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Efficiency enhancement of an industrial-scale thermoelectric generator system by periodically inputting thermal power

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ABSTRACT

This paper discusses the practicality of transferring heat energy from exhaust waste gas produced by iron and steel factories to Dowtherm T, which is employed as a heat source of a thermoelectric generator (TEG) system. The electrical performance of an industrial-level TEG system when supplied with pulsed thermal power is optimized. Heated Dowtherm T is periodically pumped into an industrial-level TEG-based heat-to-electricity conversion system (i.e., TEG unit) to generate pulsed heat power. Twelve TEGs are used in the experiments; they are evenly separated and doubly sandwiched among three heat exchangers. The conversion efficiencies at duty cycles of 21% and 46% are measured and compared. The experiments show that pulsed thermal power yields better results than the steady-state power input in terms of the conversion efficiency under the same power input conditions; the thermal power of the lower duty cycle produces a greater enhancement of efficiency. Specifically, a maximum efficiency enhancement of 3.5× is achieved for a time period of 60 min and duty cycle of 21%. These findings suggest that the thermal power input should be periodic rather than constant to greatly improve the electrical performance of an industrial TEG unit. The feasibility of employing periodic heating into waste heat recovery system is verified.

1. Introduction

Thermoelectric generators (TEGs) enable the conversion of thermal energy into electricity without any moving parts and are used for waste heat recycling to generate power from the microwatt scale [1–3] to kilowatt scale [4,5]. Their features of compactness, high level of reliability, and environmental friendliness are widely recognized, and their potential application in converting various types of heat sources into usable electricity is promising [6–10]. However, the heat-to-electricity conversion efficiency of Bi_2Te_3-based TEGs is less than 5% when the hot side of the TEG is lower than 200 °C [11–13] or higher than 500 °C [5,14]. Particularly when large-scale power production has attracted a great deal of attention [5,8,11,15] with regard to addressing the global energy shortage, such low conversion efficiency inevitably restricts the application of TEGs both at the industrial and civil level. Therefore, greatly improving the conversion efficiency is a prerequisite for diversifying the application of TEGs.

The figure of merit of a material used to manufacture the thermoelectric elements of TEGs represents its conversion efficiency. Many studies have reported that the figure of merit can be improved by synthesizing new semiconductor materials [16–19] or by reducing the dimensional structure [20–23]. However, the cost of synthesizing new materials and difficulty of fabricating TEGs with a lower dimensional structure has restricted the potential applications. As another approach, alternating temperature gradients (ATG) rather than a steady-state temperature difference has been observed to help improve the conversion efficiency of a TEG [24–27]. In addition, ATG can be applied as a heating method to every type of TEG, and it is not negatively affected by the component materials of the TEG. The fluctuating characteristics of engine operation in a waste heat recovery system make it meaningful to investigate the responses of a TEG to transient heat power [28,29]. The effect of a pulsed heat source for different heating periods, which determine duty cycles, and different time periods on the conversion efficiency of a single TEG has been studied computationally and experimentally [30]. Periodic heating has been found to significantly enhance the conversion efficiency; a maximum efficiency enhancement of 8.6× has been obtained for a duty cycle of 10% and time period of 2000 s. The periodic heating method greatly increases the TEG conversion efficiency and is a helpful technique for expanding the range of applicability of thermoelectric devices.

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Nomenclature

C	heat capacity (J kg^{-1} K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{V}$	volume flow rate (L s^{-1})
P	electric power (W)
Q	heat power (W)
R	electrical resistance (Ω)
S	Seebeck coefficient (V/K)
T	temperature (°C)
V	voltage (V)

Abbreviations

ATG	alternating temperature gradient
PH	periodic heating
SS	steady-state
TEG	thermoelectric generator

Greek letters

Δ	difference
η	conversion efficiency
ρ	density (kg m^{-3})

Subscripts

c	cold
c-in	inlet of cold side
c-out	outlet of cold side
h	hot
h-in	inlet of hot side
h-out	outlet of hot side
in	input
in-PH	input under periodic heating
INT	internal
out	output
out-PH	output under periodic heating
out-ss	output under steady–state heating

Mid-temperature exhaust gas (250–500 °C) produced by iron and steel factories carries away a huge amount of heat energy. Therefore, recycling and converting it into usable electricity can be profitable. The present authors designed a TEG conversion system that uses Dowtherm T heated up by exhaust gas as a heat source. Fig. 1 shows a schematic diagram of the design. The electric power generated by a TEG (which indicates the temperature difference on both sides of a TEG) has been reported to be affected when the flow rate of exhaust gas is modified [31]. Therefore, a practical approach is to generate periodic thermal power by controlling the heat source to optimize the electrical performance of a TEG system. As the first and most important stage of research, the present paper introduces the alternating heating method into a system that employs 12 TEGs as an energy conversion unit. The effect of a pulsed thermal power input compared to a steady-state power input under the same average power input conditions for a given time period on the conversion efficiency is observed. The results suggest that the thermal power input should be periodic rather than constant to greatly improve the electrical performance of an industrial TEG-based heat-to-electricity conversion system.

2. Experiment

Fig. 2 shows a schematic diagram of the present first-stage experimental system. The experimental facility consists of an energy conversion system (i.e., TEG unit), a heating system comprising an oil tank and mechanical pump, a chiller, and a data acquisition system that is not shown here. The TEG unit comprises three heat exchangers (150 mm × 120 mm × 3 mm) and 12 TEGs (endurable temperature < 200 °C). One heat exchanger has hot fluid flowing through to provide heat to the system, and the other two have cold water to keep the temperature of the cold side constant. The TEGs are of the same type (TEG1-199-1.4-0.5) and have the same dimensions (44 mm × 40 mm × 0.3 mm), as shown in Fig. 3a and b. The number of TEGs is set to 12 in order to fully exploit the surface area of the heat exchangers. They are separately

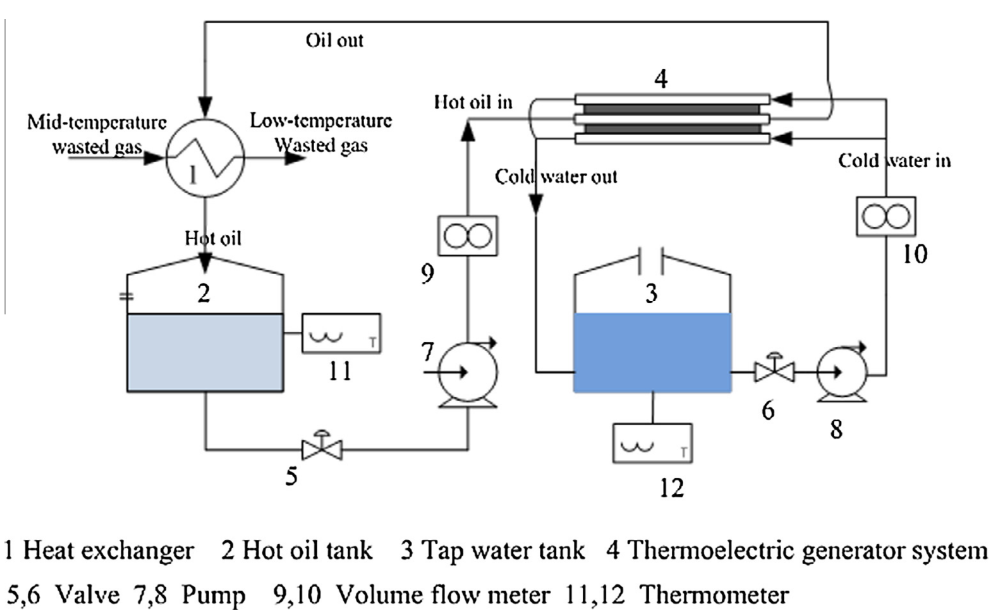

Fig. 1. Schematic diagram of a TEG unit and waste heat recovery unit combined system.