Study on development of wearable generator

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1. Introduction

Nowadays, alternative energy sources to fossil fuel are needed. The alternative should be kind to the earth, and hard to be depleted.

Recyclable energy (sunlight, wind power, geothermal heat, human power, etc.) is the major alternative which meets conditions described above. Some sources of recyclable energy are available everywhere. To generate and use electrical energy around human body with surrounding recyclable energy sources, switch of energy source will be accelerated.

Against this back ground, handy generators using recyclable energy were suggested. Among these generators, wind-up generator is the simplest and achieves great power. However, when you generate electric power with wind-up generator, you must concentrate on generation.

In this study, we focused on generators using recyclable energy which generate electric power unconsciously in daily life. We call these generators “wearable generator”. We set 3 W as the final goal of the generation intended to use for mobile electronics.

At first, we investigated various recyclable energy sources to determine the energy source which suits best for wearable generator and selected the best way for generation with the source. Second, we designed the prototype of wearable generator based on the first step, and evaluate the wearable generator prototype.

2. Investigation

We discussed on 7 energy sources (sunlight, wind power, body heat, breath, blood flow, arm motion, and walking). Fig. 1 shows the estimated results. Among these energy sources, 5 energy sources without breath and blood flow can produce 3 W of electrical power.

With sunlight, you can afford to produce 3 W and more electricity with 1000 cm^2 thin-film solar cell if you are in direct sunlight. But if you aren’t, generation of 3 W shall be hardly achieved.

With wind power, you may achieve 3 W with at least 3000 cm^2 wind mill, which will be too bulky and heavy to wear.

With body heat, 3 W is available if you wear 8000 cm^2 thermoelectric generator when there’s 30 K temperature difference between your body

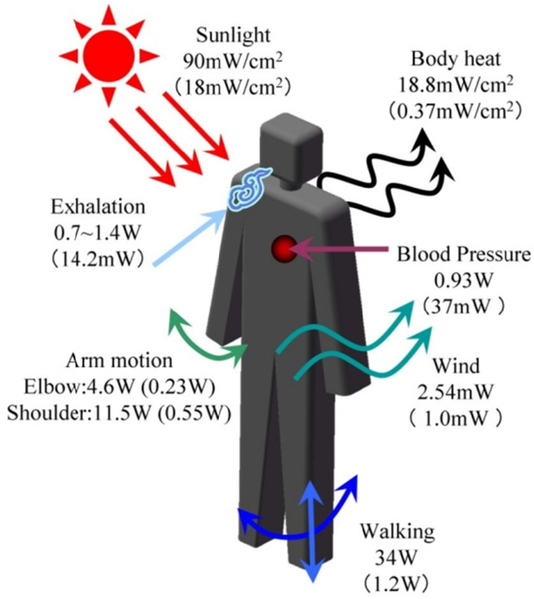

Fig. 1 Energy potential and estimated electric power generation for various sources. The latter is in parentheses.

and air. This is impractical because of the device weight and huge heat loss of user’s body.

When you produce 3 W of electrical power with bending and reaching of your elbow, you need to bear 130% more load than usual. When you produce 3W electricity with your shoulder turn, it demands 55% more load than usual. These loads are heavy enough not to be unconscious for users.

When you produce 3 W electrical power with walking, 18% more load than usual is demanded on you. This load may be light enough to be unconscious for users.

Therefore, we determined that walking is the best energy source for wearable generator. There are various ways to generate electricity with walking; the way with piezoelectric materials, with coils and magnets, directly with a motor, and so on. In this study we focused on the shoe-shaped generator with two tanks and one turbine, which is suggested by Toriumi et al[1]. and it generated 1.2 W by walking. However, there is a problem that the turbine rotates back and forth when the tanks stamped one and another.

3. Design fabrication

We designed the shoe-shaped generator based on the generator suggested by Toriumi et al[1]. Shoe-shaped generator is composed of three parts: vane turbine, tank, and shoe-shaped mounting.

Vane turbine is composed mainly of vanes, rotor, and stator. Three parts make chambers which is separated each other almost completely. The turbine rotates by volume difference of each chamber. The theoretical output torque T_{th} and the theoretical angular velocity ω_{th} are given by,

$$T_{th} = PV_{th} / 2\pi \,, \qquad \text{Eq. 1}$$

$$\omega_{th} = 2\pi Q / V_{th} \,, \qquad \text{Eq. 2}$$

where P is pressure difference between inlet port and outlet port, Q is flow rate through turbine, and V_{th} is the volume required for the turbine to rotates by 360 degrees and given by,

$$V_{th} = cn(V_{c\max} - V_{c\min}) \,, \qquad \text{Eq. 3}$$

where c is the number of suction (or discharge) per rotation, n is the number of vanes and the value is 6 in this study. $V_{c\ max}$ is the maximum chamber volume, and $V_{c\ min}$ is the minimum chamber volume.

We designed two types of vane pump. One vane pump is eccentric vane turbine (Fig. 2) and another is oval vane turbine (Fig. 3). The stator wall of the former is cylindrical and eccentrically placed with the rotary shaft. The stator wall of the latter is oval and its center is coincident with the rotary shaft. The ports number is 2 for eccentric vane turbine and 4 for oval vane turbine. All parts except stator are common. Vanes of each turbine are forced to be in contact with stator by springs set between rotor and vanes. Stators are made of A2012, rotor and vanes are made of PTFE. V_{th} of eccentric vane turbine is 20.5mL, and V_{th} of oval vane turbine is 7.8 mL.

Tank is composed of two parts: bellows and basement. With bellows, volumetric capacity of tank changes easily by a stamp. Basement has three ports for injection, ejection, and pressure measurement. Shoe-shaped mounting is to set tanks so that it is easy to stamp tanks.

Fig. 4 shows assembly drawing of shoe-shaped generator with eccentric vane turbine and Fig. 5 shows assembly drawing of shoe generator with oval vane turbine. Designed turbines can rotate unidirectionally if they are connected to tanks and check valves as Fig. 6 and Fig. 7.

In this study, we fabricated two types of vane turbine, 2 tanks, and 1 pair of shoe-shaped mounting based on the designing above.

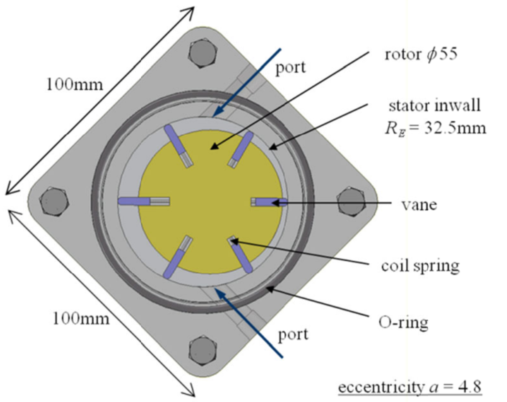

Fig. 2 Eccentric vane turbine.

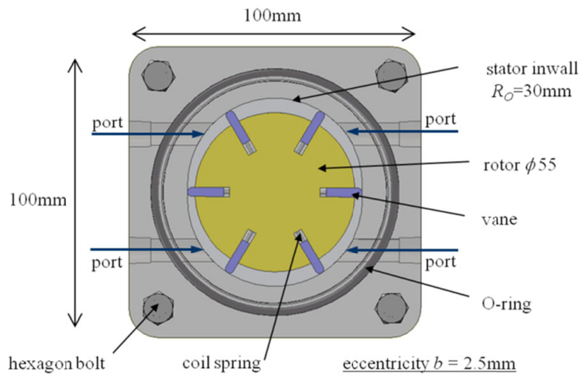

Fig. 3 Oval vane turbine.

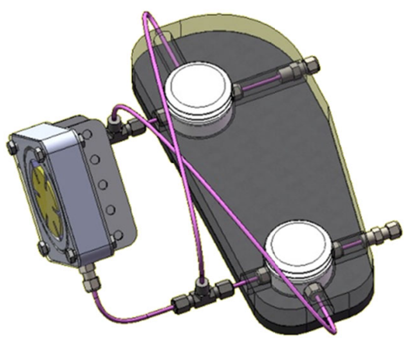

Fig. 4 Assembly drawing of shoe generator with eccentric vane turbine.

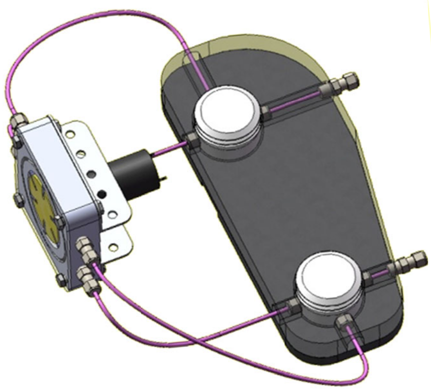

Fig. 5 Assembly drawing of shoe generator with oval vane turbine.

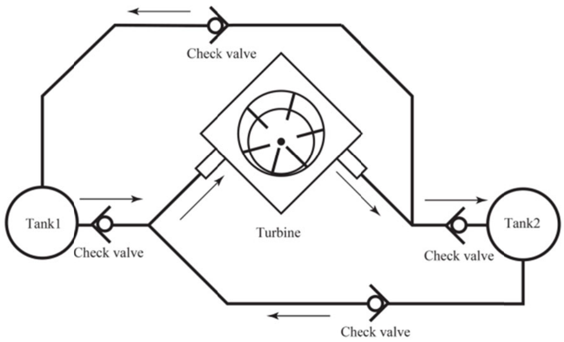

Fig. 6　A hydraulic circuit for an eccentric vane turbine to rotate in one direction.

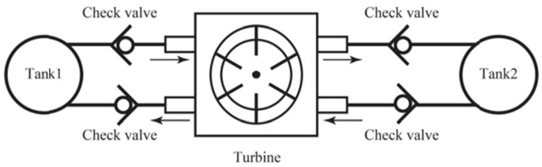

Fig. 7　A hydraulic circuit for an oval vane turbine to rotate in one direction.

4.　Evaluation

We did three experiments; Experiment 1 with water for each vane turbine basic characteristic. Experiment 2 with diaphragm pump for selection of liquid filled in turbine, tanks and tubes. Experiment 3 with fabricated tanks and shoe-shaped mounting.

In Experiment 1, one port of each vane turbine is directly connected to water tap and another port is open. As oval vane turbine has 4 ports, 2 ports are the remainders and they are closed in this experiment. Pressure is measured at adjacent of inlet port and flow rate is calculated from mass of water ejected from outlet.

As a result, the rotation speed of oval vane turbine is less than 1/4 of eccentric vane turbine in all conditions performed. Eccentric vane turbine rotates 60 rpm under the condition P = 0.11 MPa, Q = 2.1 L/min. Oval vane turbine didn't rotate under the condition P = 0.19 MPa, Q = 2.9 L/min. It is because the output torque may be small compared to the torque required for turbine rotation due to small value of V_{th}.

Therefore, we doubled the straight region of oval stator wall. We call the turbine with the newly fabricated stator oval vane turbine 2, and its $\boldsymbol{V_{th}}$ is 17.0 mL.

At the same time, it is observed that there is deformation in height of rotors. It is because of very high linear expansion coefficient of PTFE (about 0.079% at 20 ˚C[2]). Rotor height is a very important parameter for vane turbine, which determines the degree of chambers' isolation. So we grinded rotor about 0.05 mm and insert PTFE sheet into an extended space.

Then we performed the same experiment for eccentric vane turbine and oval vane turbine 2. Table. 1 shows the result.

Table. 1　The results of Experiment 1.

Type of vane turbine	Pressure P [MPa]	Flow rate Q [L/min]	Rotating speed N [rpm]
Eccentric vane turbine	0	0	0
	0.03	1.0	40
	0.08	2.5	120
	0.19	4.8	230
	0.24	5.7	260
	0.32	6.3	290
	0.45	6.6	300
	0.50	7.1	310
Oval vane turbine 2 with two ports closed	0	0	0
	0.04	1.0	0
	0.07	2.8	75
	0.20	3.8	100
	0.42	5.8	140
	0.50	6.7	150

Table.2　The results of Experiment 1 for oval vane turbine 2 with two ports connected each other.

Type of vane turbine	Pressure P [MPa]	Flow rate Q [L/min]	Rotating speed N [rpm]
Oval vane turbine 2 with two ports connected to each other	0	0	0
	0.03	1.2	30
	0.06	2.8	155
	0.19	4.1	210
	0.30	5.2	240
	0.42	6.7	255
	0.50	7.3	270

The rotation speed of each turbine was increased with pressure P and flow rate Q. It is because theoretical output torque T_{th} is proportional to P and theoretical rotation speed ω_{th} is proportional to Q as shown in Eq. 1 and Eq. 2. The rotation speed of eccentric vane turbine was improved from previous experiment. It may be caused by improvement of the degree of chambers' isolation with the process above. It is clear that the rotation speed of oval vane turbine 2 was greater than oval vane turbine as is intended. Although, according to the theory, the rotation speed of oval vane turbine 2 should more than the one of eccentric vane turbine, the result didn't consistent with the theory. The reason was supposed that closed port of oval vane turbine 2 prevent turbine rotation. So we connected two ports with a tube instead of closing ports. The results are shown in Table. 2. Compared to the previous results, the rotation speed is nearly doubled in all conditions. Therefore, remaining ports should be connected each other.

In Experiment 2, diaphragm pump was used to feed fluid into a turbine. Pressure and flow rate are measured in the same way as Experiment 1. The flow from diaphragm pump is pulse shape and similar to the flow generated by walking. Two types of fluids are used; purified water and oil (VG10). Viscosity of the oil is about 10 times larger than purified water. Chambers' isolation will improve and pressure loss will increase with increase of viscosity. The results are shown in Table. 3.

Table. 3 The results of Experiment 2.

Type of vane turbine	Liquid	Pressure P [MPa]	Flow rate Q [L/min]	Rotating speed N [rpm]
Eccentric vane turbine	Water	0	0	0
		0.08	0.9	30
		0.11	1.8	70
		0.23	3.8	180
		0.30	4.5	200
	Oil	0	0	0
		0.21	0.6	40
		0.24	1.0	50
		0.26	1.4	55
Oval vane turbine 2 with two ports closed	Water	0	0	0
		0.15	1.3	30
		0.24	1.8	50
		0.28	2.2	60
		0.29	2.4	80
	Oil	0	0	0
		0.25	0.6	7.5
		0.29	1.2	12.5
Oval vane turbine 2 with two ports connected to each other	Water	0	0	0
		0.10	0.8	75
		0.17	1.7	160
		0.27	2.5	180
	Oil	0	0	0
		0.17	0.6	17.5
		0.22	1.2	22.5
		0.24	1.7	27.5

It is clear that the turbine rotates more with purified water than the oil. It seems that tubes are long enough to have a high pressure loss and the improvement of chambers' isolation is not so effective at least for the turbines fabricated in this study. So we determined to select water for working fluid.

The rotation speed with the diaphragm pump tended to be higher than one with water under the similar conditions. It is because periodical impulses given by diaphragm pump accelerate the rotation speed.

In Experiment 3, two tanks are stamped by heel and forefoot, and feed fluid to a turbine. The pressure inside of each tanks are measured with pressure meters. Tanks and turbines are connected in following 4 ways; (1) Eccentric vane turbine and tanks are connected without check valve (the turbine rotates back and forth). (2) Eccentric vane turbine and tanks are connected as Fig. 6. (3) Oval vane turbine 2 and tanks are connected as Fig. 7. (4) Oval vane turbine 2 and tanks are connected with 6 check valves so that unused ports connected each other.

As the result of Experiment 3, the turbine rotates only when connected with tanks as (1) and turbines hardly rotate in the other ways to connect. It is because of pressure loss for check valves. It costed about 0.05 MPa for fluid to flow through a check valve. Because pressure difference between tanks was 0.10 ~ 0.20 MPa, the effect of the pressure loss might be major. To realize the way for turbines rotates in one direction, check valves run at lower pressure will be required.

We also measured the generated power with fabricated tanks and turbines connected to a motor (A-max32). Generated electricity was ±1 mW when tanks and an eccentric vane turbine as (1) and conversion efficiency was 0.02%. The motor used in this study doesn't suit for fabricated vane turbines. For practical use, it is required to select a motor from characteristics of practical vane turbine such as output torque and rotating speed.

5. Conclusion

We investigated various recyclable energy sources to determine the energy source which suits best for wearable generator and selected the best way for generation with the source at first. Second, we designed the prototype of wearable generator based on the first step, and evaluate the wearable generator prototype.

Main results obtained in this study are summarized as follows.

1. It clarify that walking is the best source for wearable generator. And we selected shoe -shaped generator in this study.
2. Two types of vane turbine and tanks, a pair of shoe-shaped mounting are designed and fabricated.
3. The rotation speed of each turbine was increased with pressure P and flow rate Q.
4. To realize the way for turbines rotates in one direction, check valves run at lower pressure will be required.
5. For practical use, it is required to select a motor from characteristics of practical vane turbine.

Reference

[1] 鳥海陽平，松本聡，正代尊久：タービンを用いた歩行発電システムの特性，2008 年電子情報通信学会総合大会，通信講演論文集 2，S-78.，S-78.

[2] The fluoropolymer handbook, Manual for the chemical applications of Teflon®. Du Pond - Mitsui Fluorochemicals Co., Ltd. (1992)