Design of a Small Wankel Engine

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Abstract—**This work presents a novel design of an ultra-small Wankel engine. With a device size of mm range and required power of mW, the rotation speed is theoretically calculated up to thousands of rpm. The PDMS MEMS process has been employed to make the Wankel engine planar and tiny. How to selecting the proper materials heterogeneously in the design stage of this engine is demonstrated herein.**

Keywords-component; Wankel engine; energy harvest

I. INTRODUCTION

Finding clean renewable energies has become a popular research topic in recent years. Using Stirling engine in harvesting the waste heat is one of the corresponding studies. Stirling engines are thermally driven by the mechanism of temperature difference and include the configurations of translational and rotary types. The rotary type Stirling engine invented by Felix Wankel in 1959 was also known as the Wankel engine. Wankel engines have several advantages over the traditional combustion piston engines in the past, for example, higher efficiency, lower vibration, and light weight [1-2].

In this work, MEMS machining method is used to fabricate an ultra-small Wankel engine for energy harvesting. Before the design of device manufacture, a theoretical discussion of the rotor dimension on the rotating speed of the Wankel engine is firstly done. Then a thermal resistance analysis is also addressed for selecting the proper materials and the corresponding MEMS processes. Silicon, glass, SU-8 resist, and PDMS are all considered as the device materials. The different working fluids inside the small Wankel engines are also proposed.

II. DEVICE DESIGN AND FABRICATION

A. Configuration of the Wankel Engine

The authors would like to manufacture an ultra-small Wankel engine by MEMS process here. Owing to the excuse that the structure of translational Stirling engine is complicated but the MEMS process is planar, so the rotary or the Wankel engine configuration is selected. However, the dimension and the materials for the engine should be assigned as well.

The housing inner wall of the Wankel engine has a mathematical form known as a trochoid or an epitrochoid shape [3-5]. The rotor is an eccentric rotor. The contour of the inner wall is shown in Fig. 1. The trajectory is depicted as the (x,y) coordinate in (1) and (2).

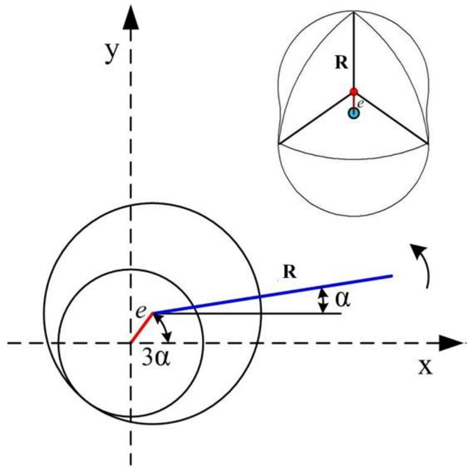


Fig. 1. The epitrochoid contour of Wankel engine.

$$x = R\cos(\alpha) - e\cos(3\alpha). \tag{1}$$

$$y = R\sin(\alpha) - e\sin(3\alpha). \tag{2}$$

where the angle α can be regarded as follows assuming the constant rotating speed ω;

$$\alpha = \omega t. \tag{3}$$

The symbols R is the longest distance from the center circle to the periphery; e is the radius of the central circle.

Basically, the relative contour of Fig. 1 depends on e and R simultaneously. Herein, the authors fixed the ratio (e/R) as 0.162, and discussed the proper value of R on the rotating speed of the rotor in the following.

B. Rotation Speed of the Rotor

Ideally consider a circle disc with a radius of r_0 shown in Fig. 2, and let it rotate with a speed of ω above a supporting substrate with a gap of d. The viscous drag torque T could be taken as the integral around the disc area by the assumption of Newtonian fluid stress on the substrate as follows.

$$\begin{aligned} T &= \int_A (stress)\quad(area)\quad(force\_arm) \\ &= \int_A \mu\left(\frac{du}{dz}\right)_{substrate} dA\cdot r \\ &= \int_0^{r_0} \mu\frac{r\omega}{d}2\pi r^2 dr \\ &= \frac{\pi\mu\omega r_0^{\ 4}}{2d}. \end{aligned} \tag{4}$$

The power needed to overcome the drag torque T under the rotation speed ω is shown below.

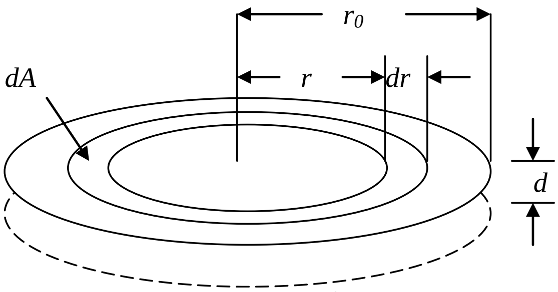


Fig. 2. The ideal disc model of the Wankel engine.

$$P = T\omega = \frac{\pi\mu\omega^2 r_0^4}{2d}. \tag{5}$$

As the authors applied the above power formula to the case of the Wankel engine, the rotating tip is not only rotating but also wobbling according to (1) and (2). So the averaged instantaneous tangential velocity $r\omega$ in (4) should be replaced with $\overline{r\omega}$ as follows.

$$\overline{r\omega} = r\omega\sqrt{1+(3e/R)^2}. \tag{6}$$

and r^2 in (4) should be replaced with $\overline{r^2}$.

$$\overline{r^2} = r^2\left[1+(e/R)^2\right] \tag{7}$$

Finally, the modified power and the rotation speed are in the following.

$$\overline{P} = \frac{\pi\mu\omega^2 R^4}{2d}\sqrt{1+(3e/R)^2}\left[1+(e/R)^2\right] \tag{8}$$

$$\overline{\omega} = \sqrt{\frac{2d\overline{P}}{\pi\mu R^4\sqrt{1+(3e/R)^2}\left[1+(e/R)^2\right]}}. \tag{9}$$

From (8) and (9), the required power P would be as small as possible when the rotor dimension R approaches to zero; the rotating speed ω would also approach to infinity when the rotor dimension is as small as possible.

As a viable device for harvesting any infinitesimal waste heat P, the trend of making the rotor R smaller is beneficial to the success of the Wankel engine herein.

C. *Thermal Resistance Analysis*

The proper choice of the heat conduction path in the Wankel engine is considered in this section. Then the required power P discussed in the previous section will be firstly estimated by this conduction heat transfer rate.

Here, the authors would like to compare the thermal conductivities of different internal working fluids in the central chamber of the engine which may be made of silicon and the PDMS substrates, respectively. These two kinds of substrate materials are of the most popular favor in MEMS area. The one-dimension, steady state, thermal conductivity equation (Fourier law) is shown as below.

$$q = kA\frac{\Delta T}{\Delta X}. \tag{10}$$

where q is heat transfer rate; k is thermal conductivity; A is cross section area; ΔT is temperature difference; ΔX is the assumed heat path length.

As people know well, the thermal resistance concept is beneficial to the first prediction of the proper heat path of heat conduction design problems. The thermal resistance R_T is defined as the temperature difference per unit heat transfer rate.

$$R_T = \frac{\Delta T}{q}. \tag{11}$$

Fourier law (10) and the definition (11) combine as below.

$$R_T = \frac{\Delta X}{kA}. \tag{12}$$

For the Wankel engine herein, there are two possible pathways for the thermal conduction heat to pass through. As shown in Fig. 3, the pathway (1) is along the periphery solid wall. The other pathway (2) is directly through the working fluid. For the sake of providing the required thermal power for rotating the engine rotor, the pathway (2) is of course the proper one.

Assume that ΔX_1 and ΔX_2 are the same; $A_1 : A_2 = 1 : 10$, and the rotor matter is negligible. If the pathway (2) is the favor one, the proper thermal resistance of $R_{T,2}$ should be much smaller than $R_{T,1}$ or expressed as the following inequality.

$$10 >> \left(\frac{k_1}{k_2}\right). \tag{13}$$

If material (1) or the chamber engine is made of silicon and k_1=157 W/mK, the thermal conductivity k_2 of the proper working fluid inside the engine chamber should be much greater than 15.7 W/mK. Only some liquid metals meet this requirement. It will encounter difficulties as packaging liquid metals into the engine chamber and the working temperature must be high for melting the metals inside the chamber.

On the other hand, if the engine chamber is made of PDMS or glass, and k_1=0.16~1.38 W/mK. Then the thermal conductivity k_2 of the proper working fluid inside the engine chamber should be much greater than 0.016~0.138 W/mK. Water and even mercury meet this requirement. The corresponding thermal conductivities of the interested

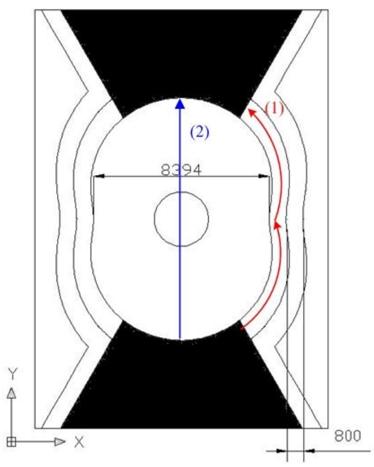


Fig. 3. Schematic diagrams of the small Wankel engine (unit: μm).

materials discussed above are listed in TABLE I [6].

Fig. 4 conclusively shows a design of the Wankel engine with the side chamber and bottom material of PDMS and with the cap material of glass. The central rotor is made of SU-8 resist. The working fluid inside the chamber is supposed to be mercury.

Three dimensions of the small Wankel engines have been designed. The values of R are assigned as 4990, 2495, and 1248 μm, respectively. In addition, there is an insulation groove has been designed to avoid the heat leak from the chamber in Fig. 4.

By the rotating speed ω_1 prediction of (9) and the conduction heat transfer rate (P is assumed to be converted from 40% of the heat conduction) of (10), the theoretical output data of the three engines with different rotor R are listed in TABLE II. The much faster ω_2 and ω_3 denote the cases that the gap between the rotor and the substrate is filled with water or air, respectively.

D. Fabrication Process

The soft lithography is selected as the fabrication technique for the small Wankel engine. A silicon mother mold is initially patterned by ICP etching and transfers to a PDMS chamber. This PDMS chamber block is bonded with a cover glass [7]. The whole processes are shown in Figs. 5-6.

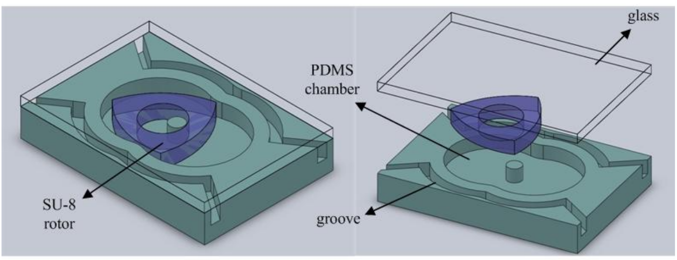
The working fluid water or mercury should be filled into the chamber after the PDMS bonding. A filling hole is left in advance for the filling and the afterward sealing is done by epoxy gluing and parylene conformal coating [7]. One finished device filled with water is shown in Fig. 7. The functions of the Cr-Au electrodes made inside the chamber are two-folded. One function is as the thermal sensors for on-site monitoring the temperature field in the engine. The other function is as the joule heating source (or the thermal actuators) for adding so enough power into the engine as to push the rotor rotating.

E. Consideration of Testing Setup

The authors have applied the ultrasonic cleaner to shaking the rotor so as not to stick to the bottom surface of the PDMS chamber.

The rotor is detached from the substrate and of a little bit rotating around the center with several RPM. So far how to set up an ultrasonic shaking for the engine rotor is one concern for the successful experiment testing.

The temperature sensing function of the embedded electrodes have also been verified to monitor the temperature



(a) (b)

Fig. 4. Three dimensional diagram of the small Wankel engine.

TABLE I. THERMAL CONDUCTIVITIES OF MATERIALS [6]

	Silicon	PDMS	Glass	Hg	Air	Water
Thermal conductivity （W/mK）	157	0.16	1.38	8.34	0.024~0.026	0.33~0.68

TABLE II. PERFORMANCE DATA OF THE WANKEL ENGINE

R (μm)	4990	2495	1248
ΔT (K)	70 (20→90℃)		
P (mW)	84.4×40% (working fluid: mercury)		
μ (N/s m^2)	1.4×10^{-2} (gap fluid: mercury)		
ω_1 (RPM)	1,920	7,720	30,700
μ (N/s m^2)	5.1×10^{-4} (gap fluid: water)		
ω_2 (RPM)	10,000	40,400	16,100
μ (N/s m^2)	2×10^{-5} (gap fluid: air)		
ω_3 (RPM)	50,800	20,400	81,400
d=18.75 μm; ΔX=11607 μm; A=8394×200 μm^2; k=8.34 W/mK			

change inside the chamber from the room temperature to the water boiling state. The Cr-Au metal is still fine as the resistive thermal detecting (RTD) material herein. However, how to combine the ceramic heating source with the fabricated engine to do the thermal testing is not easy since the thermal conductivity of PDMS wall is very small. The authors have tried to partially merge the fabricated PDMS small engine in the ultrasonic pool, and add heat directly into the hot side of the engine. Even though the temperature difference is up to 70 degree C, the engine rotor is only slightly shaking without apparent rotating. The authors re-calculated the output data of TABLE II by (9) and (10) with the working fluid changed from mercury to water. It's found that the theoretical rotating speed is around 2500 rpm subject to P=2 mW. Since the water electrolysis from the Cr-Au electrodes during heating would generate non-condensed bubbles to retard the rotation of the engine. Using water as the working fluid is then not feasible herein. The experiment of packaging the testing mercury as the working fluid is still under developing. Moreover, a cooling end packaged with a heat pipe is revealed in Fig. 8 for promoting the condensation of this small Wankel engine.

III. CONCLUSION

By the analysis of rotating speed and the thermal resistance of the possible designs of the ultra small Wankel engine in this study, the mm-size energy harvesting device is supposed to have thousands of RPM rotation speed subjected to mW power input. The fabrication process and the testing setup are also considered. Ultrasonic shaking is so far necessary to the testing for effectively levitating the center rotor without sticking issue. The authors also tried water as the working fluid inside the engine chamber and did not gain the successful result. The left choice of selecting mercury as the working fluid in PDMS engine chamber is still under way. The necessary packaging technique with conformal parylene is

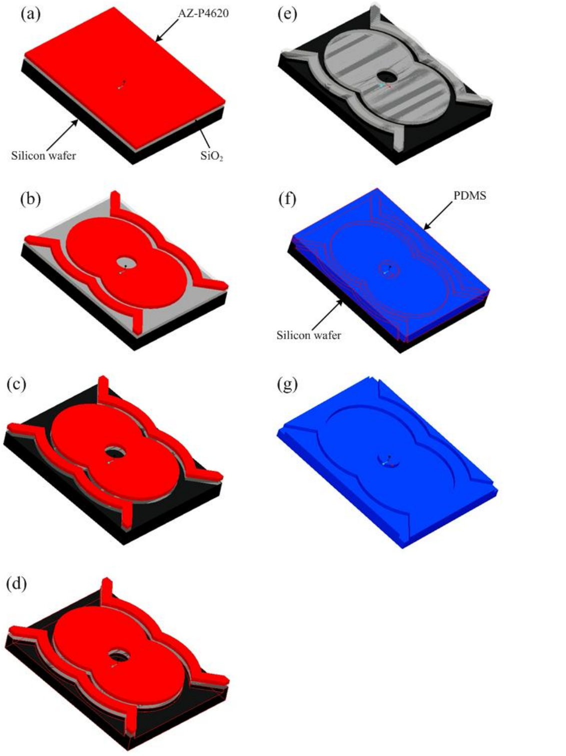


Fig. 5. Fabrication process for the PDMS chamber: (a) resist coating; (b) UV exposure and developing; (c) oxide opening; (d) ICP etching; (e) resist stripping; (f) dispensing PDMS; (g) PDMS demolding.

looked forward to avoiding mercury leakage. The Cr-Au electrodes designed as the thermal sensors and evaporator, a heat pipe installed at the cold end for condensation, are both hoped to augment the functionality of this small Wankel engine as well in the future.

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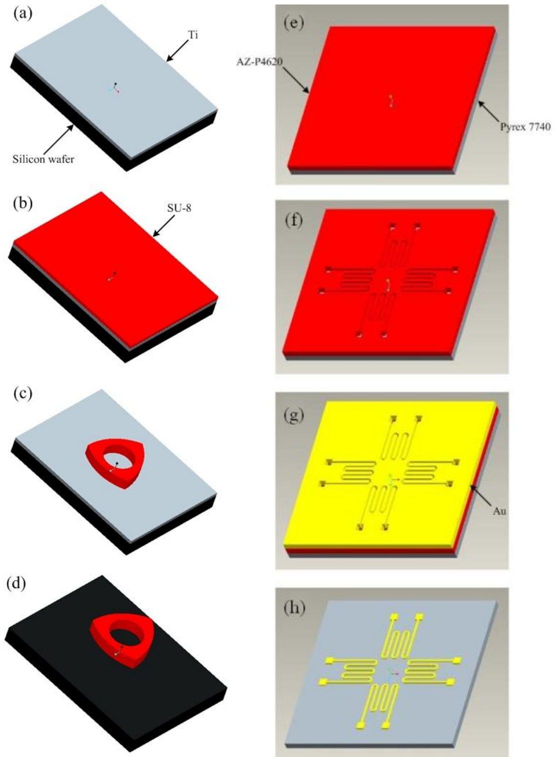

Fig. 6. Fabrication process for the rotor: (a) evaporating Ti; (b) SU-8 coating; (c) UV exposure and developing; (d) detaching SU-8 rotors from the substrate; Process for the electrodes: (e) resist coating; (f) UV exposure and developing; (g) evaporating the electrode metal film; (h) lift off process.

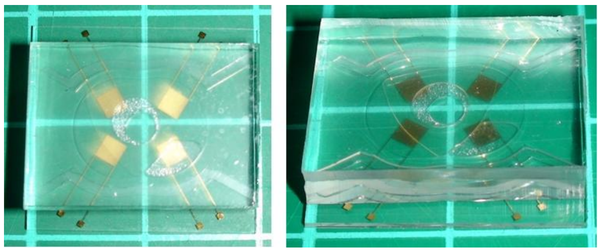

Fig. 7. A fabricated small Wankel engine (R=4990μm).

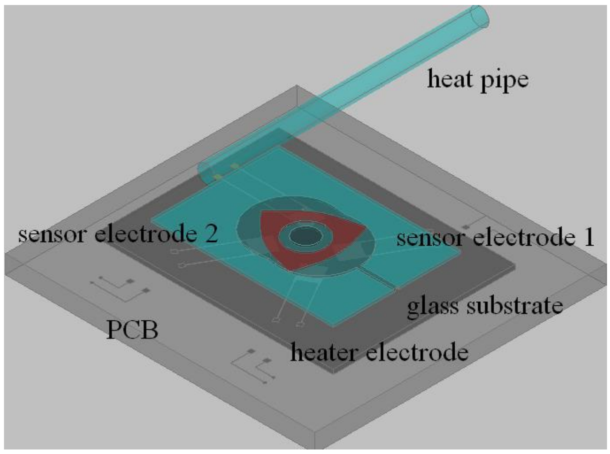

Fig. 8. The modified package of the small Wankel engine.

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