The Operation Characteristics of Knudsen Thermal Transpiration with Catalytic Reactor

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1 Introduction

The sudden burst of interest in the micro aerial vehicle (MAV) and pico-satellite systems in the past decade has provoked intensive research efforts in the development of advanced micro-power and micro-propulsion systems. Naturally, the prevailing techniques diffuse and applied in civil application, such as the personal power systems. To stabilize sustained combustion or intensive reaction for energy conversion in meso and micro scale devices, usually with a size smaller than the quenching distance of the combustion, has been considered to be one of the main challenges and different mechanisms for stabilization have been proposed, such as catalytic combustion [1], eccentric vortex combustion [2] and liquid fuel film combustion [3].

Alternatively, the problem associated with the pressure and related efficiency of the micro power and micro propulsion systems has received much less attention. The problem becomes pronounced especially in personal power systems for civil applications. Most air-breathing engine has a compressor at the end of inlet section to raise pressure for the combustor and turbine and to produce net cycle work. For space vehicles, it should be pre-stored the pressure in the fuel system. Including a high-RPM compressor or a high-pressure vessel in the micro-power and personal power systems is practically unsuitable and inefficient.

Thermal transpiration pump is recently proposed as one of the possible solution for the micro power systems. In early 1900s first thermal transpiration based compressor was studied and built by Knudsen [4]. The compressor is called Knudsen compressor. It has some advantages: no moving parts in the mechanism and using air as working fluid, so it does not have fluid viscosity and mixer efficiency problems. In 1994 Pham-Van-Diep et al. [5] increased the temperature following the capillary to make pressure gradient by thermal transpiration. A prototype of Knudsen compressor using MEMS technique was set up and tested by Muntz and his group [6][7]. This prototype used an Aerogel membrane, with nano pores and ultra-low thermal conductivity, in the gap between silicon chips. In order to generate temperature gradient, they used catalyst to induce chemical reaction for heating. In 2003 Ochoa et al. [8] built a thermal transpiration compressor with platinum as catalyst.

With all the merits of the Knudsen compressor, one still has to carefully examine the efficiency and related parameters of the thermal transpiration pumping before put it into practical application. The efficiency of the Knudsen compressor is related to the characteristics of fluids, inlet temperature, temperature difference, and pressure. In practice, a mixture of fuel and air will transpire through the Knudsen compressor, and the different transpirability of fuel and air through the membrane will affect the fuel-air ratio and so as the combustion and the pumping efficiency behind the membrane. The important parameters are fuel mixtures, catalyst material and Aerogel characteristics. In this research, variables of the operation characteristics of a Knudsen compressor with the catalytic reactor will be studied and discussed.
2 Experiments

The experimental setup is shown in Fig.1. Hydrogen (H₂) with small molecular size and high activity and flammable limit is used as fuel to react with air in the catalyst bed. Since hydrogen (H₂) has the smallest molecular volume, it is easy to operate in the Knudsen thermal transpiration system. In the experiments, hydrogen (H₂) of 99.9% in purity is used. Hydrogen (H₂) and air are first filtered to eliminate impurities then metered by flow-meter before premixing in the plenum chamber. A K-type thermocouple is used to measure temperature at the exit of the catalyst bed. The Knudsen thermal transpiration is initiated by preheating the thermal guard in front of the catalyst bed using an electrical resistant wire, which is turned off as soon as the system is initiated. A close-look of a thermal transpiration pump prototype with catalyst reactor is shown in Fig. 2, consisting of nano-pore membrane with pore size 20nm (Fig. 3), thermal guard and catalyst bed (Fig. 4). The honeycomb catalyst bed is made of Pt (platinum) on cordierite, with a covering ratio of 0.1% (wt%) and 200 cells/inch square.

3 Theoretical analysis

In the micro-channel, both the pressure gradient and thermal transpiration effects will contribute to fluid flow in the channel, and can be represented by the characteristics as follow:

\[
Q_p = \frac{M}{\left(\frac{1}{2} \sqrt{2RT_0}\right) \rho_0 \omega h^2 \frac{1}{p_0} \frac{\Delta p}{L}} \quad \text{and} \quad Q_T = \frac{M}{\left(\frac{1}{2} \sqrt{2RT_0}\right) \rho_0 \omega h^2 \frac{1}{T_0} \frac{\Delta T}{L}}
\]

Where \(Q_p\) and \(Q_T\) are the Poiseuille and the thermal transpiration fluid coefficients respectively, \(M\) \(\rho_0\), \(p_0\) and \(T_0\) are mass flow rate, density, pressure and temperature and \(w, h, L\) are the width, height and length of the channel. The relavance of both characteristic coefficients, \(Q_p\) and \(Q_T\) can be represented by Knudsen number \((Kn)\). These two coefficients can be calculated by using the database designed by Sone and Itakura [8]. The relationship is shown in Fig. 5. Based upon the theory and methods by Vargo and Muntz [5], the maximum mass flow rate of the thermal transpiration pump can be writen as:

\[
\tilde{M}_{\text{max}} = \frac{F_M}{2} \frac{\Delta T_m}{T_{\text{avg}}} \left( \frac{Q_{P,M}}{Q_{T,M}} \right) \left( \frac{X}{y_x} \right) \frac{(x/y_x)}{Q_T} \left( F_M/F_R \right) \left( A_M/A_R \right) \left( Q_{P,R} \right)
\]

where \(\Delta T_m \Delta T_{\text{avg}} A R \) are temperature difference, averaged temperature, cross-sectional area, and pass ratio of cross section; the subscript M and R indicate the characteristics of membrane and reactant flowing channel. In this research, because the channel diameter of the catalyst bed is much larger than the pore in the membrane and \(Q_{P,R} >> Q_{T,R}\) therefore Eq. (2) can be simplified as:

\[
\tilde{M}_{\text{max}} = \frac{F_M}{2} \frac{\Delta T_m}{T_{\text{avg}}} \left( \frac{Q_{P,M}}{Q_{T,M}} \right) \left( \frac{X}{y_x} \right) \frac{(x/y_x)}{Q_T}
\]

And further in dimensionless form as

\[
\tilde{M}_{\text{max}} = \tilde{M}_{\text{max}} \frac{2p_{\text{avg}}A_M}{\sqrt{2kT_{\text{avg}}/m}}
\]

Where \(k, m\) are the Boltzmann constant and molecular weight. In this research, hydrogen is used for fuel and air is for oxidant and the corresponding Knudsen number \((Kn)\) can be calculated [9].

In Fig. 6, it shows the calculated relationship between air and H₂ Knudsen number and upstream equivalence ratio. In other words, different gas molecules have different thermal transpirations. Smaller molecules tend to transpire through the membrane more easily. From the results in Fig. 6 and in Fig. 5, for the present pore size both fuel and air Knudsen numbers are large enough that the transpiration effect will be dominant and changing
the fuel concentration upstream of the membrane will not obviously affect the transpired fuel/air concentration downstream of the membrane, see Fig. 7.

4 Results and Discussions

The capability of gas transpiration for porous membrane depends on molecular mean free path and relative pore size of the membrane. That is, thickness of the porous membrane will not affect the downstream fuel-air concentration, but will the amount of the transpired gas mixture. For the mixture of hydrogen and air, equivalence ratio 0.1, with membrane pore size 20nm, and the maximum total mass transpiration rate is shown to vary with membrane thickness in Fig. 8. In Fig. 8, when the thickness of the membrane is less than 0.5 mm, the total mass flow rate will increase suddenly. On the other hand, when the thickness is larger than 1mm, variation of the total mass flow rate will become almost indiscernible. The relationship between pore size and fuel-air concentration, and thus the catalyst temperature, and the relation between membrane thickness and pore size and required mass flow rate need to be carefully evaluated in the design of a thermal transpiration system.

In general, hydrogen-air mixture can easily react on platinum catalyst surface at room temperature. The initiation of the thermal transpiration and ignition of transpired fuel air mixture on the catalyst is shown in Fig. 9. The operation conditions in Fig. 9 are: equivalent ratio 0.1 and the pressure equilibrated between the membrane and with ambient pressure by opening the chamber to the ambience. Without initial temperature difference setup by resistant heater, no thermal transpiration can be initiated and outlet temperature of the catalyst bed remains at room temperature. In this research, heated for 5 seconds with a 10W heater the system can operate automatically and continuously with stable Knudsen thermal transpiration to supply fuel-air mixture to the catalyst bed to maintain the temperature as shown in Fig. 9. Figure 10 shows that the variation of the outlet temperature of catalytic reactor with upstream equivalence ratio. The outlet temperature increases with the upstream equivalence ratio, but not as pronounced as that for direct combustion.

5 Conclusion

A prototype of thermal transpiration pump with catalytic reactor using hydrogen air mixture is successfully developed and the basic operation characteristics are discussed based on results of theoretical analysis. From the results of experiments, stable Knudsen thermal transpiration can be initiated by using electric heater initially to establish the temperature difference and the reaction of the transpired mixture in the catalyst bed will maintain the operation automatically. However, unlike the fuel-air direct combustion, changing the upstream equivalence ratio will not apparently affect the outlet temperature of the catalyst bed as the transpiration through the membrane is dependent on the pore size and the mean free path of the fuel and air molecules.

References


**Figures**

- Fig. 1 Experiment equipments
- Fig. 2 Prototype of reactor
- Fig. 3 Porous membrane
- Fig. 4 membrane and catalyst bed

![Figure 1](image1.png)

**Fig. 1** Experiment equipments

![Figure 2](image2.png)

**Fig. 2** Prototype of reactor

![Figure 3](image3.png)

**Fig. 3** Porous membrane

![Figure 4](image4.png)

**Fig. 4** membrane and catalyst bed

![Figure 5](image5.png)

**Fig. 5** Variation of $Q_P$ and $Q_T$ with Kn

![Figure 6](image6.png)

**Fig. 6** Variation of Kn of air and H$_2$ with upstream equivalence ratio

![Figure 7](image7.png)

**Fig. 7** Variation of $Q_P$ and $Q_T$ with upstream equivalence ratio for air and H$_2$

![Figure 8](image8.png)

**Fig. 8** Total mass flow rate vs. membrane thickness

![Figure 9](image9.png)

**Fig. 9** The ignition state in equivalence ratio 0.1

![Figure 10](image10.png)

**Fig. 10** Outlet temperature for different equivalence ratios