Energy Conversion and Management 146 (2017) 244–252

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Design and experimental investigation of a thermoelectric self-powered heating system

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ARTICLE INFO

Article history:
Received 9 March 2017
Received in revised form 9 May 2017
Accepted 13 May 2017
Available online 23 May 2017

Keywords:
Thermoelectric generation
Self-powered
Heating equipment
Power output
Residential system

ABSTRACT

In this paper, a combustion-driven thermoelectric residential heating system, which uses Bi_2Te_3-based thermoelectric modules, is designed, constructed, and tested. The thermoelectric modules are integrated into a heat cell of a natural gas-fired heating boiler. The experiments are carried out to examine the influences of the main operating conditions, cold fluid flow rate, temperature difference between the inlet and outlet at the heat cell and different boiler powers, on output power, voltage, current and efficiency of boiler. The two operating parameters such as the cold fluid flow rate and temperature difference are found to significantly affect the output power, and the efficiency of the boiler. The thermoelectric generator unit has a power generation capacity of approximately 36 W. This amount corresponds to about one-third of boiler's requirement. The study shows that if the combi boiler is redesigned, and its efficiency is enhanced, it can generate sufficient electrical power for electrical components of the combi boiler, such as pump, valves, blower, fan, and control panel. The self-powered heating system provides advantages commercially, and can decrease the electrical power consumption. Also, and economical analysis was conducted for the self-powered heating system and the conventional system, and it was seen that the proposed system is economically applicable.

1. Introduction

Nearly all over the world fossil fuels such as coal, oil and natural gas are the primarily energy source to generate electricity. Because of eventual depletion, and environmental hazards of such energy sources, people have started to use renewable energy sources, which are clean and cause less damage to the environment [1,2]. However, the biggest handicap is rather high initial investment cost on applications of these sources.

Thermoelectric generator (TEG) which is still a developing technology, can be thought as an alternative energy source. Thermoelectric modules convert thermal energy into electrical energy directly. In other words, they are devices, which generate electricity from a temperature difference. Although TEGs have low conversion efficiency, they are quiet, reliable, durable, environmentally friendly, and have no moving parts [3].

The thermoelectric power generation technology has been used in different applications [4–10]. Some of which are geothermal energy application using cooling water [11], waste heat recovery application with the help of TEGs [12], generating electricity with solar collectors [13–15].

Brazdil and Pospisil [16] used a system comprised of 4 TEGs to convert heat from the flue gas of a small-scale domestic pellet boiler to electrical energy for recovery of waste heat. The boiler efficiency was measured as 75.12%. They specified that the maximum measured output power was 8.5 W, and the open circuit voltage of four TEGs connected in series was 18.5 V for a temperature difference of 112.8 °C. Nuwayhid et al. [17] developed and tested a domestic woodstove TEG system with natural convection cooling. When the temperature difference was 88 °C, they obtained a power of 4.2 W, and the open circuit voltage was about 4 V. Liu et al. [18] made a theoretical and experimental analysis of a novel solar thermoelectric air conditioner with hot water supply. They carried out experiments under different operating conditions, in order to investigate the performance of the system. They found that coefficient of performance is 2.59 in cooling mode, and 3.01 in heating mode. Niu et al. [19] constructed a TEG unit, which is commercially available incorporating with a parallel-plate heat exchanger, and studied the influences of the main operating conditions, the cold and hot fluid inlet temperatures, flow rates, and load

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http://dx.doi.org/10.1016/j.enconman.2017.05.033
0196-8904/

resistance on the power output and conversion efficiency. When the hot fluid inlet temperature was 150 °C and the cold fluid inlet temperature was 30 °C, they produced a maximum power output of 146.5 W, and obtained a conversion efficiency of 4.44%.

TEGs can be used for low power requirement in daily life. A residential heating system needs electricity for its electrical components such as fan, control panel, pump and blower. These components require about a power of 120 W. When a combi boiler incorporates TEGs, required electricity for these components can be provided, and it can become a self-powered boiler. If electricity more than of boiler's electricity requirement is generated with help of TEGs, third power can be used to charge a battery, and can be used by other electrical instruments.

In the literature, there are a few studies about self-powered heating equipment using thermoelectric generators [20–25]. Qiu and Hayden [20] investigated a TEG system of power generation capacity of about 550 W at 552 °C temperature difference between the hot and cold walls of TEGs, to provide power of electrical components such as fan, pump, blower, and control panel of a heating system. They emphasized that model results were helpful in further system optimization. Qiu and Hayden [21] modelled a natural-gas-fired thermoelectric power generation system, and they obtained an electrical power of 1052.2 W from two thermoelectric modules. Qiu and Hayden [22] applied TEGs to a combustion chamber of a residential heating equipment, to measure performance of the boilers, and to develop a self-powered heating system with TEGs. They investigated the performance of TEGs in an integrated heating equipment under various operating conditions. As a significant result of their experiments, about 160 W electrical power was generated by the TEGs when the hot side temperature of the TEGs, electric current and voltage were approximately 260 °C, 8 A and 20 W, respectively. A few studies were done about self-powered heating equipment before 2000 s. Allen and Wonsowski [23] designed and tested a self-powered residential-scale hydronic central heating unit using lead-telluride-based thermoelectric modules. Killander and Bass [24] developed and tested a prototype of a self-powered wood fired stove using bismuth-telluride thermoelectric modules for home heating. Bass and Thelin [25] developed a self-powered pellet stove with help of thermoelectric technology.

In previous studies, authors investigated optimum TEG locations for self-powered heating equipment numerically [26–28]. In this study, a new thermoelectric self-powered condensing combi boiler was designed, constructed and tested. This study aims to develop a low-cost and simple configuration TEG unit using bismuth telluride-based thermoelectric modules integrated into the heat cell. The TEGs were placed where the temperature differences were optimum in the heat cell. The influences of the main operating conditions, cold fluid flow rate, temperature difference between the inlet and outlet at the heat cell (ΔT) and different boiler powers on output power, voltage, current and efficiency of the combi boiler were examined. The novelty of this experimental study is to develop a new self-powered residential boiler and to investigate the effect of boiler power on the electrical and thermal performance.

2. Experimental analysis

2.1. Thermoelectric generation

TEGs convert heat into electricity. Their efficiency is related to thermal and electrical properties of semiconductor materials in TEGs. Semiconductors based on Bi_2Te_3 are used, because they can be operated approximately up to 400 °C, and have high efficiencies. Some materials such as clathrates, skutterudites, alloys Heusler are also available, but these have not yet commercialized [29].

Fig. 1 depicts working principle of a TEG thermocouple that is assembled electrically in series and thermally in parallel. Voltage

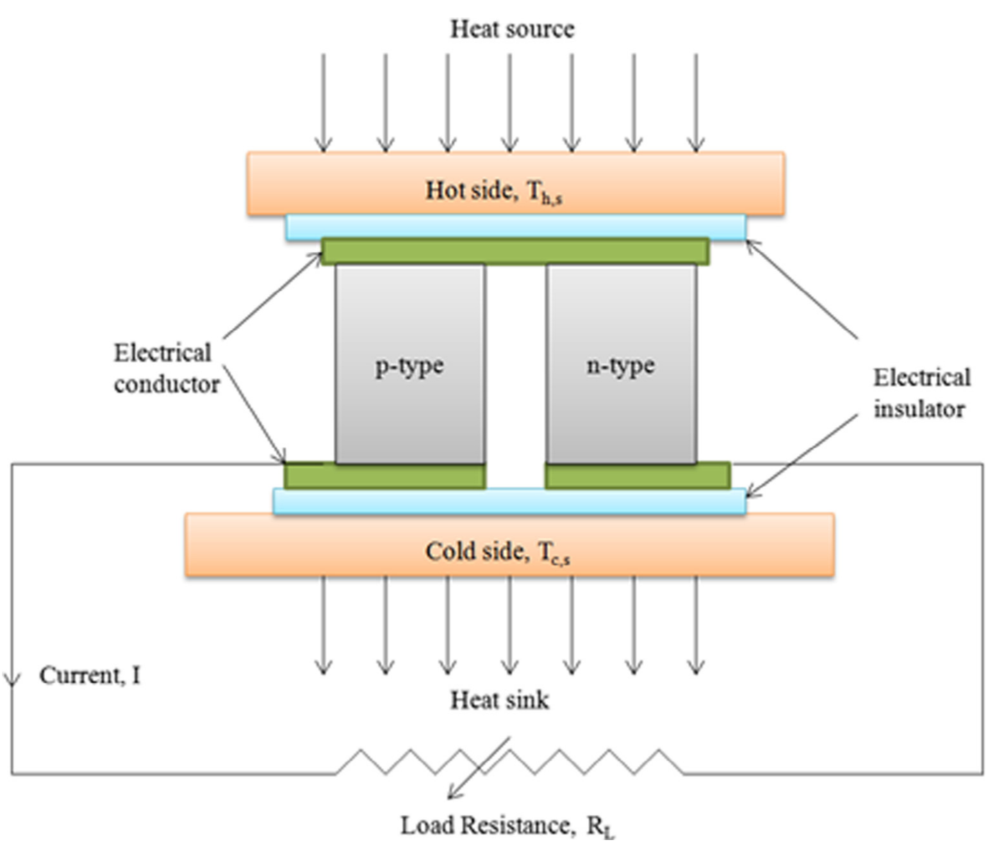

Fig. 1. Working principle of a thermoelectric element.