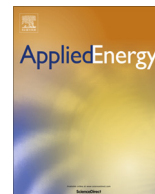




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Waste heat recovery through plate heat exchanger based thermoelectric generator system

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HIGHLIGHTS

- The HE-TEG system can realize low grade waste heat recovery by heat exchange and thermoelectric power generation.
- The heat exchange efficiency of the metal foam-filled plate heat exchanger is tested as 83.56%.
- Several methods have been proposed to improve TEG output.

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ABSTRACT

A new type of open-cell metal foam-filled plate heat exchanger based thermoelectric generator system (HE-TEG) is proposed to utilize low grade waste heat. This system can realize waste heat recovery through heat exchange and thermoelectric (TE) power generation. An experimental prototype is constructed to demonstrate the feasibility. High heat exchange efficiency of 83.56% between heated air and cold water is achieved. The maximum open circuit voltage of 16 TE couple is 108.1 mV. Several improving methods have been proposed and experimented, including adjustment of the cold water flow rate, enhancement of the heated air inlet temperature and increase of the number of TE couples. The performances of heat exchanger (HE) and thermoelectric generator (TEG) are discussed, respectively.

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1. Introduction

Nowadays, energy problems have become worldwide focuses [1]. Several national problems, such as, energy security, energy prices, increasingly competitive global markets and stringent environmental emission regulations, are primary driving forces in the search for efficient, sustainable and economically viable technologies for energy conversion and utilization. The process industries of the chemicals, food and drinks, steels and iron, pulps and paper are substantial energy users, which represent more than 50% of the industrial energy usage [2]. Hendricks and Choate [3] reported that 33% of the manufacturing industrial energy was discharged directly to the atmosphere or cooling systems as waste heat, due to the fact that most industries were incapable of recycling excessive waste heat. Moreover, the global energy demand will increase by almost 35% by 2030 compared with the 2005s level or by up to 95% without the use of energy efficient technologies [2].

Great efforts have been made in improving the energy conversion efficiency, but a considerable amount of energy is still wasted in forms of gas, liquid and solid, which requires large scope of waste energy recovery. The high and intermediate temperature waste can be directly utilized by driving steam turbine and gas turbine to generate electricity, but there are still difficulties in the utilization of waste heat in low-temperature range. TEG technology shows advantages in low grade waste heat recovery [4–8], considering its entire solid state energy conversion mode. Compared with the conventional methods, TEG technology has no moving parts, and it is compact, quiet, highly reliable and environmentally friendly.

The thermoelectric generator applications in the recovery of industrial waste heat have been discussed repeatedly. Chen et al. [9] analyzed the case of integrating TEG into thermal energy systems, especially heat exchangers and cooling systems of the combined heat and power production. Dan et al. [10] proposed a liquid metal based TEG system which served to harvest waste heat with the efficiency of 2%. Gou et al. [11] presented suggestions to enhance the TEG performance, such as increasing the waste heat temperature, expanding heat sink surface area in proper range and enhancing cold-side heat transfer capacity. As the source that

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Nomenclature

Abbreviation

HE	heat exchanger
HE-TEG	heat exchanger based thermoelectric generator
TE	thermoelectric
TEG	thermoelectric generator

Symbols

c_p	specific heat capacity (kJ/(kg K))
P	pumping power
PPI	pores per inch
q_m	mass flow rate (kg h ⁻¹)
q_v	volume flow rate (m ³ /h)
T	temperature (°C)

Greek symbols

Δp	pressure drop (Pa)
η	heat exchange efficiency
ϕ	actual heat flux (W)
ϕ_{max}	maximum heat flux (W)

Subscript

c	cold water
h	heated air
in	inlet
out	outlet

TEG utilizes is low grade waste heat, cheap or free, and there is no consume of fresh fuel for electricity production, it will be able to obtain additional benefits in terms of an improved overall efficiency. In addition, the energy conversion efficiency is quite attractive when the TEG works in a parasitic mode.

Most of TEG applications in waste heat recovery involved in effective heat exchangers [6,12,13]. In terms of heat transfer enhancement, filling metal foams in the flow channel is an attractive method. According to the research of Lu et al. [14], the heat transfer rate was enhanced by more than 15 times by inserting the metal foams in the flow channel. Mahjoob and Vafai [15] showed that inserting metal foams in the double pipe heat exchanger can significantly increase heat transfer rate at the expense of increased pressure drop. Recently, it is proposed to use metal foam heat exchanger instead of the air-cooled finned heat exchanger [16] and the conventional finned-tube heat exchanger [17]. Hsien et al. [18] experimentally studied the heat transfer characteristics of several heat sinks made of metal foams with different porosity (0.87–0.96) and PPI (10–40). Mancin et al. [19] conducted a series of experiments testing four foam samples with 5, 10, 20, and 40 PPI and the similar porosity (0.905–0.934), and they found that the pressure drop decreased as the number of pores per inch decreased from 40 PPI to 5 PPI.

The experiments in most of the reports used commercial thermoelectric modules which were mounted and utilized in a cross-plane way. However, when TE modules were sandwiched between hot and cold side, the low thermal conductivity of TE modules would block the heat exchange process. In this paper, a new type of metal foam-filled heat exchanger based thermoelectric generator system is proposed. Different from the conventional cross-plane conditions, this kind of heat exchanger is able to generate available temperature difference between cold and hot layers in an in-plane way. This system can realize waste heat recovery by combining heat exchange and TE power generation.

2. Experimental setup

Waste heat flow path of the HE-TEG system for low temperature waste heat recovery is as follows: Power generation works as a parasitic mode which is attached to heat exchanging process. The majority of waste heat is captured by the process of heating water. A portion of the waste heat flux is converted into electricity by TEG as by-product. In terms of heat exchange process, some waste heat dissipates into the surroundings through heat exchanger walls. In the end, the remaining waste heat is directly discharged into the atmosphere along with exhaust gas.

The schematic diagram of the HE-TEG system is shown in Fig. 1. This system consists of HE-TEG unit, air supply and heating unit, cold water channel and data acquisition system. Waste heat is simulated by heated air. The air is supplied by an air compressor, and then it flows through a spiral steel pipe, rapped by resistance wire, whose output power is controlled by a voltage transformer. Cold water is used as waste heat capturing fluid. Back pressure valve is mounted to control the air pressure (0.2 MPa). Globe valve and rotor flow meters are adopted to control the flow rate of heated air and cold water.

HE-TEG unit is shown schematically in Fig. 2. It is comprised of a multi-layer compact metal foam-filled plate heat exchanger and TE couples. The dimension of the assembled HE is 200 mm × 79 mm × 79 mm. Steel plates with thickness of 1 mm are used for heat exchanging mediums between cold water and heated air. Side surfaces, where TE couples are pasted, are made of steel plate either. Square steels with dimension of 12 mm × 12 mm × 12 mm are placed at corners of the heat exchanger as upholders for the flow channel. Between every two steel plates, open-cell nickel metal foams (10 PPI, porosity of 0.96) are filled in the flow channel as heat transfer enhancement mediums and assistant support materials. Cold water and heated air flow in the opposite direction as approximate counter flow. As illustrated in Fig. 2, inlet and outlet of cold fluid are set along the length direction, and in terms of the hot fluid they are set at different end of the side surface. To prevent heat loss, the HE-TEG unit is wrapped by thermally insulated ceramic fiber cloth.

Considering the special application of TE modules in the HE side surface, TE couples are self-constructed by Bi₂Te₃-based rectangle thermoelectric materials. The Seebeck coefficient, electrical conductivity and thermal conductivity are $2.18 \times 10^{-4} \text{ V K}^{-1}$, $1.175 \times 10^5 \text{ S m}^{-1}$, $1.7 \text{ W K}^{-1} \text{ m}^{-1}$ for P-type TE materials and $-2.15 \times 10^{-4} \text{ V K}^{-1}$, $1.225 \times 10^5 \text{ S m}^{-1}$, $1.9 \text{ W K}^{-1} \text{ m}^{-1}$ for N-type TE materials, respectively. Each couple consists of one P-type TE leg and one N-type TE leg with the dimension of 1 mm × 1 mm × 14 mm. The TE leg is constructed by 4 small rectangle blocks (1 mm × 1 mm × 3.5 mm), which are connected by conductive silver paste. TE couples are pasted to the back of thermally conductive and electrically insulating polyimide tapes with conductive silver paste, then the polyimide tapes are adhered to the HE side surfaces with the sticky side. In order to study the performance of TE power generation, different numbers of TE couples (1, 2, 4, 8 and 16) are integrated to the HE.

Pressure drop of heated air and cold water is measured by differential manometers. K-type thermal couples are used to measure temperatures of heated air and cold water. In addition, Pt100 sensors are mounted on middle two layers to measure side surface temperature difference. Finally, all the temperature, voltage and

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