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Efficient Power Generation from Low Temperature Heat Source

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Energy harvesting, which involves power generation from low level energies has attracted attention in Japan for online operation of sensor and electric devices. In this research, an innovative power generation system from a low temperature heat source was proposed and its possibility for energy harvesting applications was evaluated. In this system, low temperature (< Curie temperature) heat is absorbed by a paramagnetic material (e.g. Gadolinium) and this material is isothermally transformed to a ferromagnetic material at the Curie temperature. During this transformation, magnetic moment will be produced at isentropic conditions. Combining this temporary magnet with solenoid, electric power will be generated following Faraday's law of induction without any additional energy conversion, leading to efficient power generation. It can be said that this system has a large possibility as a new energy harvesting system.

1. Introduction

Energy-saving technologies have attracted attention due to the need for reducing carbon dioxide emission. To reduce energy consumption, many researchers have carried out exergy analysis employing the second law of thermodynamics (Myat et al., 2012).

Energy harvesting, which involves power generation from low level energies such as low temperature heat, vibration and light, has attracted attention in Japan for online operation of sensor and electric devices. The quality of these energies is so low that we can acquire only little power from them. These energies have been discarded into the atmosphere and neglected for a long time. Recently many electric devices have been developed that require small electric power to work regularly. Although the required amount of electric power is usually small, it is necessary to use large amount of electric power when these devices face extreme conditions. We must find a large amount of low level energy for such applications. Compared with the other low level energies, we can easily obtain low temperature heat around plants and local communities such as exhaust heat from heat exchangers.

Some researchers have investigated thermoelectric devices to generate electric power from low temperature heat (Shakouri, 2011). Although the thermoelectric devices can be used for energy harvesting, it is well known that the efficiency of these devices is low due to small entropy change by electron or hole transfer (Chen and William, 1996). The heat transfer surfaces cannot behave isothermally during heating and cooling by heat sources and sinks in the thermoelectric devices. It is also noted that some heat from the heating surface is directly transferred to the cooling surface without power generation because both the surfaces are connected by the device itself (Luo, 2008).

To increase power generation efficiency from heat, we must make the cycle close to Carnot cycle. It is well known that Carnot cycle consisting of isothermal and isentropic changes generates maximum possible electric power from heat following thermodynamics. At the same time, we should design power generation system directly from heat without any passway.

The authors have investigated magnetocaloric effect to elevate energy quality of heat at isentropic conditions (Kotani et al., 2013a) and this effect can be strongly observed around Curie temperature (Kotani et al., 2014a). Curie temperature is transformation temperature between ferromagnetic and paramagnetic material. Certain materials lose their permanent magnetic properties at this temperature. During this transformation, entropy

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change due to the magnetic moment change is maximised. From this investigation, the authors considered that power generation system using magnetocaloric effect as isentropic change in cycle has a great possibility to show high energy conversion.

In this research, we proposed an innovative power generation system from a low temperature heat source and evaluated its possibility for energy harvesting applications. In this system, low temperature (< Curie temperature) heat is absorbed by a paramagnetic material and this material is isothermally transformed to a ferromagnetic material at the Curie temperature. During this transformation, magnetic moment will be produced at isentropic conditions and electric power will be generated following Faraday's law of induction without any additional energy conversion.

This paper is organised as follows: Section 2 discusses the design concept of efficient power generation including the Carnot cycle, Section 3 illustrates the proposed power generation system through the combination of thermodynamics and electromagnetism concepts, Section 4 presents the theoretical discussion and the potentials of the proposed scheme, and Section 5 describes the concluding remarks for the study.

2. Design concept of efficient power generation

Figure 1 shows the conceptual temperature-entropy diagram of Carnot cycle. It can be understood that Carnot cycle consists of isothermal and isentropic changes.

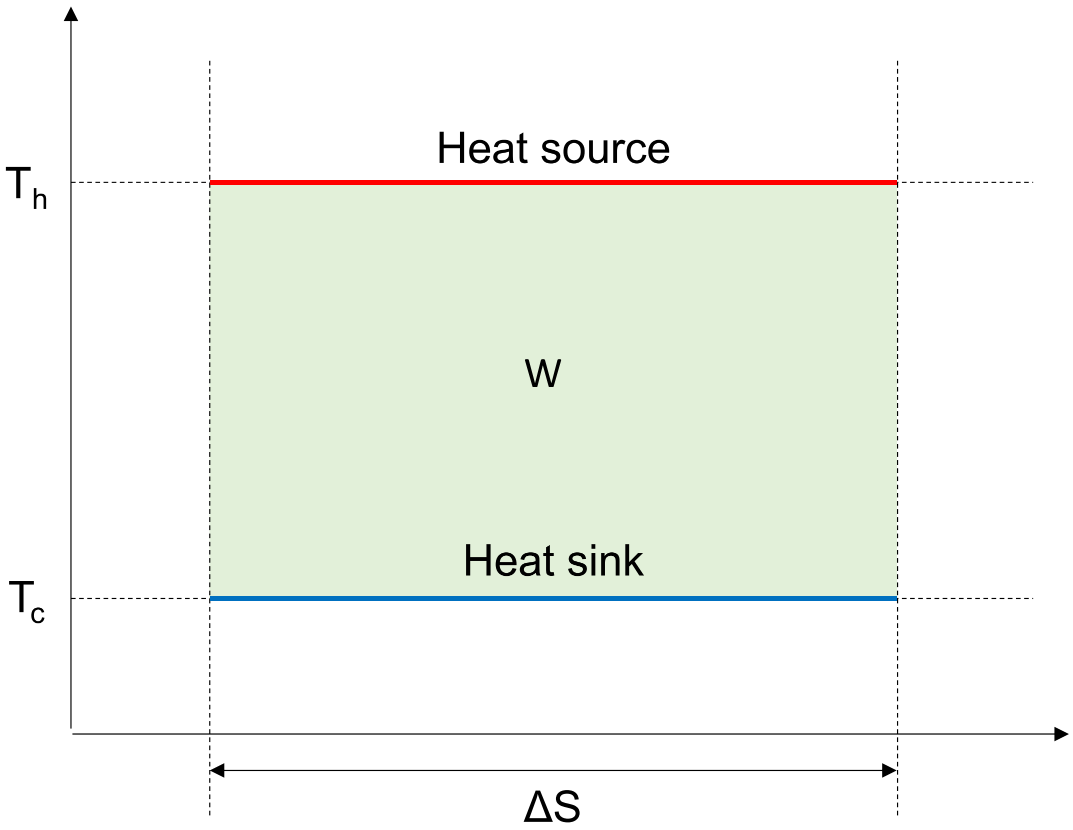

Figure 1: Temperature-entropy diagram of Carnot cycle

It is well known that green coloured area surrounded by heat source and heat sink curves (red and blue lines) shows the maximum possible work (*W*) which is represented by Eg(1) and Eq(2).

$$W = Q_{\mathrm{h}} - Q_{\mathrm{c}} \tag{1}$$

$$Q_i = \Delta S T_i \tag{2}$$

where T_{h} and T_{c} show the temperature of heat source and sink. Q_i is the heat amount absorbed from heat source (h) and supplied to heat sink (c). Δ*S* indicates the entropy change of heat source.

Theoretically, this Carnot cycle generates maximum possible electric power from heat following the second law of thermodynamics. It is necessary to make the cycle of a system close to Carnot cycle in the temperature-entropy diagram from the thermodynamics point of view in order to increase the power generation efficiency from heat. If the amounts of heat source and heat sink are large enough, the heat source and heat sink can provide and exhaust heat isothermally. According to this idea, heat surfaces consisting of latent heat exchange are suitable for power generation systems. An isentropic condition is preferable for the processes like gas compression and expansion.

3. Proposed power generation system

The authors had investigated magnetocaloric effect to elevate energy quality of heat for designing an energy saving thermal process based on self-heat recuperation in a previous study. In this process, not only latent heat but also sensible heat of the process stream is recuperated and circulated into the process without any heat addition, leading to large energy saving and exergy loss minimisation of heat transfer in the thermal process (Kansha et al., 2009). A large magnetocaloric effect can be observed around Curie temperature because maximum entropy change due to the magnetic moment change takes place at this temperature. In fact, ferromagnetic material below Curie temperature transforms to paramagnetic material above Curie temperature. This transformation leads to entropy change. For this study, we focused this phenomenon on the power generation (Kotani et al., 2014b).
One of the most famous materials that shows magnetocaloric effect at the ambient temperature (25 °C) is gadolinium. The Curie temperature of gadolinium is 19 °C. Gadolinium can be a magnet below 19 °C with magnetic field. Lower temperature heat below 19 °C can be absorbed from the heat source. The magnetic moment isothermally changes at Currie temperature. From our previous research on the magnetocaloric effect, gadolinium shows the second-order transition as shown in Figure 2.

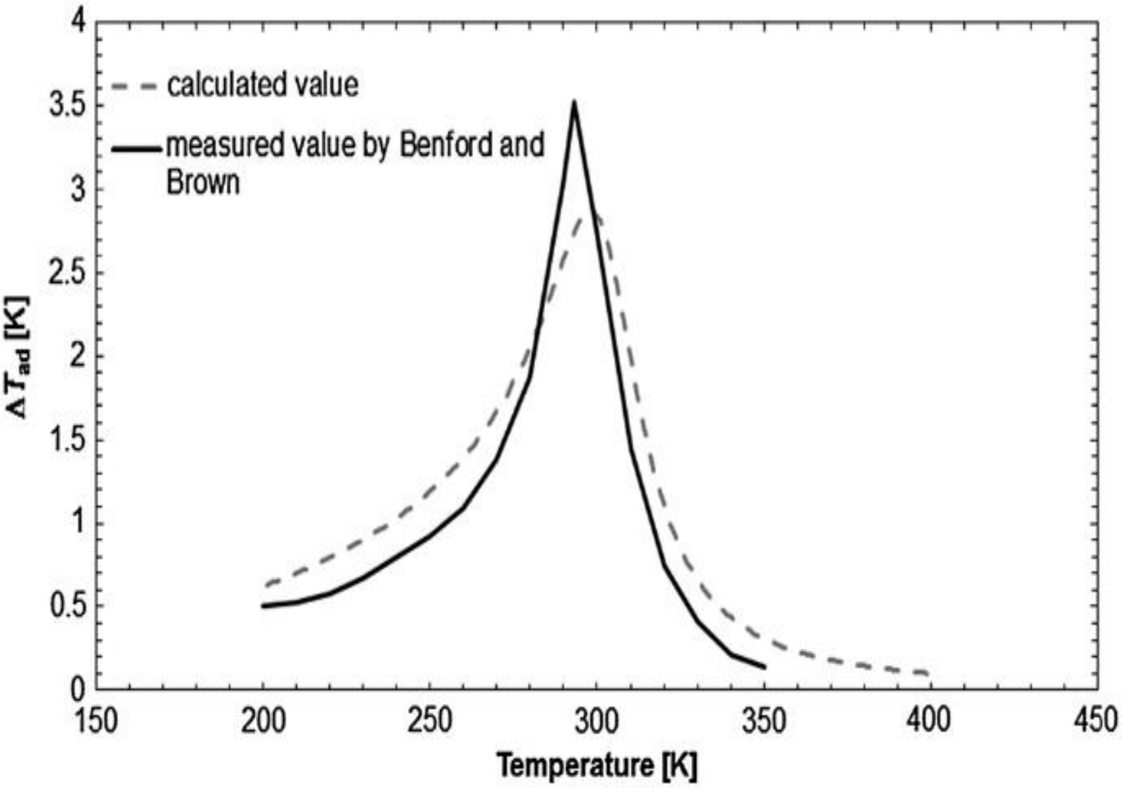

Figure 2: Comparison between calculated value and measured value of adiabatic temperature change when gadolinium is magnetised from 0 T to 1 T (Brown, 1976)

Based on the plotted data, the adiabatic temperature change when gadolinium is magnetised from 0 T to 1 T was calculated and the values were compared to the measured values determined from previous studies

(Brown, 1976). In reality, hysteresis loss and electromagnetic induction heating cause irreversibility (Kitanovski and Egolf, 2009).
The hysteresis loss depends on the physical properties of the material that is subjected to the varying magnetic flux density. The electromagnetic induction heating is the joule heat generated by the current induced by the change in magnetic flux applied to the material and the material resistance. According to these efficiencies, we found that the adiabatic efficiency of magnetisation/demagnetisation of gadolinium is about 0.92. This means that magnetisation/demagnetisation changes are close to the isentropic condition.
Combining this gadolinium temporary magnet with solenoid after absorbing low temperature heat and installing into a magnetic field for fixing spin direction, electric power will be generated following Faraday's law of induction, the electromagnetic induction. The power generation process from electromagnetic induction using solenoid is illustrated in Figure 3.
The series of the proposed power generation from low temperature heat to electric power generation are summarised as the following steps:

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. Place gadolinium into a solenoid
Step 4. Heat gadolinium above Currie temperature
(Gadolinium changes to paramagnetic material)
Step 5. Electric power is generated from the solenoid

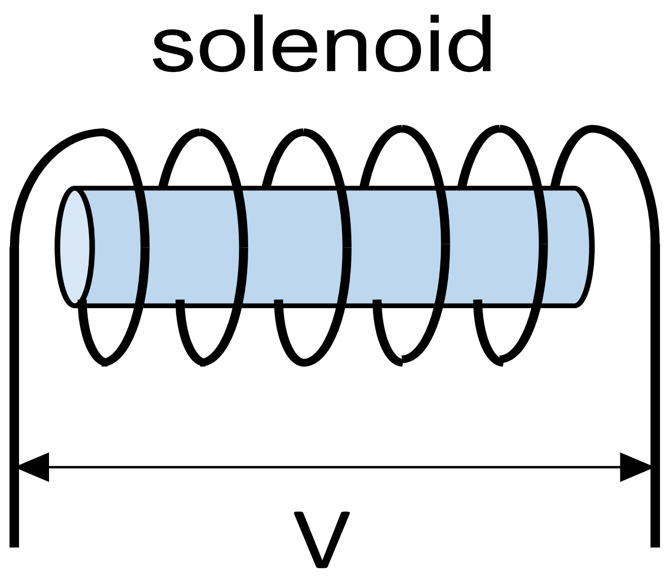

Figure 3: Power generation from electromagnetic induction

4. Discussion

Below ambient temperature, lower temperature heat has higher energy quality defined by exergy/enthalpy from the exergy point of view as shown in Figure 4. For a temperature lower than the ambient temperature, the energy quality of air continues to drop as the temperature reaches ambient temperature. In fact, there is a large amount of heat at a temperature lower than the ambient temperature in industrial plants such as exhaust heat from refrigerators, cryogenic plants, and heat exchangers. We consider utilising this low temperature and quality heat to generate electric power as a form of energy harvesting. This system can eventually be applied to an ocean thermal energy conversion, if we can scale up the electric power generation process. The authors have also reported that the temperature difference of heat transfer proportionally affects exergy loss (exergy destruction) for heating and cooling (Kansha et al., 2015).
At the same time, we can increase the generated power by adjusting the heat transfer rate by changing the heat source temperature when large amount of electric power is required. Although the temperature increase is

accompanied by the increase of exergy loss, it can be said that this system has the freedom to adjust for stable operations. It is necessary to conduct further investigations for identifying the range of adjustable parameters by experiments in the near future.

Based on the theoretical investigation, it can be understood that low power generation shows high energy conversion efficiency when requiring low power generation for regular operation of the target electric device. The loss from this system derived from the non-adiabatic changes produces heat and in turn, changes the gadolinium temperature, which results in changing the magnetic flux and generating electric power by electromagnetic induction. In this situation, this system is expected to show maximum energy conversion efficiency. Thus, it can be said that the heat transfer is a key issue for increasing power generation efficiency of this system. For this reason, we are using gadolinium particles (< 800 μm) to increase the heat transfer in our experiments.

The other concerning point is the required energy to change a ferromagnetic gadolinium to a magnet such that it is necessary to put ferromagnetic gadolinium in the magnetic field for fixing direction of spins to change to the magnet. We must pull out this gadolinium to generate power by electromagnetic induction. To pull this gadolinium, an external force is required, which causes an energy loss in the system. It is necessary to evaluate this energy loss by conducting experiments for further investigations.

Exergy loss occurs only from heat transfer between heat source and sink and the system, and adiabatic irreversibility due to hysteresis loss and electromagnetic induction heating. These exergy losses take place in any system for power generation from heat. The adiabatic efficiency of magnetisation/demagnetisation of gadolinium is about 0.92 (Kotani et al., 2013b). This value is good enough as compared with compressor and expander.

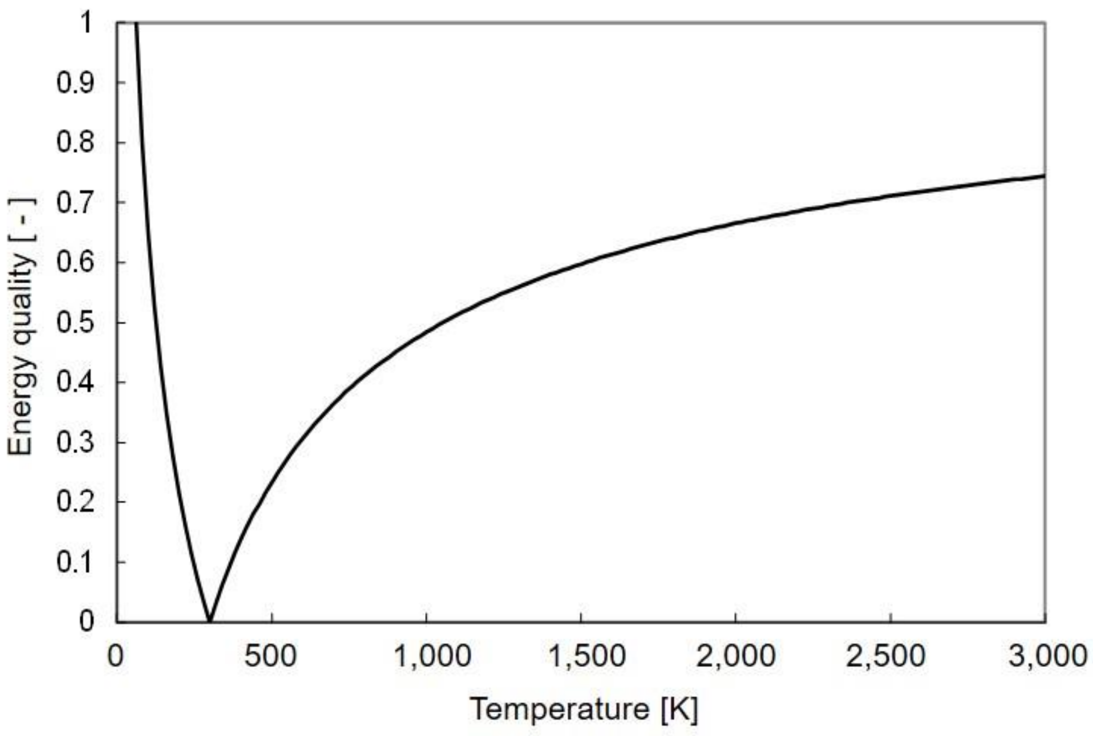

Figure 4: Energy quality of air as a function of temperature

If we are able to provide a material of which its Currie temperature is at ambient temperature, we can achieve perfect energy conversion on the exergy basis from low temperature heat to electric power using this proposed system.

Although some further investigations are still required in order to ensure the realisation of the proposed power generation system for efficient energy harvesting operation for large scale applications, it can be said that the proposed system has a large possibility to be adopted for an innovative energy efficient application from the thermodynamics and electrodynamics or electromagnetism points of view and shows new concepts and options for energy harvesting.

5. Conclusions

In this paper, we proposed an innovative conceptual design for an efficient power generation system with a low temperature heat source through the combination of thermodynamics and electromagnetism concepts and evaluated its possibility and potential to be adopted for energy harvesting applications. The study shows that perfect energy conversion on the exergy basis from low temperature heat for electric power generation can be achieved using a material with its Currie temperature at ambient temperature. Although further investigations are required to realise the proposed system for practical energy harvesting in communities and industries for large scale applications, the proposed system has a great potential and can be expected to achieve a large reduction of exergy loss in the system, leading to a high power generation efficiency as compared with conventional energy harvesting technologies.

Acknowledgments

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