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To cite this version:

Guillermo López Quesada, Giorgos Tatsios, Marcos Rojas-Cárdenas, Lucien Baldas, Christine Barrot, et al.. Pumping effect due to temperature gradients imposed in a multistage assembly consisting of long tapered orthogonal channels. 5th European Conference on Microfluidics (μFlu18) and 3rd European Conference on Non-Equilibrium Gas Flows (NEGF18), Feb 2018, Strasbourg, France. pp.447-450. hal-02062611

HAL Id: hal-02062611

https://hal.science/hal-02062611v1

Submitted on 9 Mar 2019

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µFLU-NEGF2018-120

PUMPING EFFECT DUE TO TEMPERATURE GRADIENTS IMPOSED IN A MULTISTAGE ASSEMBLY CONSISTING OF LONG TAPERED ORTHOGONAL CHANNELS

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KEY WORDS

Multistage Knudsen pump, thermal transpiration, rarefied gas flow, vacuum micropump, tapered channel, diode effect, kinetic modeling

SHORT SUMMARY

The temperature driven rarefied gas flow and the associated pressure difference in a multistage assembly consisting of a series of channels with linearly diverging or converging rectangular cross sections are computationally investigated. Each stage of the multistage assembly is consisting of one converging and one diverging channel. The net mass flow rate and the induced pressure difference between the inlet and outlet of the multistage assembly are parametrized in terms of the geometrical and operational data, paying specific attention to the diode effect and to the number of stages. The flow may be in the whole range of the Knudsen number and therefore modeling is based on kinetic theory, while the channels are taken efficiently long in order to justify the implemented infinite capillary methodology. Various flow setups are investigated to obtain the characteristic curves of the net mass flow rate versus the pressure difference in terms of channel geometry, input pressure, imposed temperature ratio and number of stages. The present work provides a powerful modeling tool in the manufacturing of a multistage Knudsen pump meeting certain pumping specifications.

EXTENDED ABSTRACT

Introduction

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 the microscale level. Accordingly, such components may need vacuum pumping to maintain proper functionality.

For years 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 applying a tangential temperature gradient along a surface without imposing an external pressure gradient. 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 [1]. Thus, analytical and numerical solutions for different configurations have been provided [2] and experimental measurements for thermal transpiration flow through channels have been reported [3]. However, when it comes to the particular point of fabricating a Knudsen pump, the progress in the field is limited mainly due to micro-fabrication difficulties and constraints linked to the control of local thermal gradients [4, 5].

In the current investigation, the effort is led towards integrating existent manufacturing and operational constraints into numerical simulations for designing a multistage Knudsen pump exploiting the diode effect. More specifically, the objective is to model a multistage cascade system consisting of a series of channels with linearly diverging or converging rectangular cross sections. Each stage of the multistage assembly consists of one converging and one diverging channel as shown in Fig.1. The methodology introduced in the case of flow between tapered plates [6], is extended to parameterize the present assembly, i.e., to compute the deduced net mass flow rate and the associated pressure difference for various channel geometries, input pressures, the imposed temperature ratios and numbers of stages.

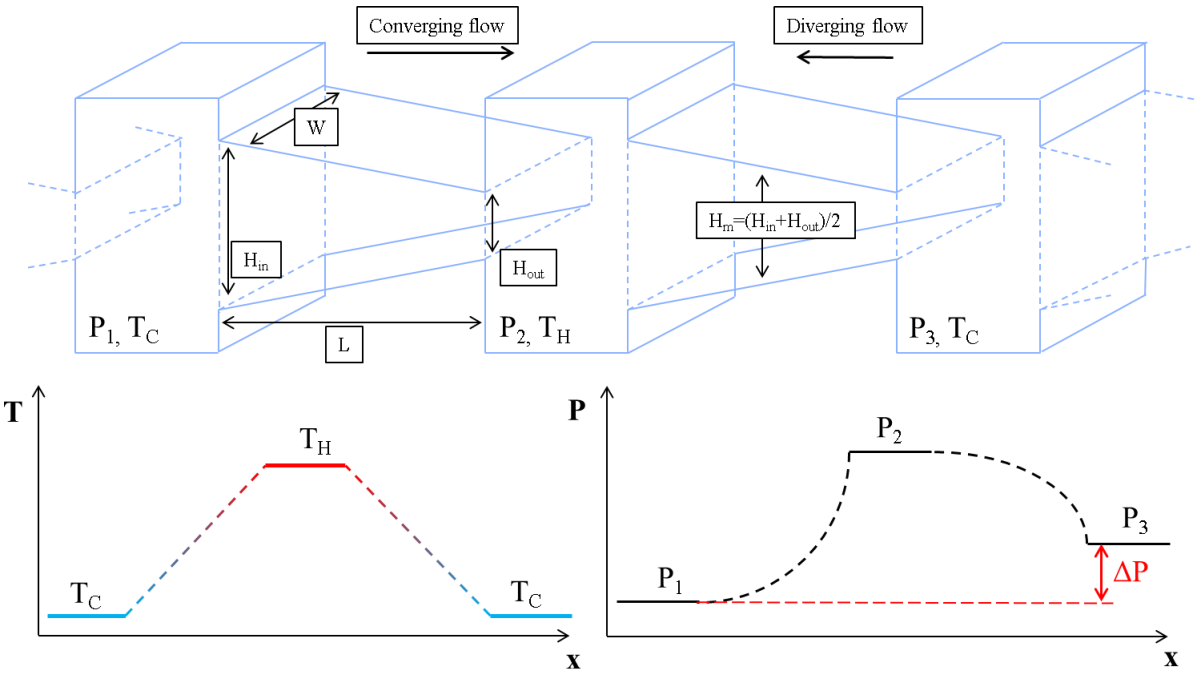

Figure 1: Outline of one pumping stage of a multistage Knudsen type cascade pump consisting of a series of tapered (convergent-divergent) rectangular channels; T_C and T_H denote the temperatures at the cold and hot reservoirs, respectively, and P_1, P_2, P_3 denote the pressures in successive reservoirs; H_{in}, H_{out} and H_m are the heights at the inlet, outlet and middle of the channel, respectively, while W and L are the width and length of the channel.

Numerical simulations

The analysis is based on the linearized 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 [7]. The computational investigation includes three cases: i) closed configuration with net mass flow rate equal to zero to achieve the maximum pressure difference (max ΔP) between the inlet and the outlet of the multistage assembly, ii) open configuration with overall pressure difference equal to zero to achieve maximum net mass flow rate and iii) the more general scenario of all intermediate flow cases achieving nonzero net mass flow rate and pressure difference. The latter scenario includes the development

of the characteristic curves (net mass flow rate versus pressure difference) of the multistage Knudsen assembly.

Following this approach, the influences of the inclination ratio ($\alpha=H_{in}/H_{out}$), aspect ratio (H_m/W), length over height (L/H_m) and temperature ratio (T_H/T_C) have been investigated. Additionally, the characteristic curves have been obtained for different configurations and the behavior of the multistage system has been analyzed for various operational conditions. The computational investigation has been performed taking into account existent manufacturing and operational constraints (geometry, size, materials, temperature control) provided by the Laboratoire d'Architecture et d'Analyse des Systèmes (LAAS, Toulouse, France) where the multistage device is planned to be manufactured.

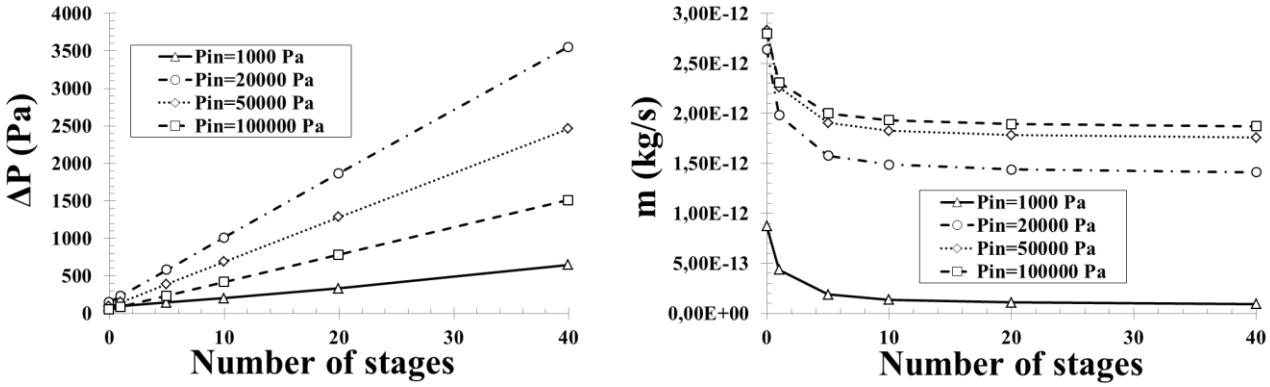

Figure 2: Maximum pressure difference (left) and maximum net mass flow rate (right) of a multistage convergent-divergent Knudsen pump in terms of number of stages at various operating pressures with H_m=10 µm, W=15 µm, L/H_m=20, T_{in}=300 K, T_{out}=400 K and α=7.

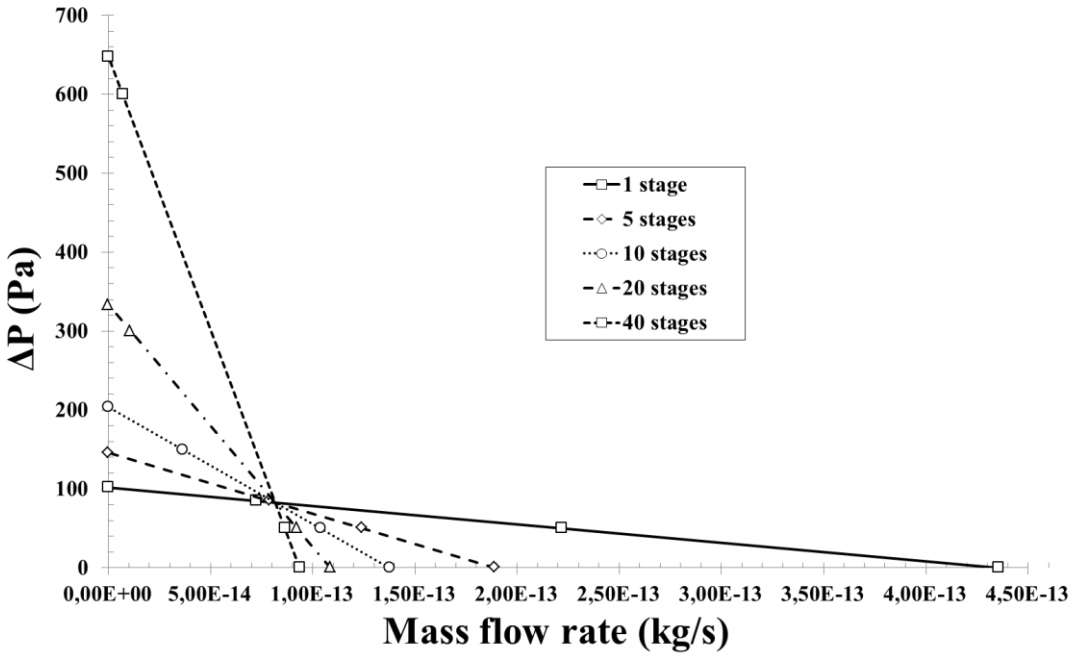

Figure 3: Characteristic curves (pressure difference vs. mass flow rate) of a multistage convergent-divergent Knudsen pump for different numbers of stages at 1000 Pa; H_m=10 µm, W=15 µm, L/H_m=20, T_{in}=300 K, T_{out}=400 K, α=7.

Typical results of the maximum pressure difference (ΔP) and net mass flow rate in terms of the number of stages at different operating pressures are presented in Fig.2. The temperature difference between the inlet and the outlet is set to T_H-T_C=100 K, which can be easily achieved experimentally [8], while the channel dimensions (H_m, α, W and L) have been provided by the LAAS. As expected, the maximum ΔP increases linearly with the number of stages of the device. It is noted however, that the maximum ΔP does not grow

monotonically with the increase of the operating pressure. It can be seen that in this set-up the maximum ΔP is obtained at an operating pressure of 20 kPa. This behavior has been also observed in [8] and it is connected to the specific rarefaction level where the maximum performance is achieved. Regarding the maximum mass flow rate, it grows monotonically with the operating pressure. Also, the maximum mass flow rate is reduced as the number of stages is increased. It is seen however that it drops rather rapidly as the number of stages is increased from one up to ten and then, as the number of stages is further increased, it is reduced very slowly in an asymptotic manner. This is a useful observation 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.

The characteristic curves for a specific operating pressure, shown in Fig.3, have been obtained by simulating the two limiting cases (closed configuration with maximum ΔP and open configuration with maximum net mass flow rate) and various flow configurations in between. These characteristic curves have been found out to be linear which implies that for mapping the performance of the Knudsen pump, the calculation of the two limiting cases are only required, reducing significantly the overall computational effort. Particular attention should be paid to the relation between H_m and W. It is noted that the diode effect of the convergent-divergent design is effective only when $H_m \leq W$ because the characteristic length controlling the intensity of the thermal transpiration phenomenon is the smallest dimension of the channel cross section. On the contrary, if $H_m > W$, the difference between the flows due to the varying height H in converging and diverging dimension becomes negligible.

Conclusion

In conclusion, an extensive computational study of a multistage Knudsen pump consisting of long rectangular tapered channels has been considered. The main output from this work is the characteristic curves that can be used in the design process of the Knudsen pump for determining the geometry and the number of stages needed to match particular pumping requirements. It is hoped that in the short future an early prototype, supported by the present design guidelines, will be fabricated in collaboration with LAAS and experimentally validated.

Acknowledgements

This project has received funding from the European Union's Framework Programme for Research and Innovation Horizon 2020 (2014-2020) under the Marie Skłodowska-Curie Grant Agreement No. 643095.

References

[1] Colin, S. (2013). Single-phase gas flow in microchannels. *Heat transfer and fluid flow in minichannels and microchannels*. Elsevier. 11-102.
[2] Chen, J. (2016). Etude numérique et expérimentale des écoulements de gaz raréfiés générés par des gradients thermiques: application à la conception de pompes Knudsen. *PhD Thesis*. Toulouse.
[3] Yamaguchi, H., Rojas-Cárdenas, M., Perrier, P., Graur, I., & Niimi, T. (2014). Thermal transpiration flow through a single rectangular channel. *Journal of Fluid Mechanics*, **744**, 169-182.
[4] Gupta, N. K., & Gianchandani, Y. B. (2011). Porous ceramics for multistage Knudsen micropumps-modelling approach and experimental evaluation. *Journal of Micromechanics and Microengineering*, **21**(9): 095029.
[5] Gupta, N.K., An, S., & Gianchandani, Y. B. (2012). A Si-micromachines 48-stage Knudsen pump for on-chip vacuum. *Journal of Micromechanics and Microengineering*, **22**(10): 105026.
[6] Tatsios, G., Lopez Quesada, G., Rojas-Cárdenas, M., Baldas, L., Colin, S., & Valougeorgis, D. (2017). Computational investigation and parametrization of the pumping effect in temperature driven flows through long tapered channels. *Microfluidics and Nanofluidics*, **21**(5)99.
[7] Sharipov, F., & Seleznev, V. (1998). Data on internal rarefied gas flows. *J Phys. Chem*, **27**, 657-706.
[8] Rojas-Cárdenas, M. (2012). Temperature gradient induced rarefied gas flows. *PhD Thesis*. Aix-Marseille Université.