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PROPOSAL OF A NOVEL KNUDSEN PUMP DESIGN BENEFITTING FROM DRILLING AND 3D PRINTING TECHNIQUES IN LOW THERMAL CONDUCTIVITY MATERIALS

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Vacuum micropump, multistage, thermal transpiration, kinetic modeling, microfabrication.

ABSTRACT

Over the past two decades a large number of MEMS and micro-devices have been developed. These miniaturized systems, such as lab-on-chip sensors, gas chromatography analyzers, etc., require micro-pumps for air sampling through the testing stages of the device. Additionally, some microscale components such as radio frequency switches, microscopic vacuum tubes and other parts that depend on electron or ion optics, require certain vacuum environment for proper operation. Simply sealing the devices is not sufficient because leaks and outgassing are excessively detrimental in vacuum devices at microscale level. Accordingly, such components may need vacuum pumping to maintain proper functionality.

The thermal transpiration phenomenon has been extensively investigated; however, functional prototypes based on this phenomenon have been only recently developed. The Knudsen pump, which is one of the devices exploiting this well-known phenomenon, is able to generate a macroscopic gas flow by solely exploiting a tangential temperature gradient along a surface without requiring any external pressure gradient [1]. Specific geometrical and operational configurations have been investigated to optimize the efficiency of the pump in terms of generated mass flow rate and pressure difference, so analytical and numerical solutions for different configurations have been provided [2] and experimental measurements for thermal transpiration flow through channels have been reported [3]. Still, fabricating a Knudsen pump is not a trivial task mainly due to microfabrication difficulties and constraints linked to the control of local thermal gradients [4, 5].

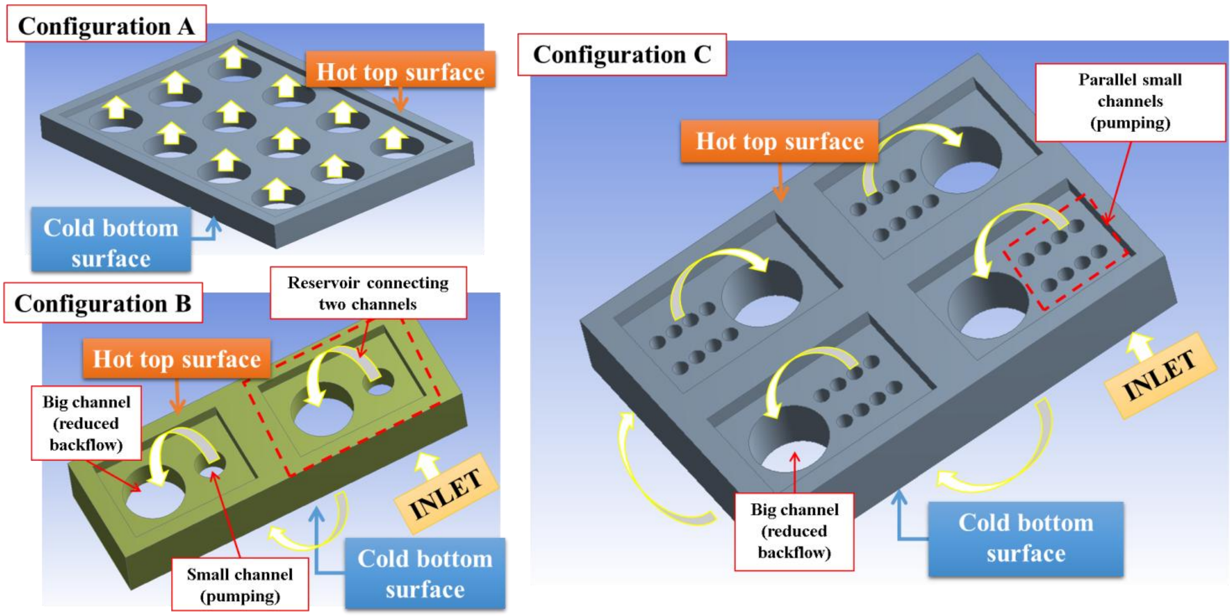

Figure 1: Representative view of the three different configurations; yellow arrows denote the pumping flow direction.

In this work, a novel Knudsen pump is proposed. Instead of following the typical process of etching along the substrate surface, the microchannels are fabricated by laser drilling or 3D printing techniques across the thickness of the wafer, as shown in Fig. 1. In this novel layout of the Knudsen pump, the microfabrication process is fundamentally simplified. Furthermore, the implementation of low thermal conductivity materials such as glass or polymers decreases the overall power consumption of the device and increases the thermal gradient that can be achieved along the wall of the channels. Additionally, by manufacturing the channels through the thickness of the device, the hot and cold regions of the Knudsen pump are spatially separated resulting to an easier temperature control. Using this design, three different configurations can be developed (Fig. 1):

A. Multiple parallel channels for high mass flow rate and low pressure difference.
B. Multistage assembly of single channels in series for high pressure difference and low mass flow rate.
C. Combination of the two previous configurations to find a compromise between achieved pressure difference and mass flow rate.

The two important performance metrics for these micropumps are the mass flow rate $\dot{m}$ and the pressure difference ΔP between the inlet and the outlet of the pump. Depending on the target application of the Knudsen pump, the required performance can vary considerably. The idea is that for a particular surface area, depending on the application of the Knudsen pump, channels can be arranged all in parallel to maximize $\dot{m}$ (configuration A), all in series to maximize ΔP (configuration B) or to compromise between the limiting conditions (configuration C).

The numerical study is based on the Shakhov kinetic model subject to diffuse boundary conditions. The deduced kinetic coefficients are introduced in a mass balance equation to yield the flow rate and the pressure difference [6]. The computational investigation involves the analysis of configurations A and B, so that their solutions are combined to characterize configuration C. Here, results for a representative configuration C are presented. Each pumping sub-stage is taken to be a square area of 200 μm x 200 μm with 100 circular channels of diameter $D = 10$ μm in parallel (easily achieved by various microfabrication processes). Each backflow sub-stage is also a square area of 200 μm x 200 μm with a single circular channel of diameter $D = 100$ μm. The length of the channels is $L = 300$ μm (following the typical thickness of glass wafers). The temperatures at the cold and hot sides of the channels are $T_C = 300$ K and $T_H = 400$ K respectively (following previous experimental experience [7]). The numerical simulations have been performed for various operating inlet pressures $P_{in} = 1$ kPa,

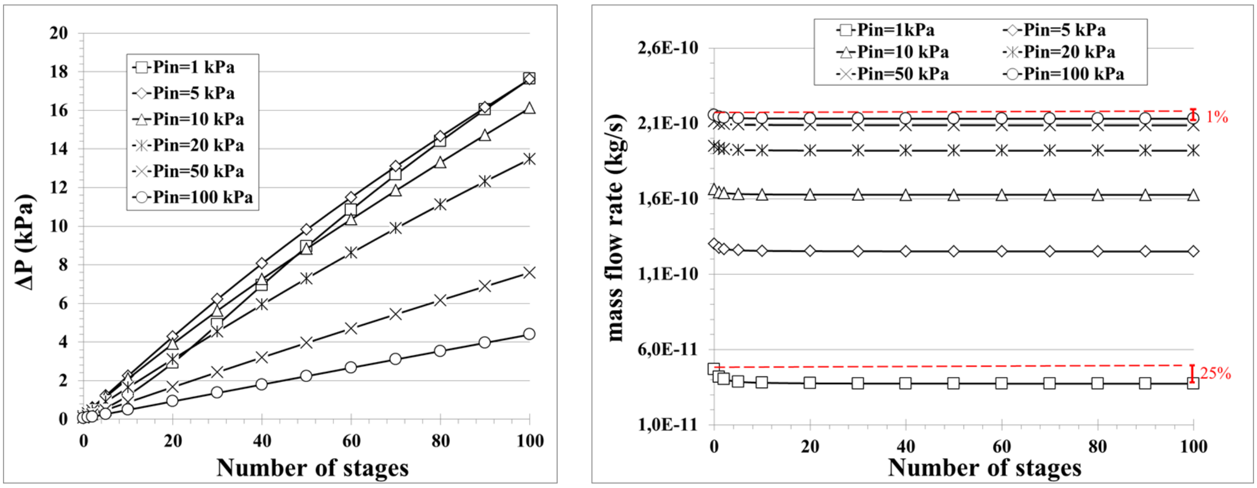

Figure 2: Pressure difference (left) and mass flow rate (right) of a configuration C multistage pump in terms of number of stages at various operating pressures.

5 kPa, 10 kPa, 20 kPa, 50 kPa and 100 kPa and considering argon as the working gas. The numerical results are based on the infinite capillary theory supplemented, when needed, by the end effect correction [6, 7]. In the backflow sub-stage the temperature driven flow is considered as negligible compared to the corresponding pressure driven flow. Based on this computational methodology the introduced error is expected to be less than 5%.

As it was expected from previous analysis in multistage systems with orthogonal channels [8], in most cases ΔP increases almost linearly with the number of stages (Fig 2-right). Only, in the case of the lowest operating pressure of 1 kPa, the pressure difference is not increased in an exactly linear manner in the first stages due to the non-linearity at higher rarefaction flow regimes (transitional regime). Depending on the size of the channel, the maximum ΔP is found at a gas rarefaction parameter δ = 4-8, which for the channel diameter D = 10 μm corresponds to an operating inlet pressure around 5 kPa. This finding has been also experimentally observed [9]. This remark also justifies the fact that ΔP increases as the inlet pressure P_{in} decreases until reaching the maximum performance at P_{in} = 5 kPa and then, for P_{in} = 1 kPa is slightly decreased. This is more evident for a small number of stages, where δ is small, while as the number of stages increases and δ is also increased the difference in ΔP is decreased and finally, by the 100th stage both cases of P_{in} =1 and 5 kPa provide about the same performance.

Regarding the mass flow rate $\dot{m}$ (Fig 2-left), it drops rather rapidly as the number of stages is increased from one up to ten stages and then, as the number of stages is further increased, it is reduced very slowly in an asymptotic manner. The reduction of the mass flow rate depends on the operating pressure, being bigger when the flow regime is more rarefied (at 1 kPa the reduction is 25%) in opposition to the very low reduction closer to the hydrodynamic regime (at 100 kPa the reduction is only 1%). This evolution of ΔP and the mass flow rate with the number of stages is interesting for designing a multistage pump since by increasing the number of stages to more than ten the pressure difference grows linearly, while the mass flow rate remains almost constant.

As a conclusion, a novel design for a Knudsen pump has been presented and computationally explored by taking into consideration tentative manufacturing and experimental constraints. The proposed design aims to achieve particular performances for targeted applications by tailoring the pumping stages (either increasing the parallel channels for enhancing the mass flow rate or increasing the number of stages to boost the pressure difference). It is noted that the presented results up to 100 stages only needs a footprint of 8 mm^2, which is more than four thousand times smaller than previous designs [4, 5]. Therefore, the compactness of the design is very good. Finally, a prototype is being manufactured and corresponding experimental work is expected to begin shortly.

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