Applied Energy 160 (2015) 843–852

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A novel thermoelectric generation system with thermal switch ☆

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HIGHLIGHTS

- A new thermal switch method was proposed to improve the output performance of TEG system with fluctuating heat source.
- The turning on temperature and turning off temperature of the TEG system with thermal switch can be easily set to maximally increase the output power and electricity efficiency.
- A one-dimensional dynamic model considering the thermoelectric effects depend on the temperature was put forward to analyze the detailed characteristics of the new system with thermal switch.
- An integrated experimental platform has been built to verify the validity of the new TEG system by experimental data.

ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form 18 November 2014
Accepted 21 November 2014
Available online 6 December 2014

Keywords:
Thermoelectric generation
Heat source fluctuation
Thermal switch
Dynamic model

ABSTRACT

The stability of output performance plays a very important role in the thermoelectric generation (TEG) system since the fluctuation problem of heat source widely exists in the industry which releases the waste heat, and the fluctuating process will cause the instability and low efficiency of the TEG system. In this article, a novel TEG system with thermal switch was proposed to address this serious problem. In order to obtain the detailed characteristics of the TEG system with thermal switch, experimental and dynamic modeling methods were employed. The experimental and modeling results show that the thermal switch can efficiently reduce the temperature fluctuation and increase the output power and efficiency of the TEG system; in addition, there is an optimal turning on/off temperature to maximally increase the output power and electricity efficiency of the TEG system. The comparison between the numerical data and the experimental results has further demonstrated the proposed model.

1. Introduction

Thermoelectric generation (TEG) is a promising technology which can convert heat into electricity directly by thermoelectric (TE) materials. It is an entire solid-state energy conversion process with many merits [1]. A typical TE device is always environmentally-friendly, quiet, reliable, compact, and has a long operating life. Due to the growing energy and environmental crises, the study on green energy technology has attracted extensive attention, including the TEG technology [2–8]. However, the development of TEG technology is greatly restricted by the low heat-to-electricity conversion efficiency of TE material. Besides improving the figure of merit (ZT) of TE material, system structure optimization is an effective and widely used approach.

TEG is a heat engine with internal and external irreversible heat transfer process, and there are many factors that can influence its performances. According to Chen et al. [9,10], the number of TE elements and heat transfer surface area of TEG play the most important roles in its power output and efficiency. Astrain et al. [11] carried out a computational study about the influence of the thermal resistances of the heat exchangers on the efficiency of a TEG device. Meanwhile, a complete numerical model of TEG with finned heat exchangers has been established to investigate the influence of various irreversibilities by Meng et al. [12]. Gou et al. [13] found that besides increasing waste heat temperature and the number of the TE modules in series, expanding heat sink surface area and enhancing cold-side heat transfer capacity in a proper range can also improve the performance of TEG system. Overall, an appropriate system structure is vitally important to TEG system.

☆ This paper is included in the Special Issue of Energy innovations for a sustainable world edited by Prof. S.k Chou, Prof. Umberto Desideri, Prof. Duu-Jong Lee and Prof. Yan.

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http://dx.doi.org/10.1016/j.apenergy.2014.11.049
0306-2619/

Nomenclature

Abbreviation

EMF	electromotive force
HSD	heat storage device
PWM	pulse width modulation
TBD	thermal buffering device
TE	thermoelectric
TEG	thermoelectric generator
ZT	figure of merit

Greek script

α	Seebeck coefficient (V/K)
Δ	increment
η	efficiency (%)
τ	Thomson coefficient ($V\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)

Latin script

A	area (m^2)
c	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
E	electromotive force (V)
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I	current (A)
m	the number of control volume
M	number of modules
n	number of thermocouples
P	power (W), perimeter (m)
q	inner heat source (W)
Q	power (W)
r	resistance (Ω)
S	contact surface
T	temperature (K)
U	voltage (V)
x	heat transfer direction

Subscript

a	air
c	cold side
ccs	copper conduction strip
cs	ceramic substrate
f	cooling fluid
fp	fixed plate
h	hot side
heb	heat exchanger base
hsd	heat storage device
in	input
off	turning off
on	turning on
s	heat source
sc	semiconductor
sl	solder layer
+	the top boundary surface
−	the bottom boundary surface

Recently, TEG systems are applied to use different types of heat sources to comprehensively utilize energy sources. Nuwayhid et al. [14–16] demonstrated a low cost stove-TEG combined maximum achievable power with acceptable economic performance. It is a feasible choice for remote regions where constant electric power supply cannot be relied upon. Qiu and Hayden [17,18] set up a self-powered residential heating system which integrated TE power generation system with combustion system. The electricity generated by TE modules cannot only power all electrical components for the residential central heating system, but also be used to charge batteries or provide electricity for other electrical loads. The applications of TE technology on waste heat recovery for automobile engines are studied by many researchers. Hsiao et al. [19] developed a TEG and cooling system to improve the efficiency of an IC engine. They found that the TE modules presented better performance on the exhaust pipe than on the radiator. Cheng et al. [20] assembled 24 TE modules to convert heat from the exhaust pipe of an automobile to electrical energy. The maximum power output achieves 12.41 W at average temperature difference of 30 K when engine speed boosts to 3500 RPM. As for the utilization of solar energy, four systems were set up by Chávez-Urbiola et al. [21] to investigate the possibility of using TEG in solar hybrid systems. The economy and feasibility of the hybrid systems are discussed in detail.

Normally, the hot side temperature of TEG is not always stable when applied to heat sources as mentioned above, and the stability directly affects the characteristics of the whole system. The performance of TEG is sensitive to the temperature on both sides of TE modules. That is to say, the fluctuant of the heat source can affect the output performance of TEG dramatically. Crane and Bell [22] described a design concept to maximize the performance of TE power generation system which worked over a broad dynamic range of thermal input power. Significant improvement can be achieved in the new system structure. Mizuno et al. [23] fabricated and examined a thermal buffering device (TBD) which was inserted between the heat source and the TE module to stabilize the heat input of TEG and to protect the module from large temperature fluctuations. They confirmed that an appropriate TBD could significantly reduce fluctuations of heat input and guarantee stable electric power supply from TEG.

Based on thermoelectric theory and all the studies above, one can come up with a general conclusion that the larger temperature difference between the hot side and cold side of a TE module usually means higher power generation efficiency. That is, the low heat source temperature means low power output and power generation efficiency with the same cooling condition on cold side. Moreover, the fluctuation of heat source will lead to rapid change of output power (P_{out}) generated by a TEG system. In this case, P_{out} may not be utilized by electric devices or stored by current condensers, and even dangerous to them.

In this paper, we dedicate to improving the system efficiency and stability of TEG system under frequently fluctuant heat source. Firstly, based on the basic concept of thermal switch proposed by McCarty et al. [24,25], a new TEG system with thermal switch was proposed. Then, a detailed numerical model including the Thomson effect and temperature dependent material properties has been established. In addition, a corresponding experimental apparatus has been designed and assembled to comparatively study the two TEG systems. Both experimental and numerical results indicate that the thermal switch presents an excellent effectiveness to upgrade the performance of TEG system under unstable heat source.

2. Modeling and simulation analysis

2.1. Fundamental of the new TEG system with thermal switch

The schematic diagram of the new TEG system with thermal switch is shown in Fig. 1. The turning on and turning off temperature of the thermal switch are preset as T_{on} and T_{off} respectively.