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Power Generation from Low Temperature Waste Heat Using Magnetic Phase Transition

Yasuki Kansha[a,b,*], Masanori Ishizuka[b]

[a]Oraganization for Programs on Environmental Sciences, Graduate School of Arts and Sciences, The University of Tokyo 3-8-1 Komaba, Meguro-ku Tokyo 153-8902, Japan
[b]Collaborative Research Center for Energy Engineering, Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku Tokyo 153-8505, Japan
kansha@global.c.u-tokyo.ac.jp

In this research, an innovative power generation system from a low temperature heat has been proposed. In the proposed system, magnetic phase transition is integrated with Faraday's law of induction, electric power is generated without any additional energy conversion, leading to achieving efficient power generation. Magnetic phase transition is a famous phenomenon that a paramagnetic material absorbs low temperature (< Curie temperature) heat and isothermally transforms to a ferromagnetic material at the Curie temperature. Furthermore, the power generation performance of the proposed system has been thermodynamically evaluated. The cycle of this system on the temperature-entropy diagram is close to a trilateral cycle suitable for a sensible heat recovery. Thus, it can be said that this system has a large possibility as a new energy harvesting system.

1. Introduction

Recently, internet of things (IoT) and cyber physical systems (CPS) originated from informatics have attracted attention in Japan to integrate information into the networks of the society (Yamada et al., 2017). To develop these technologies and systems into the society, it is necessary to develop efficient transmitters and receivers for signals, energy saving network systems and energy acquisition systems, because energy is required for exchanging information in a network. From this reason, the word, energy harvesting, have been getting a lot of attention in Japan. Energy harvesting involves electric power generation for online operation of sensor and electric devices from low level energies such as low temperature heat, vibration and light. The quality of these energies is so low that we can acquire only little power from them. Thus, these energies have been discarded into the circumstances and not well-utilized for a long time.

Nowadays, many electric devices such as sensors that require less electric power to work regularly have been developed along with development of IoT and CPS (Huang et al., 2017). Although each electric device requires small amount of electric power to work regularly, the number of applications of such electric devices for IoT and CPS are so huge that large amount of energy will be required in near future. Furthermore, it is necessary to use large amount of electric power when these devices face extreme or abnormal conditions. Therefore, a large amount of stored energy must be required for such applications. Compared with the other low-level energies, vibration and light, large amount of low temperature heat can be easily obtained around industrial plants and local communities.

One of the most famous ways to acquire the electric power from exhausted low temperature heat is to apply thermoelectric conversion elements, in other words thermoelectric devices (Shakouri, 2011). To acquire large electric potential difference, the device generally consists of p- and n-type semiconductors. However, it is well-known that the efficiency of these devices is so low because only small entropy is changed by electron or hole transfer (Chen and William, 1996). Furthermore, the heat transfer from heat sources to the device and from devices to sinks cannot keep isothermal conditions and some heat from the heating surface in thermoelectric devices is directly transferred to the cooling surface without power generation because both heat surfaces are

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connected by the device itself (Luo, 2008). Thus, these issues accelerate deterioration of the efficiency of the thermoelectric devices.
To generate electric power from heat, heat engine, it is necessary to consider thermodynamic cycle. The most famous theoretical thermodynamic cycle is Carnot cycle. This cycle consists of isothermal and isentropic changes. Therefore, the changes of this cycles are perfectly reversible, and it cannot be achieved in real heat engine. However, this efficiency can be a good index to analyse the practical heat engine. To increase the power generation efficiency, it is necessary to be close the cycle drawn in temperature-entropy diagram to Carnot cycle. From this aspect, Kansha and Ishizuka (2017) proposed a new energy harvesting system, in which isothermal magnetic phase transition took place by low temperature heat and electric power was generated by Faraday's law of induction. So far, the authors have investigated magnetocaloric effect to elevate energy quality of heat as a heat pump role at isentropic conditions (Kotani et al. 2013a) and designed heat circulation systems for process energy saving around Curie temperature (Kotani et al. 2014a). During this transformation, entropy change due to the magnetic moment change is maximized at Curie temperature (Kotani et al. 2014b).
In this paper, further investigation about the proposed energy harvesting system combining magnetic phase transition and Faraday's law of induction is summarized and the power generation efficiency of the proposed cycle was investigated from the thermodynamic cycle point of view.

2. Proposed power generation system

The authors have investigated magnetocaloric effect to elevate energy quality of heat for designing an energy saving thermal process based on self-heat recuperation in previous studies. Magnetocaloric effect is a physical chemical phenomenon caused by magnetic entropy change due to a magnetic field and its temperature. A large magnetocaloric effect can be observed around Curie temperature. Ferromagnetic material below Curie temperature transforms to paramagnetic material above Curie temperature with large entropy change terms magnetic phase transition.
To apply magnetic phase transition to energy harvesting, transition temperature must be close to ambient temperature (25 °C). To adjust the transition temperature, many researchers have developed alloys. However, the magnetocaloric effect also changes depending on alloy consistent. One of the most famous material which shows magnetocaloric effect is gadolinium. The Curie temperature of gadolinium is about 19 °C. In fact, gadolinium at lower temperature than 19 °C can be a temporally magnet with magnetic field, when gadolinium cooled by lower temperature heat (< 19 °C). The magnetic moment isothermally changes at Currie temperature with magnetic phase transition. Reversely, gadolinium at higher temperature than 19 °C will lose the magnetism. Gadolinium shows the second-order transition during magnetocaloric effect as shown in Figure 1. Hysteresis loss and electromagnetic induction heating (EIH) causes irreversibility (Kitanovski and Egolf, 2009). Due to these irreversibility, the adiabatic efficiency of magnetization/demagnetization changes of gadolinium was examined about 0.92 in our previous studies (Kotani et al. 2013b). Thus, it can be said that magnetization/demagnetization changes are close to the isentropic change.

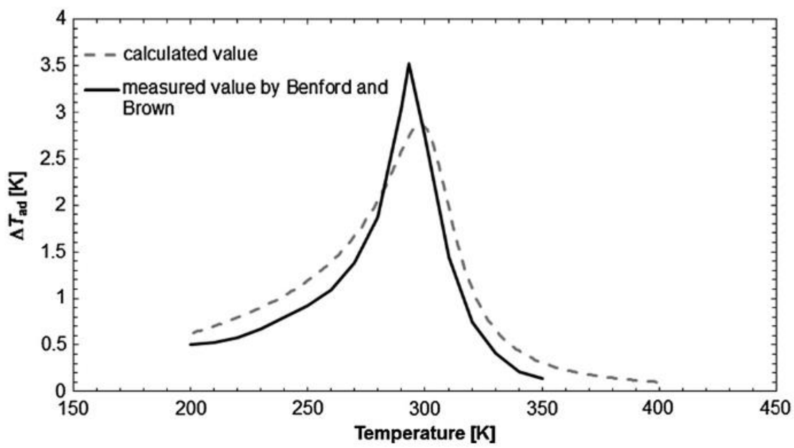

Figure 1: Comparison between calculated value (Kotani et al., 2013a) and measured value (Benford and Brown, 1981) of adiabatic temperature change when gadolinium is magnetized from 0 T to 1 T

Integrating this gadolinium temporary magnet accompanying magnetic phase transition with Faraday's law of induction, Kansha and Ishizuka (2017) proposed a new power generation system from low temperature heat for energy harvesting. The cycle of this power generation is drawn in Figure 2. Initially, gadolinium is cooled to touch with low temperature heat source below Currie temperature (< 19 °C). Then, gadolinium magnetizes and changes to ferromagnetic material (①→②). Then, ferromagnetic gadolinium is installed into a magnetic field for fixing spin direction and converts to temporally magnet. Next, this temporally magnet is put near a solenoid. At the same time, gadolinium temporally magnet is heated by higher temperature heat source than Currie temperature (>19 °C). Gadolinium temporary magnet is demagnetized and magnetic flux through the solenoid decreases by following the temperature increase of gadolinium. Thus, the electric power is generated in the solenoid due to Faraday's law of induction (②→③→①). Faraday's law of induction can be represented using Electromotive force measured by volts and magnetic flux;

$$\varepsilon = -N\frac{d\Phi}{dt} \tag{1}$$

where ε is electromotive force, N is number of turn on a solenoid, Φ represents magnetic flux, and t is time. From the Eq(1), it can be understood that electromotive force is increasing with magnetic flux change. In addition, gadolinium temporary magnet in this power generation system is demagnetized by heating from heat source (②→③), leading to reducing magnetic flux through the solenoid. Therefore, electromotive force depends on heating rate of gadolinium during heating from heat source. Furthermore, electrical power generation amount is shown by green coloured area surrounded by each change in Figure 2 from the theoretical thermodynamics cycle point of view.
The series of the proposed power generation from low temperature heat are summarized as the following steps (Kansha and Ishizuka, 2017);

Step 1. Absorb low temperature heat from a heat source below Currie temperature
(Gadolinium changes to ferromagnetic material)
Step 2. Install gadolinium into a magnetic field for fixing spin direction
(Gadolinium changes to magnet)
Step 3. Close Place gadolinium into a solenoid
Step 4. Heat gadolinium above Currie temperature
(Gadolinium changes to paramagnetic material)
Step 5. Electric power is generates generated from the solenoid

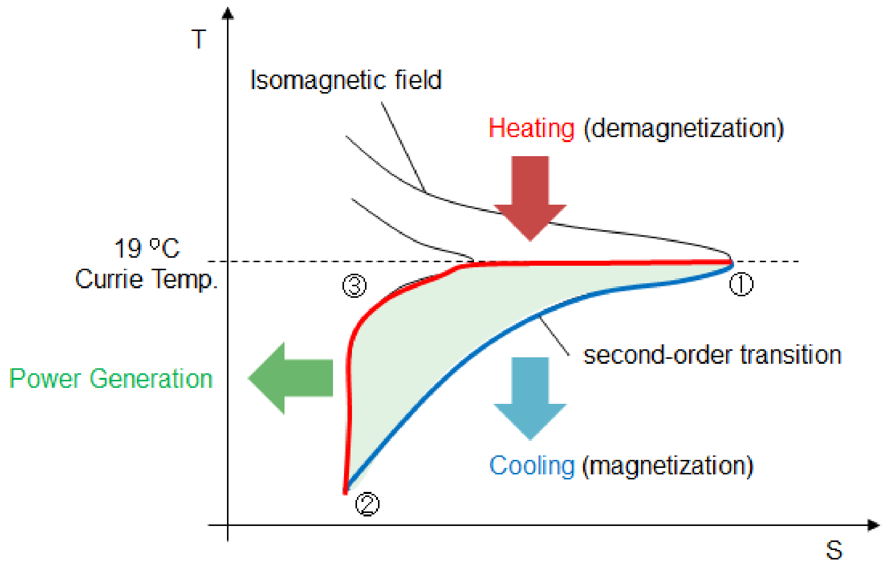

Figure 2: Thermodynamic cycle of the proposed power generation system

This cycle shown as green coloured area surrounded by each change in Figure 2 looks like a right-angled triangle. In fact, this cycle is almost same as the trilateral cycle as shown in Figure 3 which has been developed using vapor/liquid phase transition when this cycle was rotated 180 degrees. The differences between these two power generation systems are summarized in Table1. It is called that the power generation using trilateral cycle is suitable for sensible heats above ambient temperature recovery because of the minimizing exergy loss of heat transfer from heat source to working fluid as shown in Figure 3b). This is perfectly fit to the proposed power generation. Thus, the proposed system is suitable for the power generation from sensible heats below ambient temperature.

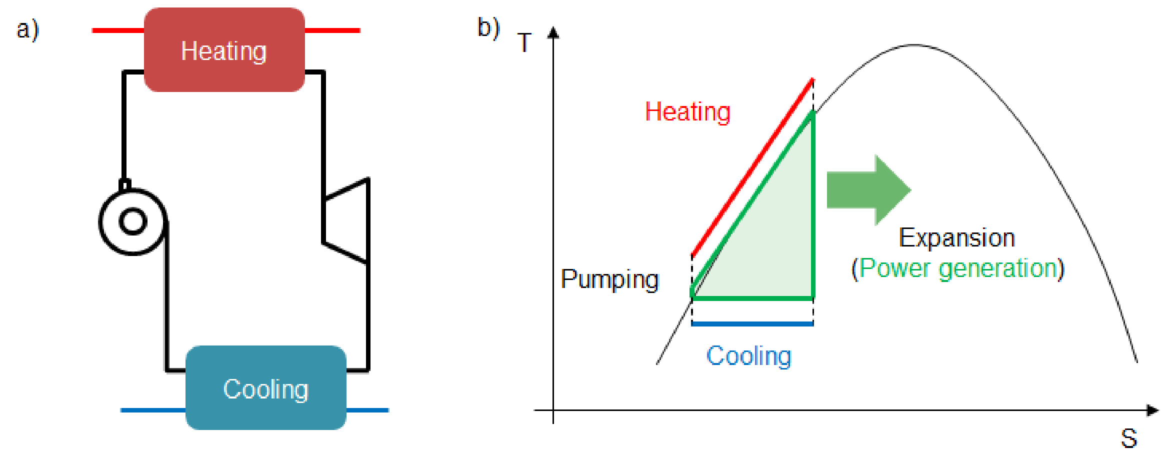

Figure 3: The images of trilateral cycle using vapor/liquid transition; a) flow diagram of power generation system, b) thermodynamic cycle

Table 1: The differences of power generation systems

	The proposed system	Power generation using trilateral cycle
Heat Source	Sensible heat below ambient temperature	Sensible heat above ambient temperature
Phase transition	Magnetic phase transition	Gas(vapour)-liquid phase transition
Transition style	Second order transition	First order transition
Working material	Magnetic materials	Vapour/liquid transition materials
Temperature	Around Currie Temperature (Case of Gadolinium: 19 °C)	Around boiling/dew temperature (Case of water: 100 °C)
Adiabatic efficiency	Relatively high (0.92)	Depends on pump and expander efficiency (expansion under liquid/vapour mixed phase)

3. Experiments

The power generation was examined by the following experiments. The experimental setup is shown in Figure 4. Gadolinium nugget (2.7 g) was prepared under refrigerator to keep the ferromagnetic conditions. Instead of installing the gadolinium into small magnetic fields to convert a temporally magnet, permanent magnet (260 mT) was attached with the edge of solenoid made of iron and 500 wired coils to create magnetic field around solenoid. By using gauss meter, the magnetic flux density of the other end of solenoid which is the nearest point to gadolinium measured 25 mT. When the gadolinium nugget in the container moved back and force around the solenoid at ambient conditions by following 35 mm arms (rotation speed: 250 degree/s), magnetic flux through the solenoid was changing follows by position of the gadolinium. By using a voltmeter and resistance (4.7 Ω), electromotive force produced following Faraday's law of induction and current were measured as shown in Figure 5. From 0.6 to 0.7 s, the large electromotive force can be observed in Figure 5. During this time, gadolinium pass through the nearest point from the solenoid. Thus, magnetic flux created by permanent magnet was affected by magnetic flux created by ferromagnetic gadolinium. To examine the power generation amount of this system, it is necessary to compare the same experiment conducting with paramagnetic gadolinium at ambient temperature. From these two experiment, 1 nW power generation during 0.1 s in 1 cycle can be observed (= 0.1 nJ).
Although the value is quite small, power generation was observed in this experiment. To acquire the large electric power, it is necessary to use high magnetic flux density and to increase the number of turns of solenoid

and cycles. In fact, that the magnetic flux density used in experiment was only 1/40 of the experiment conducted by Brown (1976) to investigate magnetocaloric effect. Furthermore, it is necessary to consider increasing heat transfer rate to affect magnetic flux created by gadolinium.

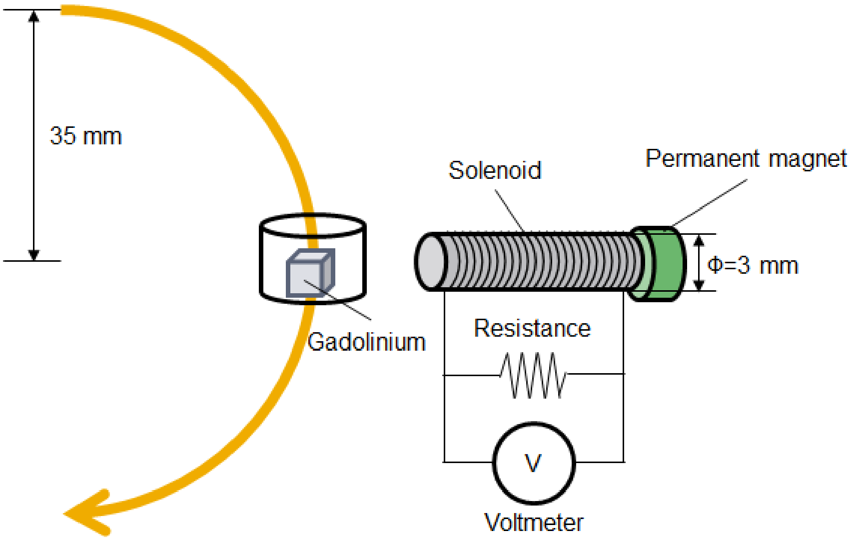

Figure 4: Experimental Setup

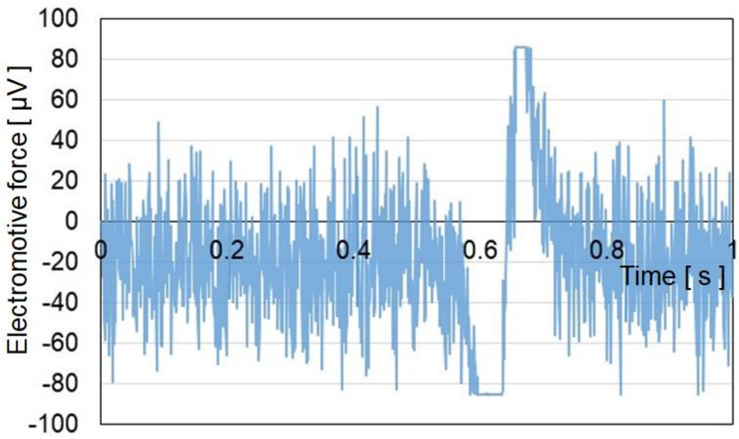

Figure 5: Electromotive force changes by experiments

4. Conclusions

In this paper, an innovative power generation system from a low temperature heat using magnetic phase transition and Faraday's law of induction has been developed and the possibility of this power generation to energy harvesting was evaluated by the theoretical thermodynamic cycle and power generation experiment. The cycle of this power generation system is close to a trilateral cycle which suitable for sensible heat recovery when achieving fast magnetic flux change. Furthermore, electric power can be generated in the experiments. Thus, it can be said that this power generation system has a great possibility for new energy harvesting from low temperature waste heat

Acknowledgments

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