Design and Analysis of a New Energy Harvesting Device Based on Knudsen Effect

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ABSTRACT

First discovered by Danish physicist Martin Knudsen in 1910, the Knudsen effect describes a rarefied flow effect of thermal creep, this effect results in a micro-scale gas pump called Knudsen compressor. Recent studies have shown that with micro-scale channels the Knudsen compressor can operate efficiently under low inlet pressure near vacuum. In this study, the possibility of Knudsen compressor filled with nano scale aerogel working at atmosphere pressure is first studied by Direct Simulation Monte Carlo (DSMC) and numerical analysis. Based on The simulation results a new energy harvesting device is proposed. The numerical analysis indicates that for a typical summer day in subtropical region, an array of multi-stages Knudsen compressor in $1m^2$ area could capture energy of 74W.

Keywords: Energy Harvesting, Solar Energy, Knudsen Compressor, DSMC.

1 INTRODUCTION

Energy is one of the biggest concerns in the 21st century. As the price of fossil energy soars and the concerns of environment protection increases, various kinds of methods are invented to capture and convert renewable energy from nature resources such as solar, geothermal, wind, ocean, and etc. For example, solar-electricity convert systems based on photovoltaic have been researched for more than 20 years and widely used around the world. Current commercial photovoltaic panel offers about 10%~13% conversion efficiency, but the capital cost is still a major issue [1-2]. New energy harvest and conversion method, such as vibration-to-electric energy conversion system, device for harvesting energy from the salt gradients, and thermoelectric generator are also been researched [3-6]. But various problems exist, mainly the energy density and the conversion efficiency [7-8].

This motivates us to investigate a new energy harvest method. Our new method is based on the Knudsen effect which is first discovered by Danish physicist Martin Knudsen in 1910 [9]. The Knudsen effect describes a rarefied flow phenomenon of thermal creep: Given two chambers connected through a small channel, when the Knudsen number, defined as the ratio of the molecular mean free path to the characteristic size of the channel, is large, the temperature difference between the two chambers would generate a gas flow. This effect results in a micro-scale gas pump called Knudsen compressor. There could be a number of promising applications provided that its performance can be optimized to meet a variety of pumping requirements. Recent studies have shown that with micro-scale channels the Knudsen compressor can operate efficiently under low inlet pressure near vacuum [10-12]. There is however lack of a reference data for Knudsen compressor working near atmosphere pressure.

In this paper, we first study the micro flow in Knudsen compressor by Direct Simulation Monte Carlo (DSMC) method, and then analyze the performance of Knudsen compressor working near atmosphere pressure in Section 2. Based on the simulation results, we propose a new energy harvest device based on Knudsen compressor in section 3. Finally, conclusions and discussions are given in Section 4.

2 NUMERICAL ANALYSIS

2.1 Direct Simulation Monte Carlo (DSMC)

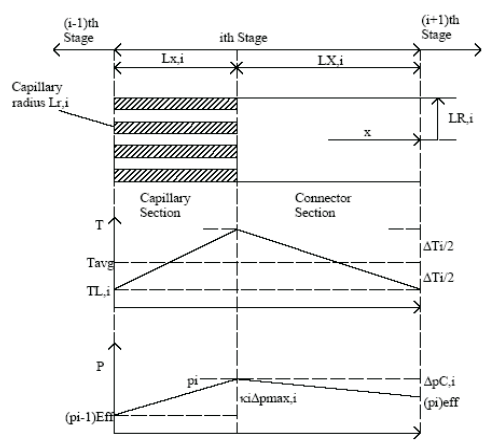

Fig. 1: Illustration of one stage Knudsen Compressor[10]

By utilizing a cascade of multiple stages, a Knudsen compressor can generate large changes in pressure. A single stage of Knudsen compressor is illustrated in Fig. 1. Each stage consists of an array of capillaries and a connector section. The temperature increase imposed along the

capillary pumps the gas from cold toward the hot direction, resulting in pressure increase in the capillary section. The gas is cooled in the connector section and thus the temperature drops to the value corresponding to the inlet of the capillary section.

The gas flow through a micro scale capillary is the driven force of the pump and it is dependent on the pressure. In order to find the optimal working condition, therefore, it is important to carry out a numerical simulation of the transpiration flow in the micro channels. It should be pointed out that as the Knudsen number, *Kn*, becomes large, the classical flow simulation method is no longer applicable. In other words, the flow can only be described from a molecular point of view. Thus, the Direct Simulation Monte Carlo (DSMC) [13] method is used. Our calculation is based on Bird's public 2D FORTRAN code. Variable soft sphere model is used for particle collision and Cercignani-Lampic-Lord model [14] is used for particle-wall reflection. Pressure boundary condition is added into the standard DSMC program.

The simulation model is a 2D channel with 5 μm length and 1 μm height as shown in Fig. 2. There is a temperature difference of 200 ^{o}K between the two ends, which is linear distributed on the channel wall.

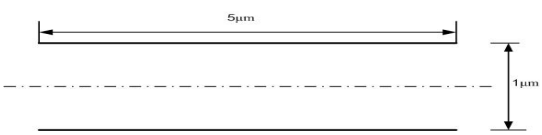

Fig. 2: Micro channel of capillary section

The total number of the computational cell is 1100. The average number of simulated molecules per cell is 20. Thus, the total number of simulated molecules in the domain is about 22000. This is a quite easy computational load. It takes only 15mins for one simulation.

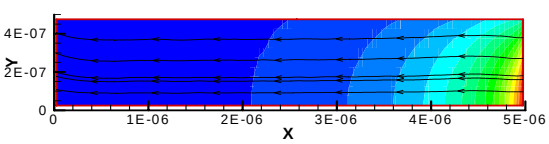

Fig. 3: Temperature distribution and flow field when Kn = 0.05

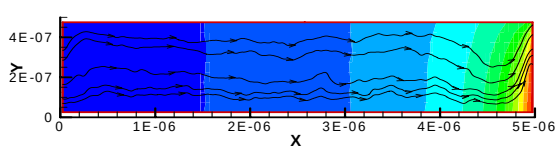

Fig. 4: Temperature distribution and flow field when Kn = 50

Fig. 3 shows the temperature distribution and the flow field of the channel at Kn = 0.05. Note that the gas flows from the high temperature end to the low temperature end. This is the pressure driven flow. Fig. 4 shows the temperature distribution and the flow field at Kn = 50. At this time it is seen that the gas flows from the low temperature end to the high temperature end. This is the thermal creep.

Compared these two figures, it is found that the Knudsen number is very important to the flow pattern in micro channel. When the Knudsen number is small, the pressure driven flow is stronger than the thermal driven flow. With the increase of the Knudsen number, the thermal creep becomes significant, and the thermal driven flow dominates. This implies there must be a critical Knudsen number at which the pressure driven flow and thermal driven flow balances.

Moreover, in Fig. 5, the gas flow against the Knudsen number is investigated by simulation. It is seen that the flow reaches a maximum at $Kn \approx 5$, which corresponds to P = 0.01 atm with the 1 μm channel. This is the optimal condition that balances the trade-off between flow velocity and gas density. This simulation result provides the foundation for us to design a practical Knudsen compressor.

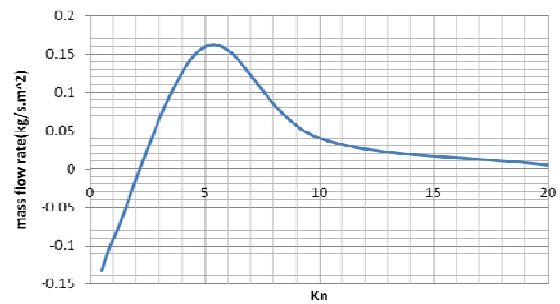

Fig. 5: Mass flow rate against different Knudsen number

2.2 Performance analysis

The existing analysis of a Knudsen compressor was based on the assumption of an ideal situation of free-molecule flow in the capillary section and continuum flow in the connector section [15]. While in practical vacuum working condition both the capillary and connector sections of the compressor will operate in the transitional flow regime. Muntz *et al.* have replaced the two simultaneous assumptions of free-molecule and continuum flow by permitting transitional flow to exist in a modeled compressor stage [12]. Analysis with the transitional model provides more accuracy result of the Knudsen compressor pump, but it is not the same as in our case.

In this paper, we want to use the Knudsen compressor working near atmosphere pressure, the molecular mean free path is therefore $\lambda \approx 6.5\times10^{-8} m$. Hence, we have

$$Kn = \frac{\lambda}{L_C} \tag{1}$$

where, λ is the molecular mean free path and L_c is the characteristic geometric length of the micro channel. For capillary section, the current membrane materials could

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give small size at about 20 nm, thus $Kn \approx 3.2$, the flow is therefore in transitional flow regime. For the connector section the channel is about millimeter scale, so the *Kn* is much smaller than 1, the flow should be continuum flow which means it is not necessary to consider of the reverse flow and pressure drop in the connection section.

Following Muntz *et al.* [12], we derived the mass flow rate and pressure ratio of Knudsen as:

$$M_i = p_{AVG,i} F_i A_i [2(k/m)T_{AVG}]^{-1/2} \{\frac{L_{r,i_i}}{L_{x,i}} \frac{\Delta T_i}{T_{AVG}} Q_{T,i} - \frac{L_{r,i_i}}{L_{x,i}} \frac{\Delta P_i}{P_{AVG,i}} Q_{P,i}\} \quad (2)$$

$$P_i = 1 + \kappa_i \frac{|\Delta T_i|}{T_{AVG}} \frac{Q_{T,i}}{Q_{P,i}} [1 + (\kappa_i / 2)(\frac{|\Delta T_i|}{T_{AVG}})(\frac{Q_{T,i}}{Q_{P,i}})] \quad (3)$$

where k is Boltzmann's constant and m is the molecular mass of the process gas. Q_P and Q_T are coefficients of pressure driven flow and thermal driven flow, respectively, and they are functions of Knudsen number *Kn*. A_i is the capillary's cross-sectional area, and F_i is the fraction of the compressor's inlet area that is occupied by the capillaries. K_i is defined as the fraction of the maximum possible pressure increase that is realized when there is no upflow in the capillaries.

In our pervious study [16], we have investigated how temperature difference influence on the pressure ratio and how *Kn* affect the mass flow with Eq. (2) and Eq. (3). In this paper, we made further analysis for optimization.

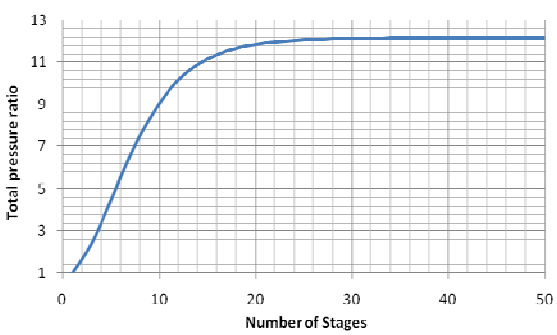

Fig. 6: Pressure ratio against the Number of Stages

For a multi-stages Knudsen compressor, the pressure ratio for each stage is different. The relationship between total pressure ratio with total number of stages, *N*, is important for design a Knudsen compressor. We set inlet Knudsen number $Kn_{in} = 3.2$, $K_i = 0.5$, $\Delta T = 200K$ and $T_{AVG} = 400\ ^oK$, using Eq. (3), we got the plot of total pressure ratio for N stages as shown in Fig. 6. It is seen that the pressure ratio increases fast with number of stages before $N = 12$, after that the trend of increasing slows down. This is because with the pressure increasing along with the multi-stages Knudsen compressor, the *Kn* is decreasing, after several stages the *Kn* becomes quite small, the thermal driven effect is thus less significant in the capillary channel. Fig. 6 implies that with a constant capillary channel size of 20 nm and inlet pressure of 1 atm, the maximum total pressure ratio is about 12, which can be reached at stages number $N = 16$.

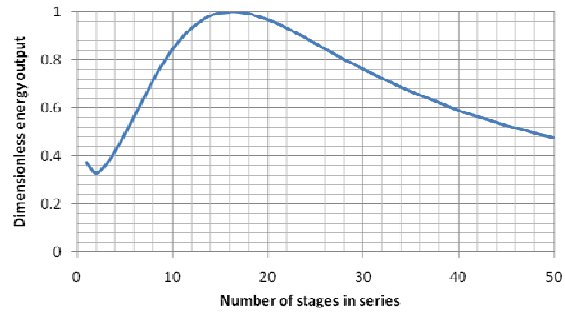

Fig. 7: Dimensionless energy output against number of stages in series

With the analysis above, we can then design a Knudsen compressor to harvest thermal energy. Assume we have a total of 1000 stages. The design optimization is to determine how to arrange the stages in one series and / or in parallel to achieve maximum output. Using the results presented above, the number of stages connected in series shall be 16. Then, they shall be connected in parallel to increase the capacity.

3 DESIGN

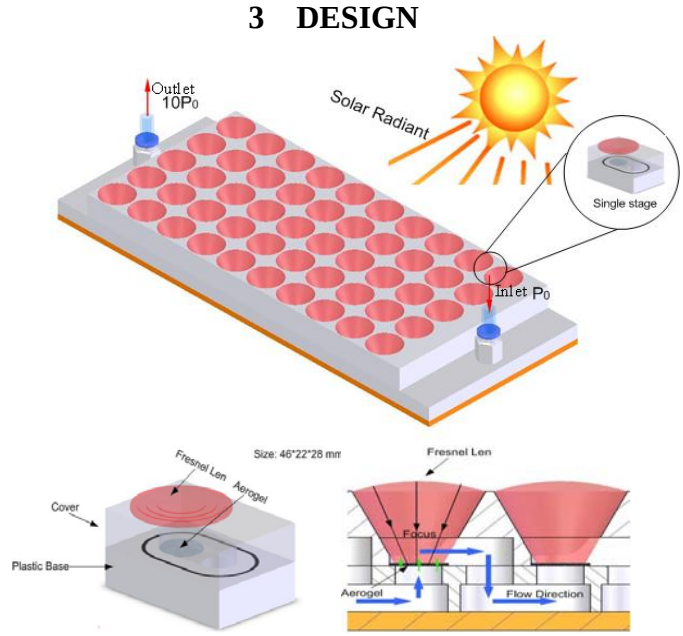

Fig. 8: Illustration of the new design

Based on the studies in the previous section, we designed a new energy harvest device as shown in Fig. 8. It is driven by solar energy. This implies that our device is to convert solar radiation to kinetic energy. The design is 1×1 m in size containing 16×62 Knudsen compressors (each compressor is 40×22×28 mm), with 16 stages are connected in series and 62 series connected in parallel. A single stage of the device is make up with a plastic base, an aerogel

membrane used as the capillary section, as well as a Fresnel lens to generate high temperature difference.

It should be mentioned that aerogel is a porous material, it has a mean pore size of 20nm giving Kn = 3.2 for air at 760 Torr. It has more than 95% void fraction in its structure resulting in low thermal conductivity for maintain the temperature difference. The other key component of the new device is the Fresnel lens, which can effectively focus the heat energy onto the micro channel of Knudsen compressor. It will not only improve the efficiency of the new device, but also make it possible to run in a wide range of temperature.

In a typical tropical summer day the solar energy on 1 m^2 area is about 1 KW. Assume the Fresnel lens can generate a temperature difference of 200 ^oK, the inlet Knudsen number Kn_{in} = 3.2 (for air at 760 Torr and 20 nm channel size), the mass flow rate will be M = 0.002Kg/s. The gas velocity is $v = M / \rho A$ =3.2 m/s. With a pressure of 11 atm, the kinetic energy will be $nMv^2/2 = 62\times0.002\times35.2^2$ = 74.3W. Therefore, the energy conversion efficiency is about 7.4 %.

4 CONCLUSION

In this paper, a new method for harvesting solar energy is proposed and analyzed. It has a number of advantages. First, it can harvest energy directly from the renewable energy sources, such as solar radiation and waste heat, and hence needs no fuel. Second, the structure is simple; there is no moving part in the system. Third, compare with the photovoltaic panel, no expensive materials is need. Numerical analysis provides information for design, fabrication and choosing of working parameters of such a device. In the future, more comprehensive simulation model will be built and experiment validation will be carried out.

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