NANOPOROUS THERMEOLECTRIC KNUDSEN PUMP INTEGRATED WITH A MICROFLUIDIC CHANNEL

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Abstract: We report on the design, fabrication, and testing of a bi-directional Knudsen gas pump integrated into a microfluidic channel, utilizing a multifunctional nanoporous Bi₂Te₃ thermoelectric material. Heater, cooler and nanoporous channels, which are the main elements for the Knudsen pump operation, are combined in the multifunctional material. This combination makes the device simple and easy to integrate in microfluidic applications. Sub-micron sized Bi₂Te₃ powder was compacted at 6 MPa and sintered at 200°C for 2 hours under running argon to make the nanoporous sample. The pump generates a maximum pressure of about 520 Pa with an input power of 1.33 W. Characterization using an IR camera and the four-probe technique is also reported. The measured flow rate is 1 μL/min.

Keywords: Knudsen pump, thermoelectric, sintering, microfluidic, nanoporous.

INTRODUCTION

Pumps are an important component of most microfluidic and lab-on-a-chip devices [1]. However, most pumps have drawbacks such as large power consumption, wear and tear due to the moving parts [2], limitations on the types of fluids that may be pumped, and difficulty to integrate with MEMS devices due to the low performance at small scale. The Knudsen pump features no moving parts, making integration easier. It is a gas pump which can be used to pump almost any type of liquid through pneumatic actuation [3]. The present Knudsen pump is suitable for low flow rate applications, including microdialysis [4] and drug delivery devices [5]. Figure 1 shows a schematic example of a thermoelectric Knudsen pump in series with a microfluidic channel. The Knudsen pump consisting of the nanoporous thermoelectric (TE) material placed inside a macrochannel will provide pneumatic pressure to move the fluid in the microfluidic channel. More complicated geometries can be envisioned in which the pump pushes or pulls the fluids to different locations in the microfluidic device.

Fig. 1: Schematic showing an example of how the TE based Knudsen pump is combined with a microfluidic device. The generated pressure causes the fluid to move inside the microfluidic channel.

THEORY

The Knudsen pump relies on the principal of thermal transpiration for its operation [6, 7]. If two chambers filled with the same gas are connected by a narrow channel, and maintained at different temperatures (Fig. 2), a net gas flow from the cold chamber to the hot chamber will be generated. The induced flow can be explained by the amount of momentum transferred by gas molecules to the channel wall. The number of molecules striking the wall from the hot side is larger than those from the cold side. This large number of collisions induces a momentum force in the opposite direction to the temperature gradient.

Once equilibrium is reached in a closed system, the relationship between the parameters $T_C, T_H, P_C,$ and $P_H$ is:

$$\frac{P_H}{P_C} = \sqrt{\frac{T_H}{T_C}}$$

Equation (1) is obtained by equating the molecular flux between the two chambers. The pressure must be in the free molecular flow or transitional flow regimes for proper operation, ideally requiring pore diameter on the order of 100 nm or smaller for operation at atmospheric pressure. Figure 3 shows a schematic of the device. Once the power is turned on, one side of the thermoelectric material becomes hot, and the other side becomes cold. Gas starts to flow through the nanoporous thermoelectric material from the cold side to the hot side by thermal transpiration. Switching the voltage polarity reverses the pumping direction.
**EXPERIMENT**

A schematic of the fabrication process is shown in Fig. 4. The device fabrication starts by ball milling (1200 RPM) of p-type Bi₂Te₃ pellets under vacuum. The three dimensions movement of the jar, containing the balls and Bi₂Te₃ pellets, provide the balls with enough inertia to crush the sample material upon impact. The grinding of about 5 gram-sample was performed in 15-minute periods separated by 30 minute cool-down periods. After milling for 5 hours, the powder was then transferred into a 13×13 mm² square die and uniaxially pressed (6 MPa) for 1 hour. The compact sample was then placed in a tube furnace where it was sintered at 200°C for 2 hours and 100 sccm running argon.

A photograph of the sintered sample is shown in Fig. 5a. An SEM image (Fig. 5b) shows the sub-micron pores through which gas will flow from the cold side to the hot side. A test was performed on the sintered sample to make sure that the pores extend through the whole thickness. The sample was mounted with a pressure transducer and a syringe using a T-connector. Once a pressure is applied to the sealed set-up, a pressure drop due to gas leaking through the pores was seen.

Thermal infrared (IR) microscopy was used to test the sintered thermoelectric sample. After soldering the connection wires, the sample was placed flat on a heated stage (60°C), and power was applied (1.33 W). A temperature distribution over the surface of the sample was measured (Fig. 6), showing cooling (<60°C) on one side, and heating on the other side (>60°C). When the voltage polarity is reversed, the hot and cold regions are reversed.
The sample was placed inside a channel machined on a plastic substrate. The channel was drawn using SolidWorks CAD software. The dimensions are 3 cm long, 13 mm wide. The drawing was saved as .igs file and transferred, to the computer connected to the CNC milling machine with VisualMill 6.0 machining program. The machine was set to 3-axis milling and the milling speed was 14000 RPM. The machining was performed in two parts, horizontal rough machining and parallel finishing machining. An end mill (3.175 mm diameter, 38.1 mm long, and 2 flutes) made out of carbide was used. Epoxy glue was applied on the sides where the sample touches the channel. A plastic cover, with glued tube (0.01 " I.D), was used to close the channel. The plastic tube will be connected to the pressure sensor for pressure head measurement.

To measure the pressure difference that may be obtained with the pump, a digital pressure sensor with a dead volume of 0.8 cc is connected to one side of the pump, and the other side was open to the atmosphere. A similar pressure sensor was used to monitor the atmospheric pressure. A custom labView program was written to plot the room pressure, the Knudsen pump pressure, and their difference.

RESULTS
The effect of the sintering temperature on the resistivity was investigated. Resistivity was measured after each sintering temperature using a 4-probe machine (Fig. 7). The lowest resistivity was seen at 200°C and that explains the choice of this temperature as the sintering temperature. A lower resistivity (higher electrical conductivity) will improve the figure of merit $Z$ of the thermoelectric material. The higher the $Z$ value, the better the thermoelectric material [8].

IR microscope was also used to investigate the effect of the input power on the generated temperature gradient (Fig. 8). The objective behind this measurement was to check for the saturation power after which the temperature gradient will not increase. The curve follows a linear trend. As the power goes up, the majority carriers (holes), responsible for carrying the heat from the cold to the hot side, migrate toward the negative side causing it to heat up, and the other side (positive polarity) becomes cooler.

The final device (Fig. 9) has a footprint of $3 \times 2 \text{ cm}^2$. Its main components are the nanoporous thermoelectric material, channel, connection wires, and the tubing. Plastic material was used for the channel substrate and cover because it has a lower thermal conductivity which helps maintain the temperature gradient necessary for thermal transpiration.

Fig. 10 shows the pressure that is obtained from the Knudsen gas pump as a function of time. 1.33 W is the input power. Pressure is permitted to come to room pressure before switching the voltage polarity.
The vertical spikes occur when the pump is turned on or off, and the addition or removal of heat causes a temporary increase or decrease in pressure due to the gas expansion or contraction. A syringe pump, connected along with the Knudsen pump and the pressure sensor, was used to measure the flowrate. The Knudsen pump was turned on first. Once the pressure reached a steady state, the syringe pump was turned on. Flowrate values from the syringe pump were varied until the overall pressure went back to zero. The measured flow rate is 1 µL/min.

CONCLUSION

Pressureless sintering was used to fabricate a nanoporous TE sample which was placed inside a plastic macrochannel to make a bi-directional Knudsen pump. The powder was compacted at 6 MPa and sintered for 2 hours at 200°C under running argon. The measured flowrate and pressure are 1 µL/min and 520 Pa respectively with an input power of 1.33 W. The pump has a footprint of 3×2 cm² and can easily be integrated with microfluidic devices. Operation at negative pressure proves that the Knudsen pump does not work due to gas heating. A nearly linear relationship was found between the generated temperature gradient and the input power.

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