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Simultaneous power generation and heat recovery using a heat pipe assisted thermoelectric generator system

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ABSTRACT

This research explores a new method of recovering waste heat and electricity using a combination of heat pipes and thermoelectric generators (HP-TEG). The HP-TEG system consists of Bismuth Telluride (Bi_2Te_3) based thermoelectric generators (TEGs), which are sandwiched between two finned heat pipes to achieve a temperature gradient across the TEG for thermoelectricity generation. A theoretical model was developed to predict the waste heat recovery and electricity conversion performances of the HP-TEG system under different parametric conditions. The modelling results show that the HP-TEG system has the capability of recovering 1.345 kW of waste heat and generating 10.39 W of electrical power using 8 installed TEGs. An experimental test bench for the HP-TEG system is under development and will be discussed in this paper.

1. Introduction

Investing in clean and renewable energy sources can significantly reduce emission of greenhouse gases and reliance on fossil fuels. In recent years, engineers and scientists have moved their attention to waste heat recovery for cheaper energy generation. Waste energy recovery techniques can also be useful for increasing the efficiency of conventional energy conversion systems. Rowe, D.M stated that the use of waste heat at temperatures below 140 °C as an energy source can be a competitive method for generating electricity [1]. Waste heat is normally produced by machinery, electrical equipment and industrial heat-generating processes. In the process industry, waste heat can be classified into high, medium, and low temperature ranges. The high temperature range is above 650 °C, medium temperature is between 230 °C and 650 °C, and low temperature is below 230 °C [2]. The operations of process industries are inefficient and emit large quantities of waste heat.

Approximately 33% of total consumed energy has been rejected to the surroundings because of inability to recycle the excess energy [3]. The estimated amount of waste heat from United States manufacturing industries was 3000 TW h/year (equivalent to more than 1.72 billion barrels of oil [3] and in the U.K 11.4 TW h/year of heat was released to the environment corresponding to 5% of their total energy consumption [4]. In Australia, the production of industrial waste increased from 13925 GW h in 2009 to 14411 GW h in 2010 [5]. These figures show the vast availability of waste heat in industrial regions. Consequently, by implementing a smart heat recovery system to convert the waste heat into useful energy can help achieve industrial cost saving.

This research focuses on utilizing gas-to-gas heat transfer which is suitable for the medium temperature range below 300 °C. Therefore the heat pipe is the most suitable heat exchanger for this range of temperature [6]. A heat pipe is an efficient passive device which has the capability of transferring heat over large distances with a small temperature drop. It has simple structural design and high thermal conductivity with no moving parts.

A thermoelectric power generator (TEG) is a device which converts thermal energy into electricity based on the 'Seebeck effect'. It has no moving parts, no vibration, is of light weight and very reliable [7]. To generate electrical power, a thermoelectric cell (TEC) is attached between a heat source and a heat sink. Because of the temperature gradient, heat will flow through the module and be rejected to the surroundings through the heat sink. If the temperature gradient is maintained, the electrical power will be continuously generated [8]. The materials to produce the thermoelectric cell (TEC) are made from a n-type and p-type couple. A figure of merit, ZT expresses the efficiency of the TEC material. Today, the most commonly available thermoelectric materials are Bismuth Telluride (Bi_2Te_3) – based alloys and PbTe-based alloys

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which they have ZT values near to unity [9]. Bell, L.E reported that to maximize the power generation efficiency, the value of ZT should be maximized and the temperature differential should be as large as possible between the hot and cold sides of the TEG [10].

There are many examples of previous studies for generating thermoelectric power using waste heat. For example, Singh et al. [11] investigated TEG power generation by using a fully passive heat pipe system for extracting stored heat from a solar pond. This research produced 3.2 W from 16 TEG modules, while the temperature different across the modules was maintained at 27 °C. Kim et al. [12] installed TEG on the I.C. engine cooling system of a passenger car. The maximum power output from this system was 75 W. The calculated module efficiency was ~2.1% and the overall efficiency of electrical power generation was ~0.3% in a driving mode of cruising at 80 km/h. Kim et al. [13] investigated thermoelectric power generation by using hot exhaust gas from hybrid vehicles. Thermoelectric cells and heat pipes were used to withdraw heat from a small surface area of a hot exhaust pipe. To increase efficiency, an enlarged surface was designed by adding 10 more heat pipes. This system produced 350 W for an evaporator surface temperature of 170 °C. Goncalves et al. [14] utilized a variable conductance heat pipe (VCHP) to regulate high temperature from engine exhaust gas. This heat pipe (VCHP) was also used to control TEG operating temperature. It was expected that the system could produce 550 W electrical power output for an input power above 30 kW.

Nuwayhid et al. [15,16] designed, fabricated and tested a high performance and low-cost thermoelectric generator (TEG) that fitted to a domestic woodstove. They found that the maximum power generated at matching load was 4.2 W for a single TEG used. Wang et al. [17] studied a combined cooling, heating and power (CCHP) systems by utilizing energy from an internal combustion engine (ICE). The results had shown that the system primary energy efficiency could reach up to 94.4%. Yilbas et al. [18] used a thermoelectric generator (TEG) and a refrigerator in a combined thermal system. It was concluded that by placing the TEG between the refrigerator condenser and its ambient will increase the COP of the combined system. Tzeng et al. [19] built an experimental setup of a thermoelectric power generation system that worked with an exhaust pipe. The effect of using metal fins as a heat absorber and heat sink was studied, and they observed that the staggered pin fin configuration produced a better thermoelectric power than the others mode.

Zhao et al. [20] developed a hybrid system that combined a direct carbon fuel cell (DCFC), a thermoelectric generator (TEG) and a regenerator. The hybrid system was capable of producing 50% larger the equivalent maximum power density than a standard DCFC system. Stevens [21] investigated the performance factors of a ground-to-air thermoelectric power generators. It was found that the fins installation on both air-side and ground side heat exchangers might reduce the thermal resistances by a factor of 2–3. Lesage et al. [22] built a test rig of a liquid-to-liquid thermoelectric generator (TEG) to exploit the availability of waste-heat. This study has developed a correlation to relate between the thermal input conditions and the maximum output power. Date et al. [23] conducted a theoretical and experimental studies of a combined solar water heating and thermoelectric power generation system. It was found that the hot water temperature can be heated up to 80 °C at 50000 W/m^2 heat flux. The system can also generate open circuit voltage of 3.02 V at 75 °C temperature difference across the TEG.

Most these studies have investigated only power generation using a TEG and none of them have considered recovering the released heat from the cold side of TEG for other uses. This paper presents a new concept of recovering waste heat and electricity conversion by sandwiching TEGs between heat pipes. This totally passive heat transfer system focuses not only on electric power generation but also considers the amount of energy that can be recovered from the rejected heat.

2. Description of the system

In this study, a theoretical model has been developed to predict the waste heat recovery and electrical conversion performances using TEGs. The input parameters in this theoretical model are based on an experimental rig which is under development, as shown in Figs. 1 and 2a. The experiment rig incorporates a TEG sandwiched between two heat pipes to achieve the temperature gradient for thermoelectricity generation. The condenser section of heat pipe 1 is thermally attached at the hot side of the TEG as a heater, and the evaporator section of heat pipe 2 provides the cooling role.

Figs. 2b and 2c show the actual heat transfer device (heat pipe) in the experimental rig and the assembly of the thermoelectric power device respectively. The heat transfer device contains of two sets of rectangular finned tube heat pipes that are attached to copper blocks. In order to minimize the interfacial thermal resistance of the heat transfer device and TEG, lead free galvanizing solder is used to thermally bond the heat pipes and copper blocks.

3. Theoretical modelling

3.1. Energy balance equations

Cold air enters from the upper part of the duct in the $-x$ direction and exits to the bottom part of the duct (+x direction) as shown in Fig. 3. The energy balance can be written as:

$$-\dot{m}Cp_{air}\left(\frac{dT_C}{dx}\right)dx = -\dot{m}Cp_{air}\left(\frac{dT_H}{dx}\right)dx \quad (1)$$

where T_C and T_H are the cold and hot air temperatures respectively. $\dot{m}$ is the air mass flow rate, Cp_{air} is the specific heat capacity of air and dx is the increment of length in the x-direction. The rate of energy transfer from the lower duct through the HP-TEG system is determined using the follow equations:

$$-\dot{m}Cp_{air}\left(\frac{dT_H}{dx}\right)dx = (T_H - T_C)/R \quad (2)$$

$$R = \left(\frac{ab}{bdx}\right)R_M \quad (3)$$

where R_M is the thermal resistance for a single row of thermoelectric power devices, a is the TEG module thickness in the x-direction and b is the module width.

An electrical heater is used to simulate the waste heat input to the HP-TEG system. The energy input is shown as:

$$\dot{m}C_p(T_H - T_C) = \dot{Q}_{in} \quad (4)$$

where $\dot{Q}_{in}$ is the rate of heat added to the HP-TEG system. By solving Eqs. (1), (2) and (4), the temperature profiles of hot and cold air in the upper and lower ducts can be determined using Eqs. (5) and (6).

$$T_H(x) = \left(-\frac{\alpha x}{a\dot{m}C_pR_M}\right) + \beta \quad (5)$$

$$T_C(x) = T_H(x) - \alpha \quad (6)$$

where $\alpha = \dot{Q}_{in}/\dot{m}C_p, \beta = T_{Ci} + \alpha\left(1 + \frac{L}{a\dot{m}C_p}\right), L$ is the duct length, and T_{Ci} is the inlet cold air temperature. The total rate of heat transfer through the HP-TEG heat exchanger is finally represented by:

$$\dot{Q}_M = N\left(\frac{\propto}{R_M}\right) \quad (7)$$