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To cite this version:

Dingdong Zhang, Franz Schweizer, Guillermo López Quesada, Samuel Bergdolt, Stefan Hengsbach, et al.. Isothermal pressure driven gas microflows in tapered microchannels with circular cross section: numerical and experimental investigations. 4th European Conference on Non-equilibrium Gas Flows – NEGF23, Mar 2023, Eindhoven, Netherlands. 172-176 (paper NEGF23-438617). hal-04070325

HAL Id: hal-04070325

https://hal.science/hal-04070325v1

Submitted on 15 Apr 2023

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NEGF23-438617

ISOTHERMAL PRESSURE DRIVEN GAS MICROFLOWS IN TAPERED MICROCHANNELS WITH CIRCULAR CROSS SECTION: NUMERICAL AND EXPERIMENTAL INVESTIGATIONS

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KEY WORDS

Microfluidics, rarefied gas flows, tapered microchannels, two photon polymerization.

ABSTRACT

Introduction

Gas flows in microdevices are of great interest for a wide variety of applications, such as vacuum generation, gas separation, gas chromatography, heat dissipation, etc. [1]. Through the advent of new 3D micro fabrication techniques, innovative architectures for new generation devices are now possible. In the perspective of developing new generation Knudsen pumps, different geometries have been reported in the literature, based on curved, sinusoidal, matrix, ratchet and tapered channels [1]. Nonetheless, most of the mentioned studies were performed numerically, and thus there is a great need of experimental investigations in this subject, specially related to 3D geometries. Pressure and temperature driven flows in long tapered channels have already been numerically investigated in the literature [2,3], however, almost no experimental data is currently available. To our knowledge, experimental work only on pressure-driven flows has been realized so far [4,5]. It was demonstrated that the predicted mass flow rate through a tapered channel was higher in the converging direction rather than in the diverging one, for the same pressure difference imposed, under moderate rarefaction conditions. This is the so-called gas flow diode effect, affected by the angle of the tapered channel, the properties of the gas and the rarefaction degree [5]. The diodicity effect created by the converging or diverging directions of the flow in the same microdevice can be of great interest for several fluidic applications. Furthermore, the transient behavior of gas microflows through these kinds of elements could be of high interest for the optimization of gas micropumps associated to sensors or actuators that require specific response time.

In this work the stationary and non-stationary behavior of the pressure driven isothermal gas flow in a tapered microchannel with circular cross-section has been numerically and experimentally characterized. In a later stage the characterized tapered microchannels will be employed in the design and fabrication of Knudsen-type micropumps. The tapered 3D microchannels were manufactured via 2-photon-polymerization (TPP). The manufacturing technique was recently validated for a straight uniform circular cross-section microchannel with gas flows in rarefied conditions [6].

State of the problem: pressure driven flows in tapered microchannels

In the present work, a tapered microchannel of circular cross section was tested (Figure 1). The diameter of the tapered channel varies linearly along the z-axis from d_{in} to d_{out}. The total channel length is defined as the distance between inlet (z = 0) and outlet (z = l), while the inclination ratio α is defined as:

$$\alpha = \frac{d_{in}}{d_{out}} \tag{1}$$

For converging channels, α is greater than 1 and for diverging channels, α is lower than 1.

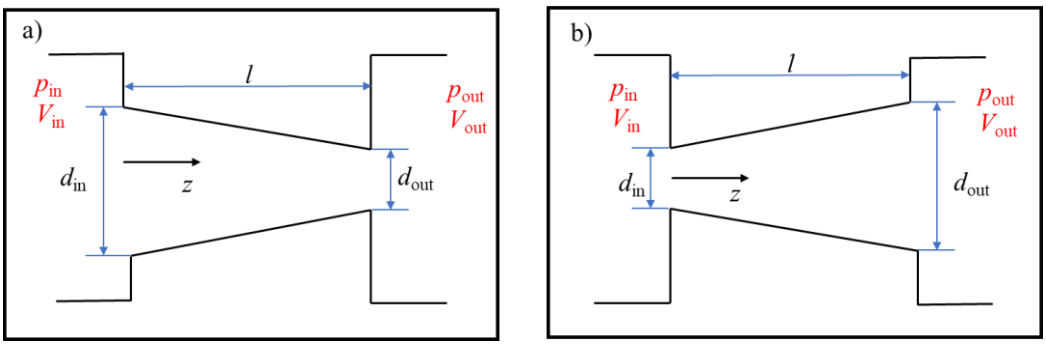

Figure 1: Design of a tapered microchannel with circular cross section. a) Converging tapered channel; b) Diverging tapered channel.

Isothermal pressure-driven rarefied flows through long microchannels have been widely investigated numerically via the kinetic theory of gases [2,3,7,8]. Through the following ordinary differential equation, it is possible to both compute the mass flowrate $\dot{m}$ and the pressure distribution along the channel [7–9]:

$$\frac{dp}{dz} = -\frac{8\sqrt{2R_gT}}{\pi d^3 G_p}\dot{m} \tag{3}$$

Here, R_g is the specific gas constant, d is the cross-section diameter which varies along the z-axis, T is the temperature and G_p is the dimensionless mass flow rate and is a function of the local rarefaction parameter $\delta(z)$. In the present work, G_p was obtained through the linearized Shakhov model for purely diffuse boundary conditions [7,10]. The rarefaction parameter for circular channels can be expressed as:

$$\delta(z) = \frac{pd}{\mu\sqrt{2R_gT}} \tag{4}$$

where the pressure p and the diameter d are functions of z, while the dynamic viscosity μ was defined via the hard-sphere model. Eq.(3) can be solved when two out of three variables are known. For instance, the mass flow rate $\dot{m}$ can be calculated by specifying the inlet and outlet pressures p_{in} and p_{out}. With this method, both stationary and transient gas flows through a microchannel can be numerically investigated. The transient flow was considered as a succession of quasi-steady states.

Experimental method

The pressure driven mass flowrates were measured via the constant volume technique [6,11]. The experimental setup consists mainly in two tanks connected through the microchannel (Figure 2) and two

capacitance diaphragm gauges (CGA and CGB). It is possible to relate the pressure variation with time measured inside both tanks to the mass flowrate through the channel for an isothermal flow:

$$\dot{m}_i = \frac{V_i}{R_g T}\left(\frac{dp}{dt}\right)_i \tag{5}$$

where $i = 1, 2$ is the index denoting the tank, V is the tank volume and t is the time. The gas flow in the microchannel is obtained by imposing an initial difference of pressure between both tanks, and pressures varies with time in both tanks until a zero flow equilibrium state is reached. It is possible to engender a flow from Tank 1 to Tank 2 and vice versa, thus creating a flow in a converging or diverging direction of the micro-structure.

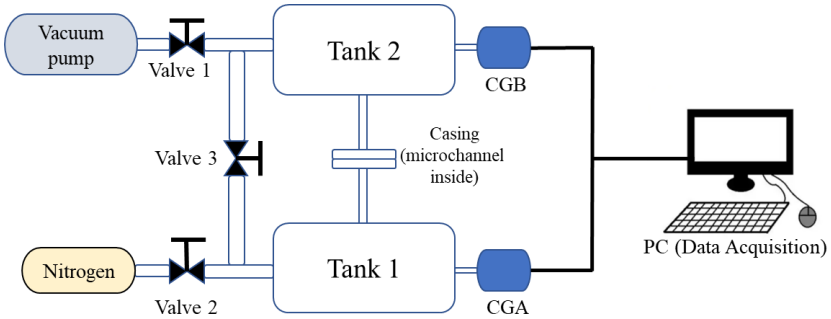

Figure 2: Diagram of the experimental setup. Two tanks are separated by Valve 3 in order to generate a gas flow through the microchannel with an initial pressure difference between the two tanks.

Fabrication method

Recently, two-photon-polymerization (TPP) has been successfully applied for manufacturing three dimensional devices for rarefied gas flows applications [6]. The same fabrication technique has been here chosen to fabricate microchannels with variable circular cross-section. TPP can generate complex 3D microstructures of intricate inner geometries with high precision. The process of manufacturing is based on the focusing of a laser beam into a viscous liquid photosensitive material (IP-Q Nanoscribe GmbH) to induce a photochemical reaction only in a high intensity focal spot volume. The channel was created inside a polymerized cube of approximately 1 mm^3 (Figure 3). This structure was deposited over an aluminum substrate of dimensions 25 mm × 25 mm × 0.5 mm. The substrate includes an orifice of approximately 200 µm in diameter that allows connecting the tapered channel to the rest of the experimental setup. The tapered channel dimensions were measured through a conventional microscope, thus they are to be considered external measurements ($l = 973$ µm, $d_{in} = 32$ µm, $d_{out} = 426$ µm). It should be noted that the internal dimensions of the channel can vary significantly from the external measurements. As reported in [6] there could be an internal and external shrinking factor of up to 25%. Furthermore, as already observed in straight channels, this shrinkage causes also the formation of a funnel-shaped inlet and outlet. Measurements via µ-tomography will be realized on the sample for proper characterization of the inner structure of the channel.

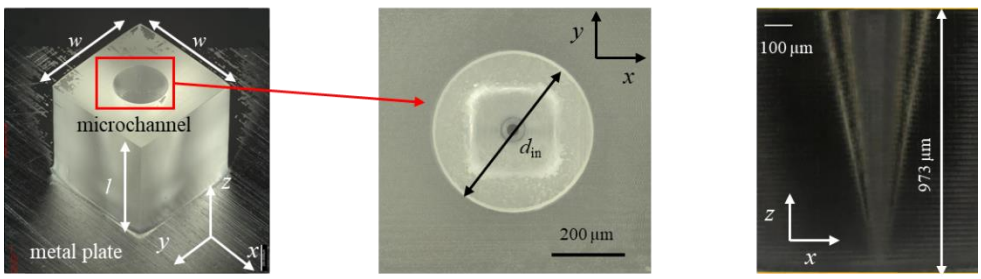

Figure 3: Tapered microchannel with circular cross-section manufactured by TPP on an aluminum metal plate. Left: 3D structure of full microdevice. Middle: Top view of the microchannel measured by digital microscope Right: Side view of the microchannel measured along the length by digital microscope.

Discussion of numerical and experimental results

Both converging and diverging directions of the flow were numerically and experimentally investigated with the same initial pressure difference $\Delta p = 200$ Pa between inlet and outlet tanks, and for different rarefaction conditions. For sake of clarity, results are presented as a function of the inlet pressure (Figure 4). The numerical simulations were carried out using two different sets of diameters: i) the externally measured inlet and outlet diameters (d_{meas}) and ii) inlet and outlet diameters with a shrinking coefficient in order to fit the experimental data ($d = 0.86 \cdot d_{meas}$). The length l and the inclination ratio α of the channel are kept constant. On the one hand, as expected, the experimental data for the first case show significantly lower mass flowrates over the whole range of inlet pressures compared to the numerical results (Fig. 4 left). On the other hand, the numerical simulations using diameters equal to 86% of the external diameters show rather good agreement with the experimental data. Some deviations can be observed as rarefaction increases, and they could be attributed to extremity effects not taken into account in the numerical model, which is not valid for too short channels.

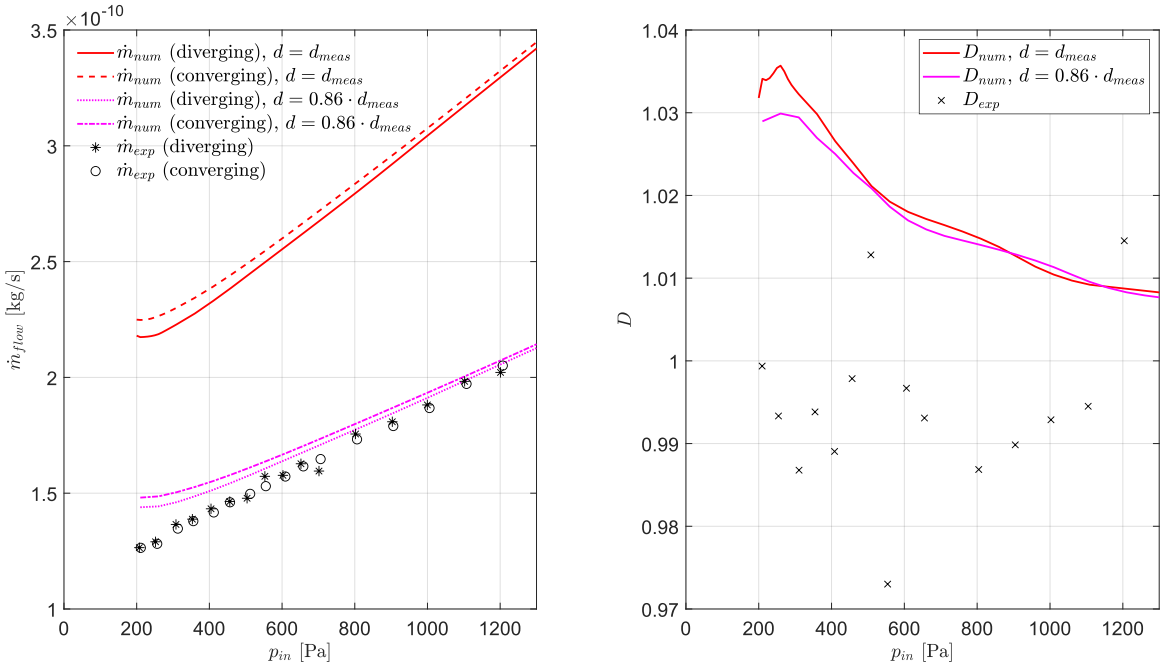

Figure 4: Left: data of mass flow rate vs inlet pressure for converging and diverging directions; Right: diodicity versus inlet pressure.

For the numerical results it can be noted that the mass flowrate in the converging direction is always slightly higher than in the diverging direction. This is more clearly noticeable by plotting the diodicity, which is defined as

$$D = \frac{\dot{m}_{con}}{\dot{m}_{div}} \tag{6}$$

It is shown that the diode effect increases in a small range of the transitional flow regime, for pressures ranging from 200 Pa ($\delta = 0.28$) to 260 Pa ($\delta = 5.03$), and it is confirmed that it decreases from transitional to slip-flow regime, that is for pressures ranging from 260 Pa ($\delta = 5.03$) to 1110 Pa ($\delta = 31.7$). This diode effect, however, is not really significant, with a diodicity always lower than 1.035. The experimental results show that there is no clear difference between the measured mass flow rates in the converging and diverging directions. The measured diodicity fluctuations are within the experimental uncertainties of the measured mass flowrates (~ +/- 5%) (Fig. 4 right). It should be noted that the lack of diodicity can also be linked to inlet and outlet fabrication defects which might be present in the device,

and these deviations are not taken into account by the numerical simulations. Additional investigations are needed in order to correctly characterize the inner geometry of the sample.

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