A PLANAR CASCADING ARCHITECTURE FOR A CERAMIC KNUDSEN MICROPUMP

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ABSTRACT

This paper describes a 9-stage Knudsen pump with planar architecture that uses nanoporous ceramic for thermal transpiration. While operating at 55 K above room temperature, the pump provides a maximum pressure head exceeding 12 kPa at a sealed outlet, or a gas flow rate of ≈3.8 μL/min. against a pressure head of 160 Pa. Experiments also demonstrate the capability of the pump to steer water droplets at speeds exceeding 1200 μm/s through a 250 μm fluorinated ethylene propylene capillary. The packaged volume for the 9-stage pump discussed here is 25x25x7.25 mm^3. These characteristics indicate that the pump is potentially useful in microfluidic systems intended for both gas and liquid phase chemical sensing.

KEYWORDS

Knudsen pump, thermal transpiration, nanoporous ceramic, gas flow, liquid flow.

INTRODUCTION

Gas micropumps are needed for a wide range of portable microsystems ranging from gas-analyzers to cooling systems. The past couple of decades have witnessed the development of some of the most promising micropumping techniques known to date [1, 2]. However, micropumps that are suitable for applications such as the operation of pneumatic microvalves, micro gas-chromatographs, etc., are still required. Designs based on peristaltic arrays of electrostatically driven diaphragms are promising [3, 4]. While extremely energy-efficient, they continue to evolve with respect to drive voltage requirements, cost, reliability, structural complexity etc. Piezoelectric and thermopneumatic pumps have also been reported [5, 6]. A complementary gas pumping mechanism, thermal transpiration driven Knudsen pump, can be potentially useful in addressing some of these challenges faced by conventional approaches. Knudsen pumps are also useful for applications requiring non-pulsatile flows. They have no moving parts; hence they are potentially more reliable and structurally simple.

Knudsen pumps are based on the phenomenon of thermal transpiration. Reynolds and Maxwell separately analyzed the phenomenon and presented their work contemporarily in the year 1879 [7, 8]. In 1910, Knudsen demonstrated the possibility of using thermal transpiration for the purpose of gas pumping [9]. Due to the unavailability of sufficiently small capillaries the Knudsen pump operation was traditionally limited to sub-atmospheric pressures. However, recent developments in microfabrication techniques have made sub-micrometer scale channels possible, which are essential for Knudsen pump operation at atmospheric pressure. Atmospheric pressure operation of Knudsen pumps was first demonstrated by Vargo *et al.* [10]. They used (bulk) aerogel, a specialty material, for their mesoscale Knudsen compressor. This device could generate a best case pressure difference of 11.5 Torr (1.5 kPa) using helium. This was followed by the first fully micromachined Knudsen pump by McNamara *et al.* [11]. They used a set of lithographically patterned nanochannels for thermal transpiration at atmospheric pressure. This pump could evacuate a microcavity to a vacuum pressure of 46.6 kPa.

In this paper we present a multistage Knudsen pump, in continuation of our previously reported effort on a zeolite based single stage Knudsen pump [12, 13]. The earlier pump continues to show promise, but it could generate only a limited pressure head of 1 kPa. This is partly because it used only one stage, and partly because of leakage paths in the naturally occurring zeolite that was used for thermal transpiration. Here, we report a 9-stage Knudsen pumping architecture that uses a superior material for transpiration and can provide a pumping pressure head in excess of 12 kPa, which is better aligned with the needs of various microfluidic systems [14, 15]. The phenomenon of thermal transpiration, device design and fabrication, and experimental results are discussed in the following sections.

THERMAL TRANSPIRATION

The phenomenon of thermal transpiration is characterized by the ability of a narrow channel to sustain an equilibrium pressure gradient when subjected to a longitudinal temperature gradient [16, 17]. A narrow channel, in this context, is defined as one in which the gas flow is in the free molecular or transitional regimes. The transitional and the free molecular gas flow regimes correspond to 0.1<Kn<10, and Kn>10 respectively, where Kn, the Knudsen number, is the ratio of the mean free path of gas molecules to the hydraulic diameter of the channel

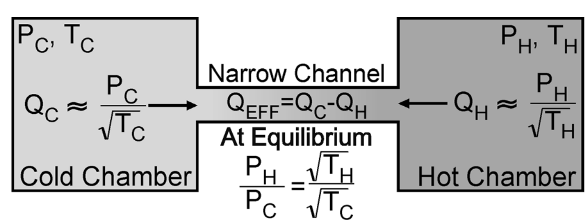

Fig. 1: Schematic layout of a Knudsen pump. At equilibrium, the ratio of pressures in the two chambers is equal to the square root of the ratio of temperatures in the respective chambers.

[18]: Kn = λ/d.

Figure 1 illustrates the concept of the Knudsen pump. Suppose there are two chambers at unequal temperatures (T_H, T_C) that are connected by a narrow channel, there is an effective movement of gas molecules from the cold chamber to the hot chamber. At equilibrium, the ratio of the pressure in the hot chamber (P_H) to the pressure in the cold chamber (P_C) is given by the ratio of square roots of their absolute temperatures.

Sharipov's model [19] is one of the most representative models for thermal transpiration through nanochannels [20]. Based on a set of temperature and pressure flow coefficients that are numerically evaluated for a wide range of Knudsen numbers, it is applicable to practically all flow regimes. Sharipov's model suggests that for a nanochannel with hydraulic radius a and length l, the average gas flow rate through the nanochannel is:

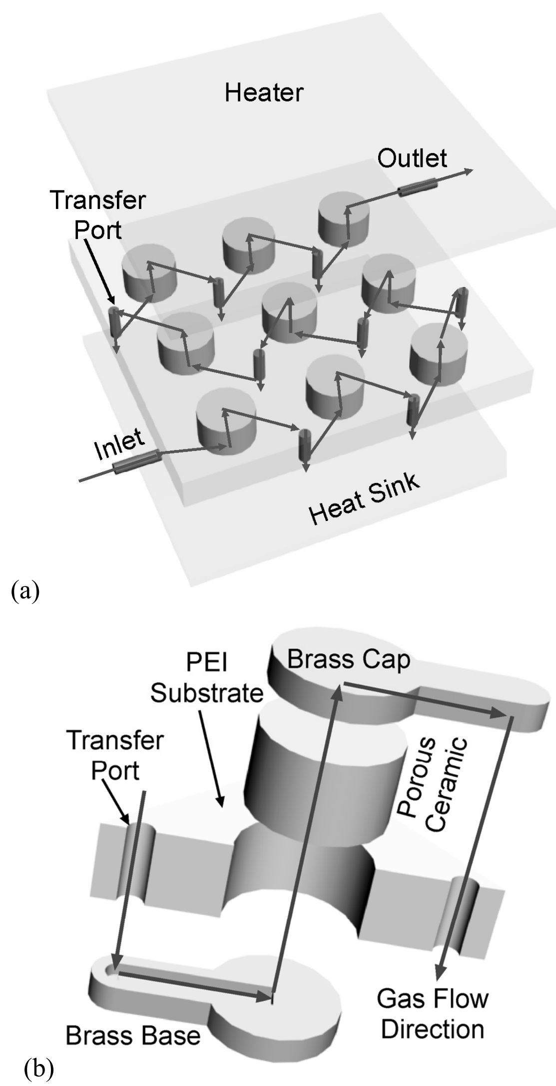

Fig. 2: A schematic layout of the ceramic based 9-stage Knudsen pump. (a) The arrows mark the direction of gas from one stage to next. (b) Exploded view of one of the stages. Arrows show the direction of flow through different elements.

$$\dot{M}_{avg} = \left[Q_T \frac{T_H - T_C}{T_{avg}} - Q_P \frac{P_H - P_C}{P_{avg}} \right] \frac{\pi a^3 P_{avg}}{l} \left[\frac{m}{2k_B T_{avg}} \right]^{1/2} \quad (1)$$

where T_{avg} and P_{avg} are the average temperature and pressure in the nanochannel; m is the mass of a gas molecule; k_B is the Boltzmann constant; Q_T and Q_P are the temperature and pressure gas flow coefficients, which depend on a rarefaction parameter:

$$\delta_{avg} = \left[\frac{\pi^3}{2} \right]^{1/2} \frac{aD^2 P_{avg}}{k_B T_{avg}} \quad (2)$$

where D is the collision diameter of the gas molecules flowing across the nanochannel. In general, if T and P are the temperature and pressure along the length of narrow channel and dT/dx and dP/dx are the respective gradients:

$$\frac{dP}{dx} = \frac{Q_T}{Q_P} \frac{P}{T} \frac{dT}{dx} \quad (3)$$

DEVICE DESIGN AND FABRICATION

The 9-stage Knudsen pump discussed in this paper has a 3x3 planar array of monolithically integrated single stage pumps connected in series. Figure 2a shows a schematic layout, with arrows along the gas flow. A thermally insulating material, in this case polyetherimide (PEI), is chosen for the substrate to minimize the parasitic heat loss. Nine cavities (dia. ≈5.2 mm) and 8 transfer ports (dia. ≈1 mm) are machined into it. A ceramic disc, 2.85 mm thick and 5 mm in diameter, is inserted into each cavity and bonded peripherally. The ceramic used in this study, is a 15 bar porous ceramic (Soil Moisture Equipment Corp., USA). Brass caps with embedded microgroove channels are used to seal each ceramic disc from above and below, and direct the gas flow laterally, into/out of each stage through the transfer ports (Fig. 2b). Thermally conducting caps minimize the possibility of parasitic heating of the transpiration elements. Figures 3 show the components and the final assembled device. The packaged volume is 25x25x7.25 mm^3.

A planar architecture is chosen for the pump because it allows a common heater at the top and a common heat sink at the bottom of the device, making the structure simple and thermally efficient. The heater is a thin, etched foil resistive element of 29.5 Ω, laminated between insulating layers of Kapton (Minco, MN).

EXPERIMENTAL RESULTS

Test Set-Up

The fabricated micropumps are tested in two modes: 1) *Pressure mode*: a pressure sensor attached to the sealed outlet of the Knudsen pump. This mode of testing is used to characterize the maximum pressure head that the device can generate. 2) *Flow mode*: a clear Tygon tube (0.79 mm ø) with water plugs is connected at the outlet. This mode is used to quantify the gas flow rate as a function of both pressure head and input power.

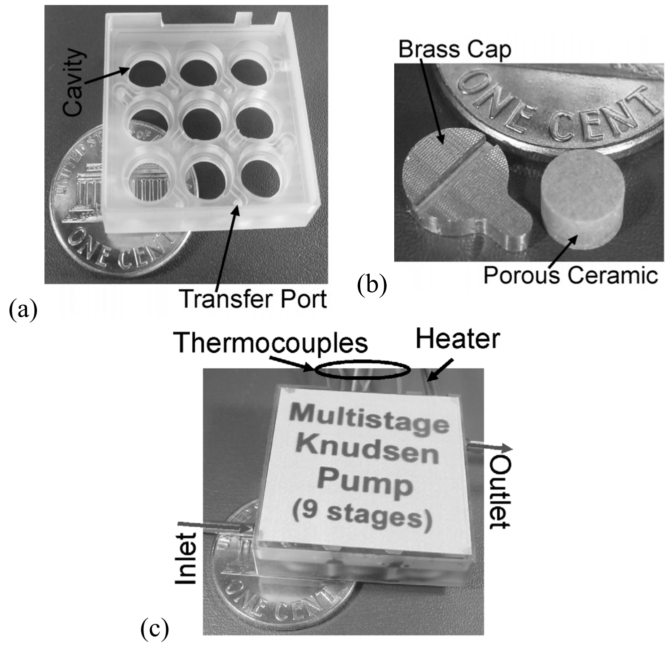

Fig. 3: Ceramic based 9-stage Knudsen pump: (a) patterned polyetherimide; (b) Brass cap and nanoporous ceramic; (c) Final assembled 9-stage Knudsen pump with an inlet/outlet, heater and thermocouples.

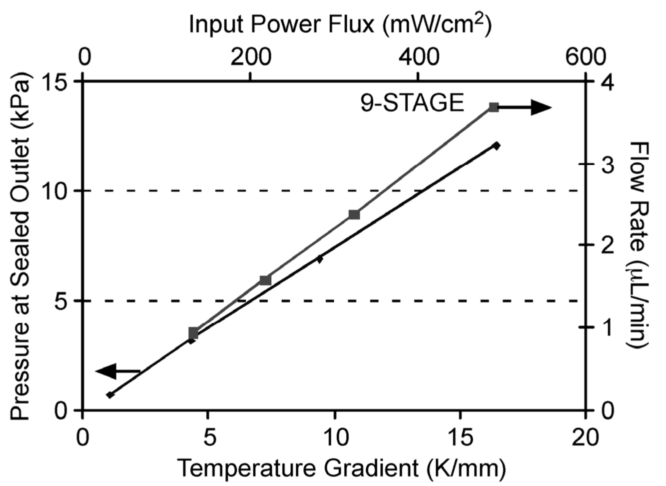

Fig. 4: The left Y-axis plots the maximum pressure achieved by the 9-stage Knudsen pump with outlet sealed and the right Y-axis plots (its) achievable flow rates. The flow rate and the pressure head generated depend linearly on the temperature gradient across the ceramic discs.

Measurement Results

Experiments indicate that the gas flow rate and the maximum pressure at the sealed outlet of the pump vary linearly with the steady state temperature gradient applied across its 9 stages. Figure 4 shows the pressure and flow rate plots as the temperature gradient across the transpiration elements rises from 0 to 16 K/mm. The device requires 200 mW of input power for each K/mm rise in temperature gradient. While operating in pressure mode, a steady state temperature gradient of 16 K/mm across the device results in a maximum pressure head in excess of 12 kPa. Under similar operating conditions, in the flow mode tests, the device generates a maximum gas

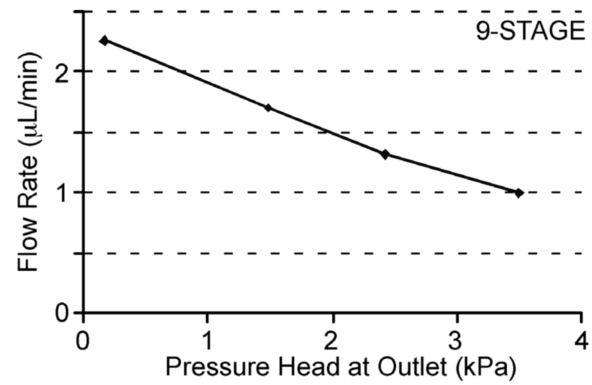

Fig. 5: Steady state gas flow rate for different pressure heads at 1.9 W input power, which results in a temperature gradient of ≈9.5 K/mm.

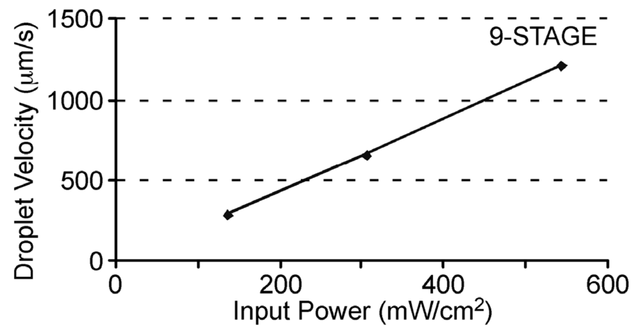

Fig. 6: Liquid manipulation capabilities of the 9-stage pump through a fluorinated ethylene propylene capillary with ID 250 µm.

flow rate of ≈3.68 µL/min at 160 Pa. Figure 5 shows the gas flow rate generated by the device against different pressure heads, while operating with a temperature gradient of about 9.5 K/mm and a power of 1.9 W. As expected, the flow rate reduces linearly with the increasing pressure head at the outlet. The reduction is ≈0.3 nL/min. per Pa increase in the pressure head.

Further tests demonstrate the capability of the pump to steer water droplets at speeds >1200 µm/s through a fluorinated ethylene propylene capillary with ID 250 µm (Fig. 6). These flow rates are measured for pressure head of ≈925 Pa.

CONCLUSION

A planar 9-stage Knudsen pumping architecture is described that is intended to provide both performance and simplicity. Nanoporous ceramic elements are used for thermal transpiration at atmospheric pressure. The pump achieves a maximum pressure difference of 12 kPa or a gas flow rate of ≈3.68 µL/min at 160 Pa. These performance metrics demonstrate the feasibility of using ceramic based Knudsen pumps for various microfluidic applications. In particular, the pump could drive a water droplet at velocity in excess of 1200 µm/s through a 250 µm ID capillary.

Having proven the feasibility of this architecture to achieve desirable flow rates at required pressure heads, lithography based techniques may be used to further optimize the thermal efficiency, size and performance metrics of the device.

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REFERENCES

[1] D.J. Laser, J.G. Santiago, "A Review of Micropumps," *Journal of Micomechanics and Microengineering*, vol. 14(6), 2004, pp. R35-R64.

[2] N.T. Nguyen , X. Huang, T.K. Chuan, "MEMS-Micropumps: A review," *ASME Journal of Fluid Engineering*, vol. 124(22), 2002, pp. 384-392.

[3] C. Cabuz, W.R. Herb, E.I. Cabuz, T.L. Son, " The Dual Diaphragm Pump," *IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, 2001, pp. 519-522.

[4] H. Kim, A.A. Astle, K.Najafi, L.P. Bernal, P.D. Washabaugh, "A Fully Integrated High-Efficiency Peristaltic 18-Stage Gas Micropump with Active Microvalves," *IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, 2007, pp. 127-30.

[5] C.G.J. Schabmuller, M. Koch, M.E. Mokhtari, A.G.R. Evans, A. Brunnschweiler, H. Sehr, "Self-Aligning Gas/Liquid Micropump," *Journal of Micromechanics and Microengineering*, vol. 12(4), 2002, pp. 420-424.

[6] W.K. Schomburg, J. Vollmer, B. Bustgens, J. Fahrenberg, H. Hein, W. Menz, "Microfluidic Components in LIGA technique," *Journal of Micromechanics and Microengineering*, vol. 4(4), 1994, pp. 186-191.

[7] O. Reynolds, "On Certain Dimensional Properties of Matter in the Gaseous State," *Philosophical Transactions of Royal Society London,* vol. 170, 1879, pp. 727-845.

[8] J.C. Maxwell, "On Stresses in Rarefied Gases Arising from Inequalities of Temperature," *Philosophical Transactions of Royal Society London,* vol. 170, 1879, pp. 231-256.

[9] M. Knudsen, "Eine Revision der Gleichgewichtsbedingung der Gase. Thermische Molekularstromung," *Annalen der Physik,* Leipzig, vol. 336(1), 1909, pp. 205-229.

[10] S.E. Vargo, E.P. Muntz, "Initial Results from the First MEMS Fabricated Thermal Transpiration-Driven Vacuum Pump," *AIP Conference Proceedings*, n 585, 2001, pp. 502-509.

[11] S. McNamara, Y.B. Gianchandani, "On-Chip Vacuum Generated by a Micromachined Knudsen Pump," *Journal of Microelectromechanical Systems*, vol. 14(4), 2005, pp. 741-746.

[12] N.K. Gupta, Y.B. Gianchandani, "A Knudsen Pump Using Nanoporous Zeolite for Atmospheric Pressure Operation," *IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, 2008, pp. 38-41.

[13] N.K. Gupta, Y.B. Gianchandani, "Thermal Transpiration in Zeolites: A Mechanism for Motionless Gas Pumps," *Applied Physics Letters*, vol. 93(19), 2008, p. 193511.

[14] M.A. Unger, H.-P. Chou, T. Thorsen, A. Scherer, S.R. Quake, "Monolithic Microfabricated Valves and Pumps for Multilayer Soft Lithography," *Science*, vol. 288, 2000, pp. 113-116.

[15] S.K. Sia, and G.M. Whitesides, "Microfluidic Devices Fabricated in Poly(dimethylsiloxane) for biological studies," *Electrophoresis*, vol. 24, 2003, 3563-76.

[16] L. Loeb, *The Kinetic Theory of Gases*, McGraw Hill, 1934, pp. 355-359.

[17] E. Kennard, *Kinetic Theory of Gases*, McGraw Hill, 1938, pp. 327-332.

[18] G.E. Karniadakis, A. Beskok, N. Aluru, *Microflows and Nanoflows: Fundamentals and Simulation*, Springer, New York, 2005, Chap. 1.

[19] F. Sharipov, "Rarefied Gas Flow Through a Long Tube at Arbitrary Pressure and Temperature Drop," *Journal of Vacuum Science and Technology A*, vol. 15(4), 1997, pp. 2434-2436.

[20] N.K. Gupta, Y.B. Gianchandani, "Gas Flow in Nano-Channels: Thermal Transpiration Models with Application to a Si-Micromachined Knudsen Pump," *Transducers*, 2007, pp. 2329-2332.

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