Microfluidic Knudsen Pump Prototype for Hydrogen

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Context

The widespread use of hydrogen as both an industrial process gas and an energy storage medium requires fast and selective detection of hydrogen gas. New sensors are developed in order to meet the increasingly stringent performance requirements in several different emerging applications [1]. For example, hydrogen gas sensors are applied for facilitating the safe use of hydrogen in fuel cells and hydrogen fueled vehicles, etc… Compared with conventional sensing devices, MEMS hydrogen sensors have the advantages of low power consumption, high sensitivity and fast test speed [2].

Hydrogen Micro Knudsen Pumps (H2-µKP) can deliver, in an efficient and controlled manner, hydrogen gas microflows towards a sensing device, a micro hydrogen combustor or a micro fuel cell [3]. µKP are non-mechanical micro-compressors with no moving parts which are thus very robust and stable in time. The main physical principle of action is known as thermal transpiration which requires only a temperature gradient to displace the gas from a cold to a hot region, thus creating a pumping effect [4, 5] (Fig. 1).

Recent progress has been made on KP transporting other gas species. Good examples are the devices created at the University of Michigan which were integrated into gas chromatography microsystems. The fabrication of these devices is generally realized by means of UV-lithography on silicon substrates [6] or by assembling stacks of porous media [7] in order to create the necessary thermodynamic conditions for thermal transpiration to be effective for the right device dimensions. No such devices have been fabricated in Europe or Asia yet.

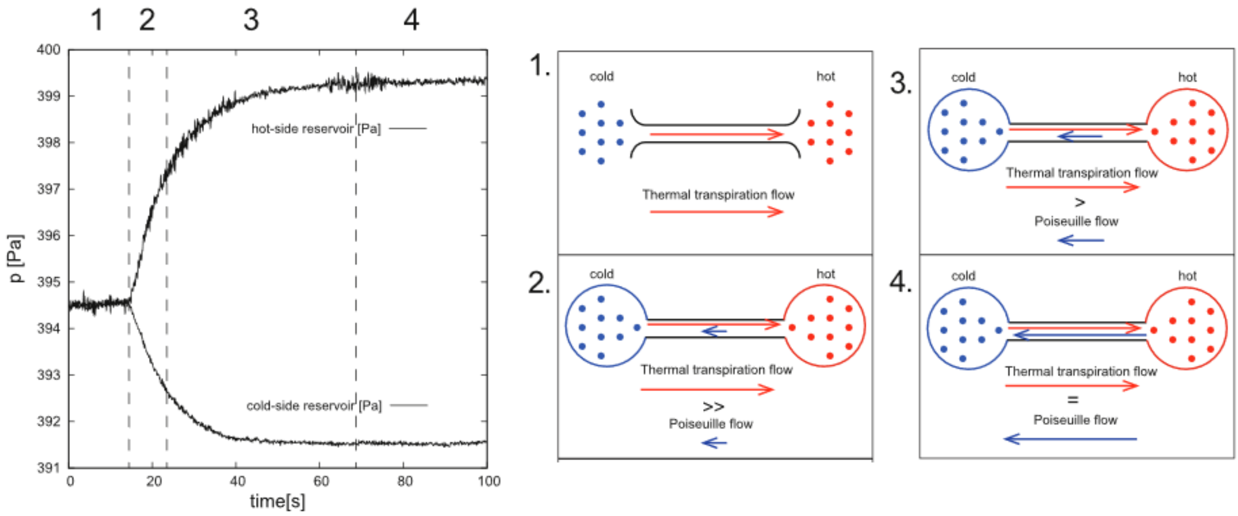

Figure 1. Working principle of thermal transpiration and its pumping effect in a micro device. At stage 1, a large connection is open between the cold and hot reservoirs. At stage 2 this connection is closed thus activating a transient phenomenon [4].

An innovative and optimized µKP has been designed by ICA through computational fluid dynamics (CFD) simulations [8]. A preliminary design has been chosen as a good candidate for fabrication, which consists of a multistage system that can uniformly heat and cool each stage of the pumping device in a uniform manner [8]. Each stage is formed by an array of n parallel narrow pumping microchannels, followed by one wide channel where the reduced counter thermal transpiration flow will appear. This design aims to provide high performances both in terms of generated difference of pressure and pumped mass flow rates, due to the multi-stage cascade system and to the multiple narrow microchannels per stage, respectively. The thermodynamic efficiency of the applied KP has to be high, thus, the temperature gradient control inside the *KP* has to be very accurate. Therefore, a novel H2-µKP design based on a combination of isothermal surfaces and materials with low thermal conductivity is needed [6].

In order to produce such a µKP, new materials and the latest state-of-the-art micro- and nano manufacturing technologies have to be used. As previously mentioned, most high-precision microfabrication processes have been initially based on lithography techniques as the semiconductor industry has been leading the market. However, silicon displays a high thermal conductivity that increases the heat transfer through the solid between the hot and cold reservoirs and results in a high-power consumption, while increasing the difficulty of adequately controlling the temperature gradient along the microchannels. On the contrary, by using bulk materials with lower thermal conductivity, such as glass or polymers, the thermal management of the device is simplified and the performance can be improved by maintaining higher temperature gradients in simpler structures. Based on all the above information, a polymer-based fabrication technique, such as 3D laser writing, is without doubt a better candidate for manufacturing a first KP prototype.

The main objective of this project is to design, fabricate and test a first prototype of H2-µKP at the Institut Clement Ader (ICA) in Toulouse in collaboration with the Institute of Microstructure Technology (IMT) of the Karlsruhe Institute of Technology. ICA has strong expertise in microfluidics for gas flow applications and more specifically in the field of thermal driven flows [4, 8, 9, 10], while IMT has strong expertise in microfabrication processes, such as 3D laser printing [11, 12].

At the moment the consortium has made major progress in the process of fabricating a first µKP prototype by proving that the 3D writing technique is effectively suitable to contain gas under rarefied conditions, and by prototyping a single stage of the pump with adequate channel dimensions (Fig. 2).

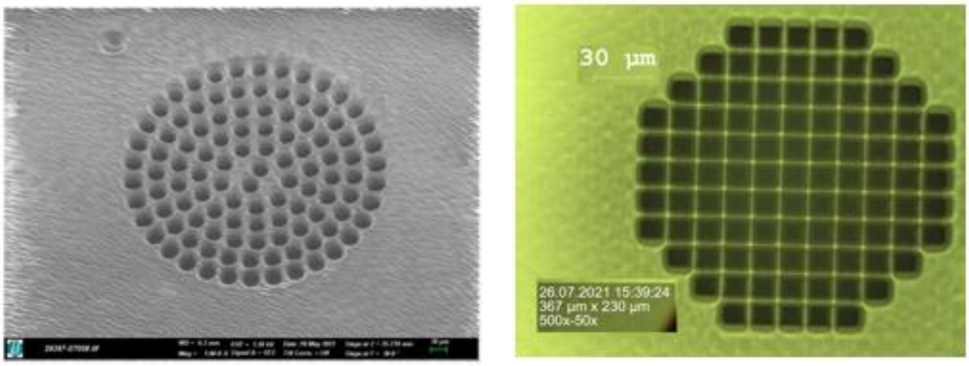

Figure 2. First fabricated samples of a single KP stage. Left: 109 tubes in parallel structure of 7 μm diameter. Right: 97 square channels in parallel of 10 μm height.

Expected results

The PhD project that is proposed in collaboration between ICA-INSA and IMT-KIT will be devoted to extend the 3D laser writing fabrication process to multistage pumps, to guarantee the correct temperature regulation of the pump and to optimize the design and characterize the heat power supply needed in order to achieve the desired pumping characteristics in terms of difference of pressure or mass flow rate delivery, when used to transport hydrogen.

Methodology

The planed steps for this project will consist in:

1- Experimental tests on single stage pump prototypes in isothermal conditions
2- Development of an experimental apparatus that allows macroscopically heating and cooling the single stage prototype
3- Experimental tests on single stage prototypes in non-isothermal conditions (Knudsen pump)
4- Development of a gas test rig for hydrogen flows. Experimental tests with hydrogen.
5- Numerical modelling and design optimization of multistage Kn pump working with hydrogen
6- Development and fabrication of the new multi-stage Knudsen pump prototype
7- Experimental tests on the multi-stage prototype in isothermal and non-isothermal conditions
8- Design and implementation of a fully integrated "on chip" heating system for the final μ-KP
9- Experimental tests on the final prototype

International collaboration

The PhD student will be the bridge between the two institutions. He/she will have to manage a project between France and Germany, spending roughly half of the PhD duration in each institution. The numerical modelling and experimental tests will be mainly done at ICA facilities while the fabrication process will be developed at IMT.

Candidate Requirements

- Master-level degree in Mechanical Engineering or Physics.
- Communication skills and good written/verbal knowledge of the English language
- A good background in fluid mechanics and/or heat transfer and/or microfabrication.
- Experience in experimental techniques is a plus.
- Willingness to work in a multi-cultural environment
- Aptitude for international mobility

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