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Modeling and performance analysis of a two-stage thermoelectric energy harvesting system from blast furnace slag water waste heat

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ABSTRACT

A physical and numerical model of two-stage thermoelectric energy harvesting system driven by blast furnace slag water waste heat is established. The performance of the system with counter-flow type heat exchangers is investigated by numerical simulation. In the case of the temperatures of heat reservoirs change over flow passage, the effects of inlet temperature of flushing slag water, convective heat transfer coefficient and flow passage length on the power output, efficiency, maximum power output and maximum efficiency as well as optimal resistance ratio of the system are analyzed. Moreover, the electrical current range corresponding to the maximum power output and maximum efficiency is obtained. Simulation results show that the maximum power output of 0.44 kW and maximum efficiency of 2.66% are available with inlet temperature of blast furnace slag water at 100 °C if load resistance is matched. The optimal resistance ratio corresponding to the maximum power output is about 1.13.

1. Introduction

Thermoelectric generation is classified as direct power conversion [1–5]. It has lots of features and advantages compared with traditional generators, for example, the absence of moving components results in an increase of reliability, and reduction of extra maintenance; the modularity can provide a wide-scale application without significant losses in performance. Besides, these devices produce no noise and waste in the conversion process. Therefore, thermoelectric generator has been regarded as a useful and attractive device for direct energy conversion [6–10] and potential application in waste heat recovery [11–14].

As energy shortage and environmental deterioration are growing, energy saving and emission reduction have become global obligation and responsibility [15–19]. Yu and Zhao [15] employed hot and cold water as heat reservoirs and analyzed the performance of thermoelectric generator with the parallel-plate heat exchanger. Meng et al. [16] established a numerical model of commercial thermoelectric generator with finned heat exchangers taking into account inner and external multi-irreversibilities. Gou et al. [17] established a dynamic model for waste heat recovery in thermoelectric generator to assess the effects of heat reservoirs on the dynamic characteristics. Kazuaki et al. [18] analyzed energy economy for a combined thermoelectric generator on top of a steam turbine cycle, and demonstrated the advantage of adding a thermoelectric on top of a steam turbine cycle. Stevens [19] established an energy harvesting device that produces milliwatt-scale power uses a thermoelectric generator operating between the air and ground temperatures.

Since the single stage thermoelectric generator cannot operate in the case of large temperature range [20–25], and due to the performance limits of thermoelectric materials and requirements of adapting different heat reservoir conditions, some authors have investigated the performance of thermoelectric generator composed of two stages and more [26–32].

In the process of promoting the transformation of materials in the iron and steel industry, rich and variety of waste heat is generated. Taking advantage of these waste heats can effectively reduce energy consumption [33–35]. Chen et al. [36] provided an overview of residual heat recovery in iron and steel enterprises in China based on single stage and multi-element thermoelectric generation, and the calculations showed that electricity power of 21 kWh, 43 kWh and 60 kWh can be recovered from 1 GJ waste heat with temperature difference of 100 °C, 200 °C and 300 °C, respectively. Meng et al. [37] established a model of single stage

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Nomenclature

A	area (m^2)
B	flow channel width (m)
c	specific heat capacity at constant pressure (J kg^{-1} K^{-1})
G	mass flow rate (kg s^{-1})
H	flow channel height (m)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
I	electrical current (A)
K	thermal conductance (W K^{-1})
L	length (m)
P	power output (W)
Q	heat flow rate (W)
R	electrical resistance (Ω)
r	load resistance ratio
T	thermodynamic temperature (K)
t	Celsius temperature (°C)

Greek symbol

α	Seebeck coefficient (V K^{-1})
σ	electrical conductivity (Ω^{-1} m^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
θ	fill factor
η	conversion efficiency

Subscripts

c	cold junction
f	flow passage
g	air gap
h	hot junction
L	load
m	intermediate junction
1	heat source
2	heat sink

and multi-element thermoelectric generator driven by blast furnace slag flushing water sensible heat with parallel-flow type heat exchangers, and analyzed the power and efficiency performance, as well as the recovery period of the equipment cost.

On the basis of research achievements mentioned above, this paper will establish a physical and numerical model of two stage thermoelectric energy harvesting system driven by blast furnace slag water waste heat, and analyze the effects of key parameters on the power output, efficiency, optimal electrical current as well as optimal resistance ratio of the system.

2. Harvesting system setup and model

A schematic diagram of the harvesting system driven by blast furnace slag water waste heat is shown in Fig. 1. The system is consisted of two parts. The first part contains two heat exchangers between heat reservoir and two-stage thermoelectric generator module. As is well known, the performance of counter-flow heat exchanger is better than that of parallel-flow one, this paper aims at discussing the system's performance with counter-flow type heat exchangers between blast furnace slag water and cooling water. The second part is the two-stage thermoelectric generator. The waste slag washing water flows through the hot-side heat-exchanger channels and heats the upper surface of thermoelectric module. The cooling water driven by a pump flows through the cold-side heat-exchanger channels and absorbs heat from the lower surface of thermoelectric modules.

The generator consisted of a top stage and a bottom stage with the same pairs of thermoelectric elements. Each element is composed of p-type and n-type semiconductor legs. The thermoelectric power-generation element is assumed to be insulted, both electrically and thermally, from its surroundings, except at the junction-reservoir contacts and the junction between the two stages. The structure parameters of two heat-exchangers and the geometric dimensions of each element of the two-stage modules are assumed to be the same.

The thermodynamic model of two-stage thermoelectric generator system driven by blast furnace slag waste heat is shown in Fig. 2. The temperatures of slag washing water and cooling water are $T_1(x)$ and $T_2(x)$, respectively. The temperatures of the hot-junction and cold-junction are $T_h(x)$ and $T_c(x)$, respectively. The top stage and bottom stage of the thermoelectric generator are assumed to be well contacted, so the thermal contact resistance between the two modules is neglected. The temperature of the cold-side junction of top stage and the temperature of the hot-side junction of bottom stage are assumed to be the same, i.e. $T_m(x)$.

Since the thermoelectric thermocouples are not closely packed for insulation, there exists an air gap between the thermocouples. Thus heat flow from the heat reservoir directly flows through the air gap rather than through the thermocouples, and the heat flow is

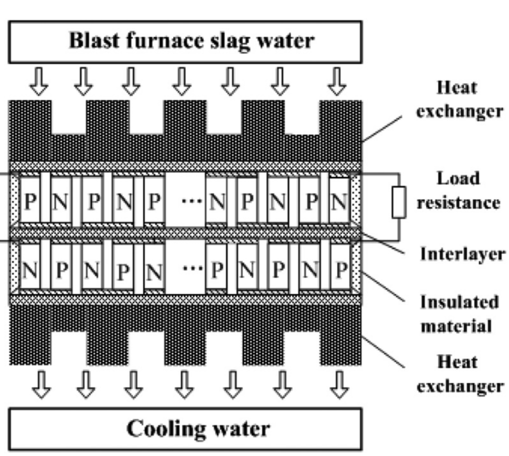

Fig. 1. Schematic diagram of two-stage thermoelectric generator system driven by blast furnace slag water waste heat.

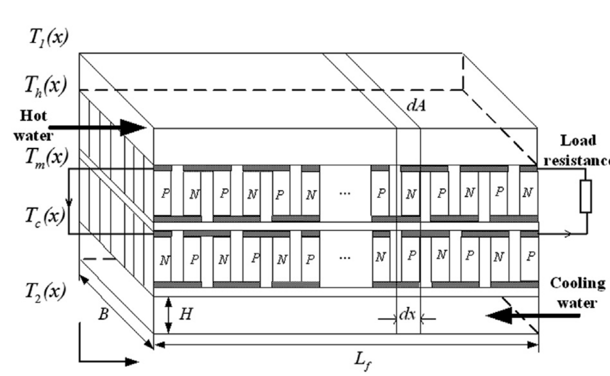

Fig. 2. Thermodynamic model of two-stage thermoelectric generator system driven by waste heat.