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Cylindrical thermoelectric generator with water heating system for high solar energy conversion efficiency

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HIGHLIGHTS

- Proposed cylindrical thermoelectric generator for high solar energy conversion efficiency.
- Established structure and development process for cylindrical skutterudite thermoelectric generator.
- Evaluated efficiencies of the solar cogeneration system under real sunlight.
- System has high solar energy conversion efficiency, cogenerating hot water, and electrical power.

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ABSTRACT

Thermoelectric generator (TEG) with water heating system, which utilizes solar energy with a high total energy conversion efficiency, is promising environmental technology for eco-housing and factories to reduce their carbon footprints. In this study, a newly developed cylindrical TEG consisting of ring-disk thermoelectric material is proposed showing that the total energy conversion efficiency is higher than that of a conventional pillar-type TEG. The cylindrical TEG is implemented using high-performance $CoSb_3$-based filled skutterudite thermoelectric materials and a unique 45Ni-55Fe electrode as the hot-side junction. The solar TEG performance is demonstrated under the real sunlight, which is concentrated by a Fresnel lens. The maximum thermoelectric efficiency of the presented solar TEG is 1.8%, with a water heating efficiency of 59% when the temperature difference across the TEG is 428 °C. Further improvement should be achieved by lowering the internal resistance of the TEG and increasing the average dimensionless figure of merit of the thermoelectric materials.

1. Introduction

Using solar energy is a key technology for developing a sustainable future for humanity. For example, solar water heaters and solar cells have been used in eco-houses. A commercial solar water heater has a high solar energy efficiency of 40–60%, but they generally produce an excessive amount of hot water for residential consumption. On the other hand, a solar cell can generate electricity, but their solar energy conversion efficiencies in practical use are below 20%. As both hot water and electricity are indispensable for life, installing both a solar water heater and solar cell in the same house could be a suitable solution. This is, however, not realistic in practice because of the high cost and limited roof area. Therefore, a cogeneration system with a surface area equivalent to that of either a solar water heating system or a solar cell is desirable. Here, a solar thermoelectric generator with a water heating system is studied. A thermoelectric generator (TEG) is suitable for such cogeneration where a heat flow, which gives rise to a temperature difference and thereby electrical power between the hot and cold sides of the thermoelectric materials, penetrates the TEG, and is absorbed by water at the cold side. In the case of a house powered entirely by electricity, this cogeneration system could drastically save power, because heating water requires a large amount of power. In addition, the more electricity the cogeneration system can supply, the more beneficial it would be, because it can be directly integrated into the system of an all-electric house. By the way, a hybrid concentrated photovoltaic-thermoelectric system is suggested to get electrical power more than the conventional solar cell [1] but the total solar energy conversion efficiency is still lower than that of a solar water heater.

The thermoelectric efficiency of a TEG depends on the dimensionless figure of merit (ZT) of thermoelectric materials used for the TEG. ZT is defined as

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Nomenclature

ZT	dimensionless figure of merit of a thermoelectric material
σ	electrical conductivity of a thermoelectric material (S/cm)
S	Seebeck coefficient of a thermoelectric material (μV/K)
κ	thermal conductivity of a thermoelectric material (W/mK)
T	temperature of a thermoelectric material (°C)
ZT_{ave}	average ZT from the cold- to the hot-side of the TEG
T_c	cold-side temperature of TEG (°C)
T_h	hot-side temperature of TEG (°C)
ΔT	T_h–T_c (°C)
E_R	thermal radiation from materials (W)
ε	emissivity of materials
A	surface area of thermal radiation (cm^2)
T_S	ambient temperature of materials (°C)
Q_{in}	incident solar energy to Fresnel lens (W)
Q_{in}^{TE}	incident solar energy to TEG (W)
η_{op}	optical concentration efficiency ($=Q_{in}^{TE}/Q_{in}$)
A_{open}	opening area of Fresnel lens (cm^2)
D_{sun}	the global solar radiation (W/m^2)
T_{in}	temperature of the water inlet (°C)
T_{out}	temperature of the water outlet (°C)
v	water flow rate (ml/min)
T_{surf}	temperature at the TEG surface (°C)
R_{load}	load resistance (mΩ)
V_{load}	voltage across the load resistance (mV)
Q_{out}	energy collected as hot water (W)
P_{TE}	maximum electric power generated by TEG (W)
V_{oc}	open circuit voltage of the TEG (mV)
R_{in}	internal resistance of the presented TEG (mΩ)
R_{rate}	ratio of R_{in} to the ideal value, which is the sum of resistance of the thermoelectric materials used
η_{TE}	solar thermoelectric efficiency ($=P_{TE}/Q_{in}^{TE}$ (%))
η_{HW}	solar water heating efficiency ($=Q_{out}/Q_{in}^{TE}$ (%))
η_{TEG}	ideal thermoelectric efficiency (%)
η_{TEGR}	ideal thermoelectric efficiency considering thermal radiation loss (%)

$$ZT = (\sigma S^2/\kappa)T, \tag{1}$$

where σ, S, κ, and T are the electrical conductivity, Seebeck coefficient, thermal conductivity, and temperature, respectively. An averaged ZT (ZT_{ave}) from the temperature of the cold-side (T_c) to that of the hot-side (T_h) of the TEG is important for estimating the thermoelectric efficiency, which is defined as

$$ZT_{ave} = \left(\int_{T_c}^{T_h} ZTdT\right) \bigg/ (T_h - T_c). \tag{2}$$

The ideal thermoelectric efficiency (η_{TEG}) is then expressed as

$$\eta_{TEG} = \frac{T_h - T_c}{T_h} \times \frac{(1 + ZT_{ave})^{1/2} - 1}{(1 + ZT_{ave})^{1/2} + T_c/T_h}. \tag{3}$$

η_{TEG} increases with increasing ZT_{ave}, and ΔT ($=T_h$–T_c). Therefore, high-ZT materials, such as bismuth-telluride (i.e., $ZT = 1.1$@373 K (n-type) [2], 1.86@320 K (p-type) [3]), lead-chalcogenide ($ZT = 1.5$@800 K (n-type) [4], 2.3@923 K (p-type) [5]), and $CoSb_3$-based filled skutterudite ($ZT = 1.7$@850 K (n-type) [6], 1.06@700 K (p-type) [7]), are commonly used for TEG. The efficiencies of TEGs using bismuth-telluride and skutterudite were reportedly 7.2% at $T_h = 280$ °C [8] and 8.4% at $T_h = 600$ °C [7], respectively. The thermoelectric efficiency was further increased to 12% at $T_h = 576$ °C when ZT_{ave} was increased by using a segmented TEG consisting of bismuth-tellurides and skutterudites [9].

A solar TEG has been investigated in 1954 using ZnSb thermoelectric materials [10]. The solar thermoelectric efficiency of a solar bismuth-telluride TEG was 4.6% at $T_h = 200$ °C when evaluated at AM1.5G (1 kW/m^2) [11]. The efficiency increased to 7.4% at $T_h = 600$ °C when a segmented TEG, consisting of bismuth-tellurides and skutterudites, was used [12]. These solar thermoelectric efficiencies were determined using artificial sunlight. The differences between the solar thermoelectric efficiency and thermoelectric efficiency of TEG interfacing with the heat source mainly lie within the optical concentration conditions and radiation at the hot-side of the TEG. Therefore, we design optics and absorbing structures within the TEG for high solar thermoelectric efficiency instead of convectional flat panel wavelength-selective solar absorbers [11,12]. The solar thermoelectric efficiency evaluated using real sunlight was much lower, for example, that of the bismuth-telluride TEG was 0.8% [13]. One of the reasons for this may be the differences between the two light sources. To confirm the practical performance, the efficiency using real sunlight should be evaluated.

Regarding solar cogeneration system, Sundarraj et al. reported a thermoelectric efficiency of 1.2% and thermal efficiency of 61% for a solar cogeneration system, evaluated by heating experiments [14], and Zhang et al. reported a thermoelectric efficiency of 1.59% and thermal efficiency of 47.54% from a pilot experiment at 1 kW/m^2 [15]. Nia et al. experimented using real sunlight, and reported a thermoelectric efficiency of 1.7% and thermal efficiency of 51.33% [16]. For those experiments, conventional pillar-type TEGs were used. Other studies on solar TEGs were briefly described by Sundarraj et al. [17].

In this paper, a new solar TEG structure, which is a cylindrical one using ring-disk thermoelectric materials, is proposed for a cogeneration system. Note that this cylindrical TEG is different from previously reported ones such as pillar-type TEGs consisting of cylindrical thermoelectric legs [18] and cylindrical structures consisting of pillar-type TEGs [19–22]: Crane et al. [19] and Huang et al. [20] applied the TEGs to exhaust gases from vehicles; Ong et al. [21] and Manikandan et al. [22] applied to solar heat. In Section 2, the comparison of the simulation results of the cylindrical TEG with a conventional pillar-type TEG is presented. The selections of thermoelectric materials and electrodes are described in Section 3, and fabrication details of the solar TEG are presented in Section 4. In Section 5, the evaluation of the present solar TEG under real sunlight is demonstrated. Further analyses and discussions of the present system are addressed in Section 5, leading a conclusion that the present cylindrical solar TEG significantly should improve the total solar energy conversion efficiency over any conventional solar TEG.

2. Design of thermoelectric generator

Fig. 1 shows the configuration of the present system, which has a solar tracking mechanism so that the solar TEG is always facing the sun,

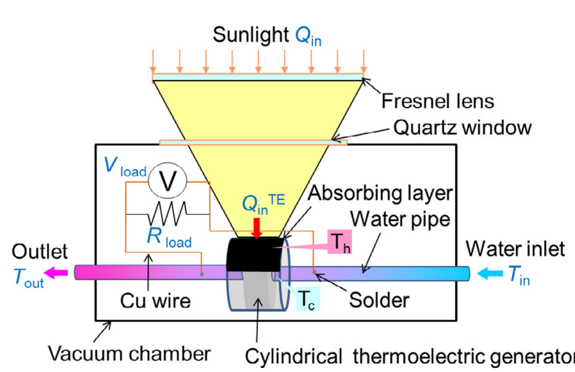

Fig. 1. (a) Configuration of the proposed cogeneration system.