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REVIEWING THE EARLY STAGES OF A KNUDSEN PUMP DESIGN: MODELING AND MANUFACTURING

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KEY WORDS

Knudsen pump, thermal transpiration, tapered channels, vacuum micropump, kinetic modeling, micro-fabrication.

ABSTRACT

For years, the thermal transpiration phenomenon has been widely studied but regarding its real application to pumping, functional prototypes have been developed only in the recent years. The Knudsen pump exploits the well-known thermal transpiration phenomenon, and is able to generate a macroscopic flow of gas by solely applying a tangential temperature gradient along a wall without any initial pressure gradient. Since the Knudsen pump allows gas movement only when the gas is under rarefied conditions, specific geometrical configurations need to be investigated to optimize the functionality of the pump in terms of its detailed geometry taking into consideration the operating pressure level in the system [1]. Thus, analytical and numerical solutions have been provided for different cases [2] and experimental works for measuring the thermal transpiration in simple configurations have been achieved [3]. However, when it comes to the particular point of fabricating a real working Knudsen pump, the progress in the field has been limited mainly due to micro-fabrication difficulties and constraints linked with the control of local thermal gradients.

In the current investigation, the effort is led towards integrating real manufacturing constraints into numerical simulations for designing and fabricating a Knudsen pump with tapered channels that works thanks to the diode effect. The diode effect in a tapered channel is due to the fact that, under the same operating conditions, the convergent channel is able to generate a bigger difference of pressure than the divergent channel. Then, when connecting successive tapered channels as shown in Figure 1, there will be two opposite thermal transpiration flows due to the temperature gradient on the walls of both channels, but the thermal transpiration in the convergent channel will be stronger than the one in the divergent channel. So, as a result, there will be a pumping effect in the direction of the convergent channel.

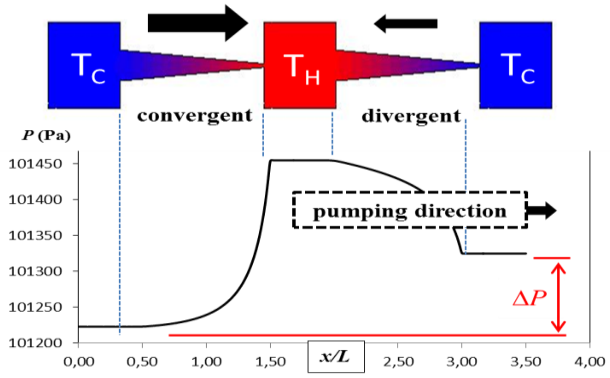

Figure 1: Flow direction due to the diode effect on tapered channels

The numerical work is performed using a Computational Fluid Dynamics (CFD) code and a kinetic code applying the Discrete Velocity Method (DVM) while the manufacturing constraints for this design –geometry, sizes, materials, temperature control- are explored by discussions with researchers from LAAS (Laboratoire d'Architecture et d'Analyse des Systèmes, Toulouse, France). From this collaboration, the fabrication of an early prototype, supported by these numerical simulations for optimizing the design, should be achieved at LAAS.

Depending on the operational conditions, the Knudsen pump working range could vary from the slip regime to the transitional or even the free molecular regimes, and the CFD approach alone, which is designed for solving flows in the continuum and slip regime, is not enough for providing results in this wide range. On the other hand, the DVM code can solve the flow in the whole working range, but the computational effort needed dramatically increases when approaching the continuum regime. Hence, the two methods complement each other and the solutions provided for the slip regime overlap and can be compared providing a way of double-checking the simulations performed. As it can be observed in Table 1, as the simulations approach less rarefied conditions (rarefaction parameter δ increases) the solution of the two methods are drawn closer. Moreover, the simulation work is not only focused on solving the flow problem, but also in designing the whole device. Consequently, heat transfer simulations are made with the CFD code for designing the temperature control system able to achieve the best temperature gradient along the walls of the channel and thus to assure a measurable thermal transpiration flow. This temperature gradient will be used then for solving the flow with a temperature distribution representative of the actual temperature distribution in the real device.

In conclusion, the on-going work tries to perform numerical simulations taking into account existent manufacturing constraints for designing and producing a working Knudsen pump. Within the framework of the MIGRATE project, further research on this Knudsen pump design with tapered channels as well as with alternative designs will be developed in order to manufacture appropriate and optimized working Knudsen pumps to be tested during the project.

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	δ	H_{max}/H_{min}	m_{CFD} [kg/m/s]	m_{DVM} [kg/m/s]	deviation m_{CFD} - m_{DVM}
convergent	5	2	1,38E-06	1,06E-06	-23%
divergent			1,69E-06	1,23E-06	-27%
convergent		4	9,09E-07	7,30E-07	-20%
divergent			1,30E-06	9,48E-07	-27%
convergent	8	2	1,45E-06	1,24E-06	-14%
divergent			1,75E-06	1,46E-06	-17%
convergent		4	9,62E-07	8,46E-07	-12%
divergent			1,36E-06	1,13E-06	-17%
convergent	10	2	1,47E-06	1,32E-06	-10%
divergent			1,78E-06	1,56E-06	-12%
convergent		4	9,81E-07	8,99E-07	-8%
divergent			1,38E-06	1,21E-06	-12%
convergent	15	2	1,50E-06	1,47E-06	-2%
divergent			1,81E-06	1,71E-06	-6%
convergent		4	1,01E-06	9,86E-07	-2%
divergent			1,41E-06	1,35E-06	-4%
convergent	20	2	1,51E-06	1,55E-06	3%
divergent			1,83E-06	1,94E-06	6%
convergent		4	1,02E-06	1,04E-06	2%
divergent			1,42E-06	1,46E-06	3%

Table 1: Preliminary comparison of numerical simulations for thermal transpiration flows of argon on tapered channels with linear temperature gradient along the walls in convergent and divergent directions for various rarefaction parameter values (δ).
Length=100μm; Height at the middle of the channel=10μm; Temperature ratio (T_H/T_C)=2