector design variations.

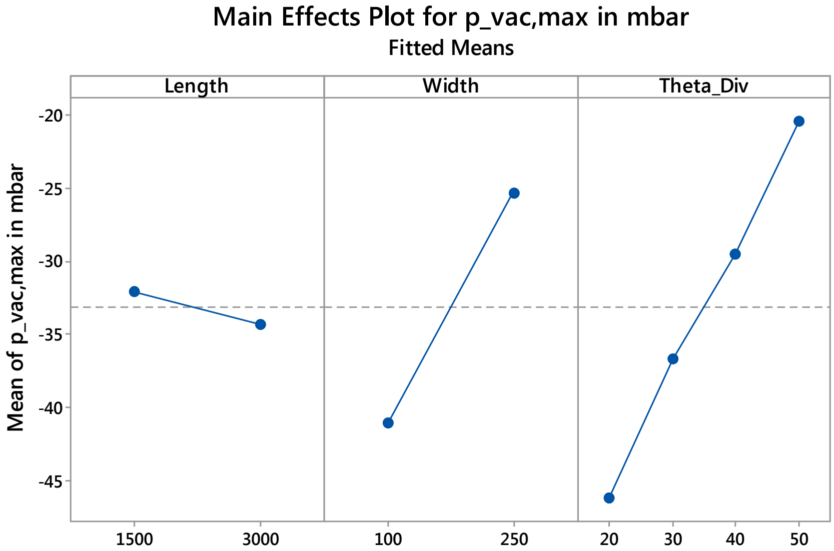

Figure 6. Results of the DoE: Dependence of the maximum vacuum pressure $p_{vac,max}$ measured at the suction inlet on the constriction length, width and divergent angle. As it turns out, the divergent angle has the greatest effect.

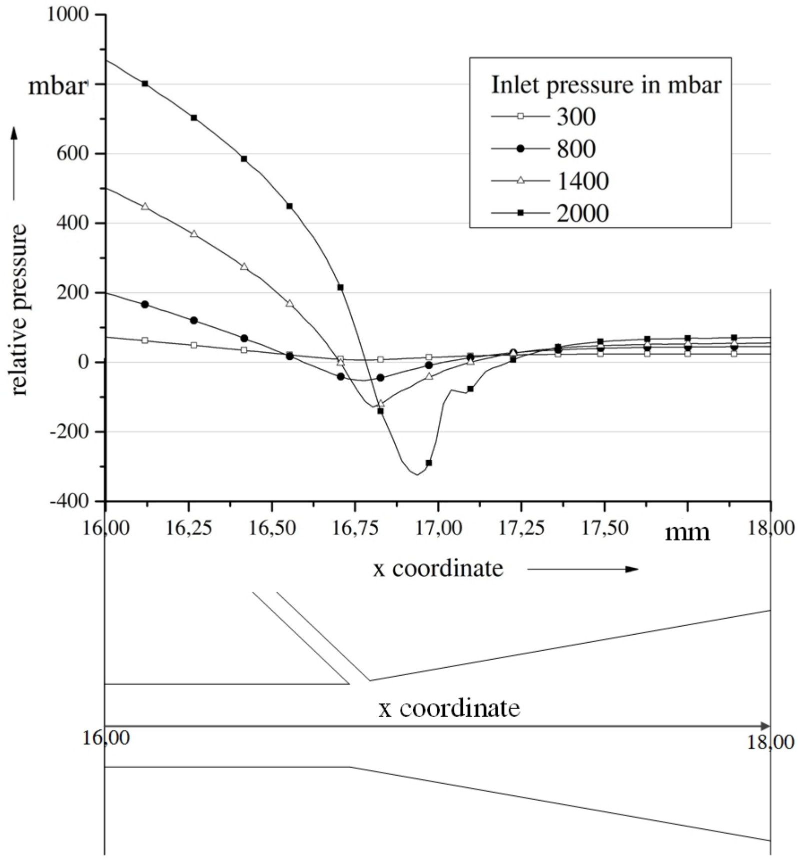

Figure 7. Results of the CFD simulation and relevant part of the Venturi device: The plot shows the relative pressure at the suction inlet in relation to the inlet pressure. The results show that the point of the maximum vacuum pressure is not fixed at the end of the constriction but changes with different inlet pressures.

4. Conclusions

This contribution reports the statistical examination of a Venturi injector based on the design of experiments (DoE) approach. The aim was to investigate the impact of the geometrical dimensions of the constriction on the maximum vacuum pressure at the suction inlet. Measurement results show that the divergent angle has the greatest influence on the suction pressure. The maximum vacuum pressure generated was -54.9 mbar at an inlet pressure of 1400 mbar with a constriction length of 3000 µm, a width of 100 µm and a divergent angle of 20°. The experimental results were supported by a CFD simulation using ANSYS Fluent.

Previous work [4, 5] described the design of a Venturi tube based on the geometrical parameters of the constriction. The experimental results presented in these publications showed that a vacuum pressure is generated along the entire range of applied inlet pressures. In contrast, our results show that the vacuum pressure collapses when the inlet pressure rises above a threshold inlet pressure. The measurements presented in this contribution clearly show a nonlinear correlation between inlet and outlet pressure. In previous work it was claimed that the greatest pressure drop occurs just before the divergent section [4]. The simulative and experimental results reported here could not support this claim and show that the location of the minimum pressure is not fixed, but it moves with changing inlet pressure.

Acknowledgments

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