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Thermoelectric power generation driven by blast furnace slag flushing water

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ABSTRACT

Focusing on the low recycling rate of low temperature waste heat in China's iron and steel industry, this study presented a technical solution recycling blast furnace slag flashing water sensible heat based on thermoelectric power generation. The physical and numerical models are established. The effects of some key parameters such as slag washing water temperature, the thermoelectric element length, the packing factor of the thermoelectric module and heat exchanger flow passage length on the performance of the thermoelectric power generation device are analyzed. The results showed that for blast furnace slag flushing water at 100 °C, water temperature drops 1.5 °C per meter, about 0.93 kW electrical energy can be produced per area and conversion efficiency of 2% can be achieved. The cost recovery period of the equipment is about 8 years.

1. Introduction

The energy consumption has become one of the main problems which restricts the sustainable development of China. The recovery and utilization of different kinds of waste heat can effectively reduce energy consumption. The research of the recovery and utilization of waste heat becomes very important [1–4].

Iron and steel industry waste heat is rich, variety and in a wide temperature range. Taking advantage of these waste heat is of great significance for reducing energy consumption and emissions [5]. According to the statistics of China's iron and steel enterprises, the average recovery of waste heat resources is only 25.8% while low temperature waste heat recovery rate is less than 1%.

Power generation is the highest value utilization among various waste heat utilization forms. However, the lower waste heat temperature, the lower efficiency of power recovery and the greater difficulty from a technical perspective. Conventional steam turbine power generation system cannot be used for low temperature waste heat power recovery [6]. For the blast furnace, converter and electric furnace slag sensible heat, only water quenching method recovering hot water has been applied while the others are still in the experimental research stage [7]. Using the flashing water sensible heat to heat the residents in winter is the main utilization way in China. This simple and low-cost way has been widely used but has two problems: first, slag water contains a great deal of heat but the heating load is small usually. Second, heating is only applicable in northern China cities in winter while the southern cities and summer have no such needs [8].

Thermoelectric power generation is one of the three most potential power generation technologies in the 21st century. In recent years, with improved conversion efficiency and dropped cost of thermoelectric materials, thermoelectric power generation technology has moved from the aerospace, military and other frontiers toward the industrial and people's life. In the field of low-grade waste heat utilization, thermoelectric power generation technology can compete with conventional power generation technologies and become the main way of low-grade thermal power generation gradually [9].

According to the market statistics, in the field of thermoelectric materials consumption, low-grade thermoelectric power generation accounts for 30% market share, which exceeds cooling and heating. Thermoelectric-based power generation technology recycling industrial waste heat has become one of the research hotspots in the energy saving field. Suzuki and Tanaka [10–13] designed a series of thermoelectric generators and deduced analytical

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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	convective heat transfer coefficient (W m^2 K^{-1})
I	electrical current (A)
K	thermal conductance (W K^{-1})
L	length (m)
N	number
P	power output (W)
p	power-per-area (W m^{-2})
Q	heat flow rate (W)
R	electrical resistance (Ω); thermal resistance (m^2 K W^{-1})
T	thermodynamic temperature (K)
t	Celsius temperature (°C)
u	velocity (m s^{-1})

Greek letters

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

Subscripts

1	hot fluid
2	cold fluid
c	cold junction
cp	ceramic substrate of thermoelectric module
ex	heat exchanger
f	flow channel
g	air gap
h	hot junction
L	load
n	N-type semiconductor leg
p	P-type semiconductor leg

expressions of electric power in case of the cylindrical thermoelectric tubes, flat thermoelectric panels, cylindrical double tubes, multiple cylindrical tubes exposed to two thermal fluids. Their research has important significance for large-scale thermoelectric power generation. Yu and Zhao [14] presented a numerical model to predict the performance of thermoelectric generator with the parallel-plate heat exchanger. The simulation results showed that the variations in temperature of the fluids in the thermoelectric generator are linear. Niu et al. [15] constructed an experimental thermoelectric generator unit incorporating the commercially available thermoelectric modules with the parallel-plate heat exchanger. They found that the hot fluid inlet temperature and mass flow rate significantly affect the maximum power output and conversion efficiency. Astrain et al. [16] calculated the efficiency of a thermoelectric generation using the heat of the smoke from a paper mill's combustion boiler as heat source. The results demonstrated that it was possible to generate about 1 kW per meter of chimney height, that is, about 300 W/m^2. Meng et al. [17] established a numerical model of commercial thermoelectric module with finned heat exchangers. Hot water at 60–100 °C and cold water at 27 °C were employed as heat source and sink of the generator module. The results showed that the maximum power output of 0.13 W and the maximum efficiency of 0.87% were available from a module. Jang et al. [18] investigated the power output performance of the TEG module which embedded in the chimney walls. The three-dimensional turbulent flow in a chimney used for venting flue gas from either a boiler or stove was analyzed. Lu et al. [19] tried to conceptually combine exhaust heat exchanger with muffler in the form of 1-inlet and 2-outlet, 2-inlet and 2-outlet as well as the baseline empty cavity. The test results showed that 1-inlet and 2-outlet increased hydraulic disturbance and enhanced heat transfer, resulting in the more uniform flow distribution and higher surface temperature than the others.

On the basis of research achievements mentioned above, this paper presents a thermoelectric power generation technology-based blast furnace slag flushing water waste heat recovery solution. The physical model is established and numerical examples are provided to analyze the key design parameters of the device. Finally, economic analysis is performed adopting commercial thermoelectric module specifications. The results may provide some guidelines for the applications of thermoelectric power generation technology in industrial waste heat recovery.

2. Flushing slag water driven thermoelectric power generation device and the physical model

Flushing slag water is continuous fluid form of waste heat. The heat transfer and energy conversion of recycling process based on thermoelectric power generation technology can be described as: the hot fluid (blast furnace slag water) temperature decreases gradually along the flow. Meanwhile, part of the heat rejected is taken away by the cold fluid (cooling water at room temperature); the other part of the heat is recovered by the thermoelectric power generation modules and converted to electrical energy.

The blast furnace slag water waste heat recovery system based on thermoelectric power generation technology is shown in Fig. 1. It is mainly composed of two parts. One is the thermoelectric power generating module which can convert thermal energy to electrical energy. Another is the heat exchanger between thermoelectric modules and waters. The structure of the flow channel cross-section of the plate–fin heat exchanger is shown in Fig. 2. A P-type and an N-type semiconductor leg compose a thermoelectric element. Due to the insulation requirements and process limitations, thermoelectric elements cannot be closely arranged and then a air gap exists inside the module. This causes part of the heat flows through the air gap directly (gray arrows in Fig. 1).

The physical model of the flushing slag water driven thermoelectric power generation device is shown in Fig. 3. This model

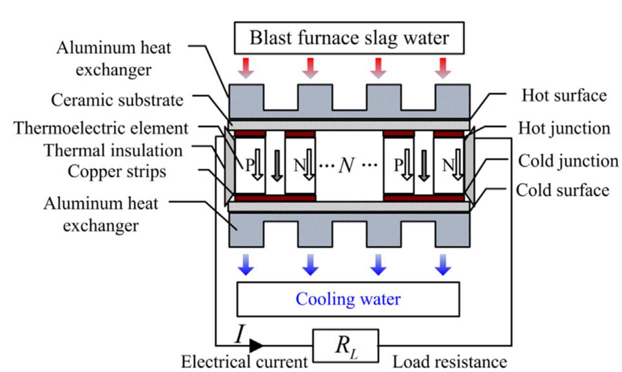

Fig. 1. Schematic diagram of the blast furnace slag water heat recovery device based on thermoelectric power generation technology.