A Numerical Investigation of Thermoelectric Generators for Heating Appliance

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Abstract

Thermoelectric is a new technology and therefore, thermoelectric modules are used in many fields such as heat exchangers, waste heat recovery, solar and geothermal energy applications. In this study, heat cell of a condensing combi boiler was modified, and its power generation, and heat transfer in the thermoelectric modules were numerically investigated by using FLUENT program. The study was carried out for different hot fluid flow rates, cold fluid flow rates, and cold fluid inlet temperatures. Besides, parametric study was examined by taken into account radiation. Temperature difference between thermoelectric generator surfaces and power generation were evaluated for different hot fluid flow rates, cold fluid flow rates and cold fluid inlet temperatures. It was found that the power generation and the temperature differences between thermoelectric generator surfaces changed slightly with increasing the cold fluid flow rate and inlet temperature. Furthermore, the power generation and the temperature differences between thermoelectric generator surfaces were directly proportional with the hot fluid flow rate. The thermoelectric generator system has produced up to 140 W. Other heat energy sources such as waste heat, geothermal energy, and solar energy may be a good opportunity for power generation using thermoelectric generators.

Key words: Thermoelectric generator (TEG), power generation, temperature difference, numerical simulation

1. Introduction

Nearly all over the world, fossil fuels such as coal, oil and natural gas are used to genarate electricity. Because of eventual decrease and environmental hazard of such energy sources, people have started to use renewable energy sources, which are clean. However, on appllications of these sources, encountered biggest handicap is a rather high initial investment cost. Therefore thermoelectric technology, which is developing at the present time, can be thought as an alternative source. Thermoelectric modules (TEMs) are converting thermal energy into electrical energy directly. In other words they are devices, which generate electricity from temperature difference. The thermoelectric power generation technology has been used widely over the last 30 years, such as self-powered heating systems, geothermal energy, automobiles, power plants and other industrial applications. TEGs have a few advantages, such as that they are quiet, reliable, sturdy, environmentally friendly have no moving parts. Besides these advantages, however, the most important disadvantage of thermoelectric power generators (TEGs) is the low

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conversion efficiency [1].

There are many applications of TEGs. For example, Hsu et al. [2] constructed a system to recover waste heat comprised of 24 TEGs to convert heat from the exhaust pipe of an automobile to electrical energy, and they found that the open circuit voltage (Voc) was increased linearly with and power output was increased rapidly with increasing the temperature difference. They specified that maximum power output was approximately 12.5 W. For recovery of waste heat, Brazdil and Pospisil [3] used a system to recover waste heat comprised of 4 TEGs to convert heat from the flue gas of a small-scale domestic pellet boiler to electrical energy. 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. Qiu and Hayden [1] put through a TEG system of power generation capacity of about 550 W at a 552 °C temperature difference between the hot and cold walls of TEGs to provide power to electrical components such as fan, pump, blower, and control panel of a residental heating system. They emphasised that model results were helpful in further system optimization. Qiu and Hayden [4] modelled a natural-gas-fired thermoelectric power generation system, and they obtained the electrical power of 1052.2 W when the hot side temperature of the TEGs was about 1000 °C. The produced electrical energy was supplied to all the electrical components for a residential heating system. Again, Qiu and Hayden [5] applied, to the combustion chamber of a residential heating equipment, to measure performance in the boilers and to develop self-powered heating system with TEGs. They investigated the performance of TEGs into 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 approximetally 260 °C, 8 A and 20 W, respectively. Gür and Atik [6] designed a power generation system by using concentrated solar energy sources, and thermoelectric generators. One side of thethermoelectric modules is heated by a multiplied beam while the other side is cooled by a water circulating naturally. In this system they used 4 TEGs connected serially. Besides the power value was measured by measuring the voltage on the outer resistance connected to the circuit. Ahiska et al. [7] carried out a TEG system of maximum 42 W by using heated and cooled water, when the cold side temperature was about 80 °C and the cold side temperature was 15 °C. In addition, they compared with TEG and photovoltaic systems and found that TEG systems' efficiency was 9 times of photovoltaic ones. In this study, it was modelled a thermoelectric self-powered condensing combi boiler which bismuth telluride-based thermoelectric modules was integrated into. The TEGs were placed on where the temperature differences were optimum in the heat cell. Simulations were performed to examine the influences of the different hot fluid flow rates, cold fluid flow rates and cold fluid inlet temperatures. Besides, temperature difference between thermoelectric generator surfaces and power generation were evaluated.

2. Materials and Method

2.1. Thermoelectric generation technology

Figure 1 shows that TEGs convert heat into electricity. Their efficiency is related to thermal and electrical proporties of materials, which are used as thermocouple in TEGs. Today, semiconductor materials have the maximum efficiency. Most commonly used semiconductors are based on Bi2Te3 and endured approximately up to 400 °C. Some materials such as clathrates, skutterudites, alloys Heusler are available more than durable based on Bi2Te3 ones, but these haven't commercialized yet [8].

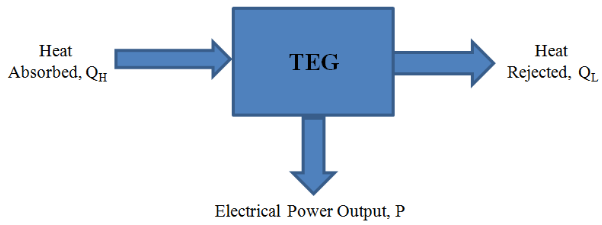

Figure 1: Schematic showing the energy flow in a TEG [9]

Working principle of a TEG thermocouple is shown, which is assembled electrically in series and thermally in parallel, in Fig. 2. Voltage difference is generated between junctions of the thermocouple due to transmission of stored loads in semiconductors, while heat moves from hot surface to cold surface.

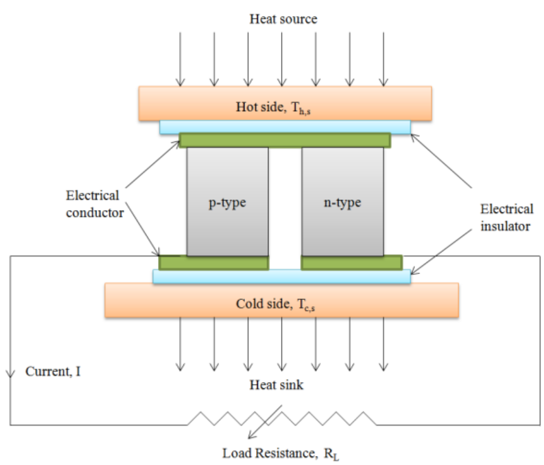

Figure 2: Schematic diagram of the thermoelectric element [10]

2.2. Numerical method

The heat cell of the condensing combi boiler was modelled in FLUENT numerically. Solid model is also shown in Figure 3. Mesh structure can be seen in Figure 4. In addition, the boundary conditions of the simulation are presented in Table 1. To simplify the numerical analysis, some assumptions are made as follows.

- The system runs at unsteady process.
- Flue gases exit to the atmosphere.
- Combustion gases are modelled as air.

• Simulations are performed under laminer conditions and with radiation.

Table 1. Boundary conditions

	Boundary type	**Boundary value**	**Temperature**	**Type rates**
Combustion gases inlet	Mass inlet	7-14 g/s	1717 °C	Hot gas mixture
Water inlet	Mass inlet	200-400 g/s	50-70 °C	Water
Outer walls	Convection	Air	47 °C	Stainless steel
Inner walls	Integrated	Conduction	-	Stainless steel

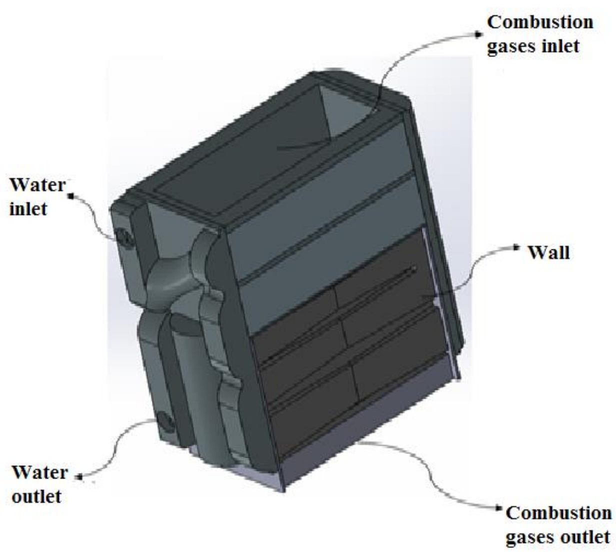

Figure 3: Solid model of heat cell [11]

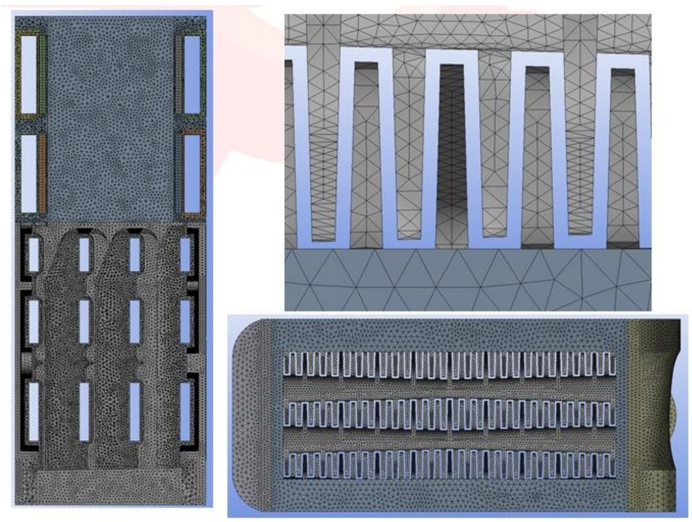

Figure 4: Mesh structure on fins and water channel [11]

The TEGs were built on the top two channals where temperature difference is maximum. Total 14 modules were used. In addition, on each channal was defined as TEG-1, TEG-2, TEG-3 and TEG-4. This configuration is shown in Fig. 5. In addition, water and combustion gases are defined as cold fluid and hot fluid, respectively.

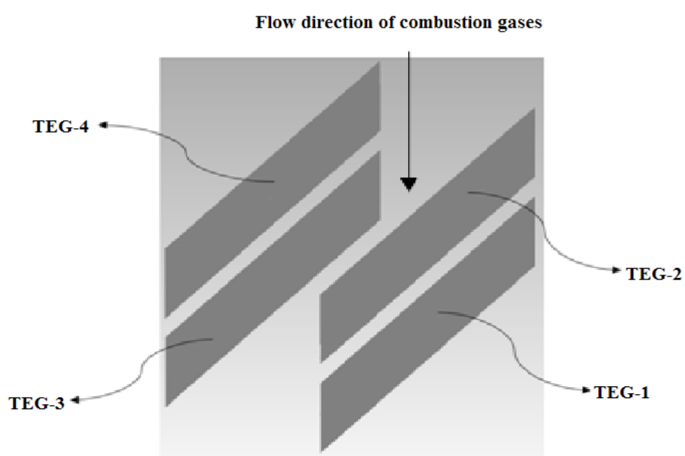

Figure 5: Configuration of TEGs in heat cell [11]

3. Results

In this study, the influences of the cold fluid flow rate, the hot fluid flow rate and the cold fluid inlet temperature on power output and temperature differences between TEGs' surfaces were investigated.

Figure 6 shows the variation of temperature differences between TEG surfaces and power output with respect to the hot fluid flow rates. Temperature differences between the TEGs increase with increasing hot fluid flow rate while cold fluid flow rate and cold fluid inlet temperature are fixed to 295 g/s and 60 °C, respectively. When the hot fluid flow rate increases, the heat transfer increases to hot surfaces of TEGs, too. Consequently, temperature differences between the TEG surfaces increase. Since temperature differences increase, the power output increases in parallel with this rise due to equations of

$$V=\alpha\,\Delta T \qquad (1)$$
$$P=VI \qquad (2)$$

where V, α, T, P and I show output voltage, Seebeck effect coefficient, temperature difference between the TEGs surfaces, power output and output current, respectively. In addition, for mass flow rate of 14 g/s, power generation is 140 W. As a result of simulations, it is found that the maximum power output can be obtained for the hot fluid flow rates.

Figure 7 presents the variation of temperature differences between TEG surfaces and power output with respect to the cold fluid flow rates when the hot fluid flow rate and cold fluid inlet temperature are fixed at 11 g/s and 60 °C, respectively. Temperature difference and power output are changed slightly with decreasing cold fluid flow rate. The power output of about 115 W is obtained for cold fluid flow rate of 400 g/s. In addition, temperature difference between TEG-2 and TEG-4 surfaces are higher than TEG-1 and TEG-3, due to the fact that TEG-2 and TEG-4 are placed at the inlet of the heat cell. Generated power is about sufficient for combi boiler, since the boiler needs approximately power of 120 W.

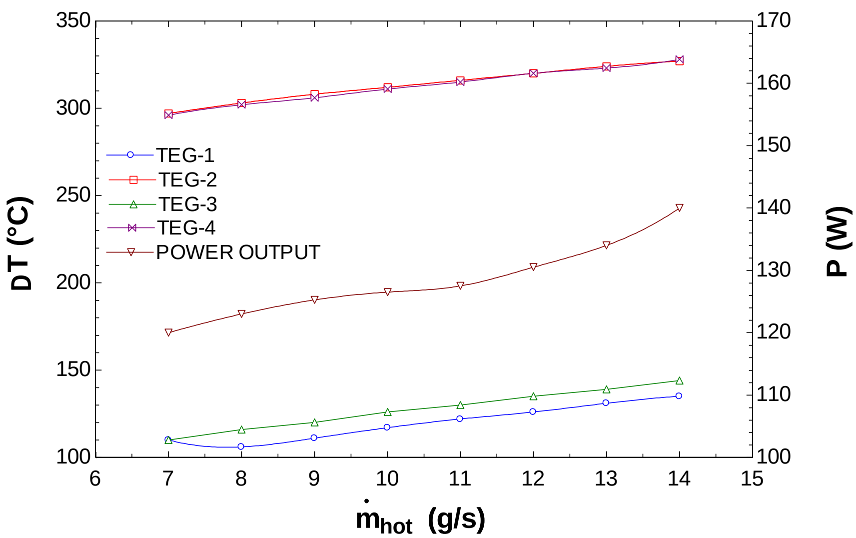

Figure 6: Variation of TEG surface temperature differences and power output with respect to the hot fluid flow rates

Figure 8 illustrates the variation of temperature differences between TEG surfaces and power output with respect to the cold fluid inlet temperatures for the fixed hot fluid rate and cold fluid flow rate. Both temperature difference between TEG surfaces and power output are approximately constant with increasing cold fluid inlet temperature. Because it is observed that temperature differences are constant with decreasing inlet temperatures, generated power is not much affected. As can be seen in Fig. 8, temperature differences between TEG-2 and TEG-4 surfaces are higher than TEG-1 and TEG-3, because of the same reason as explained above.

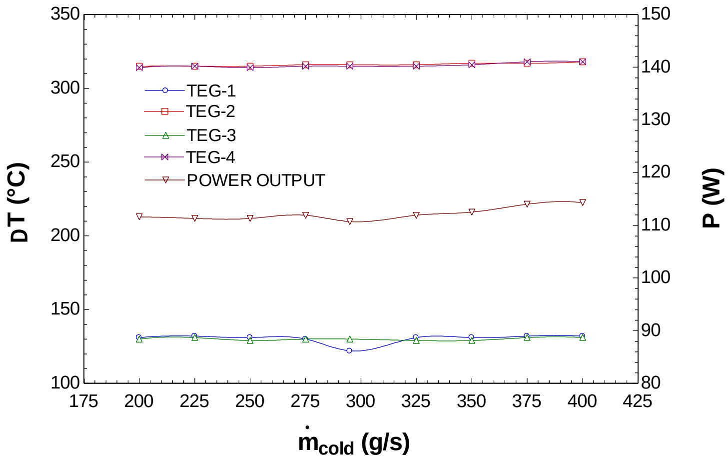

Figure 7: Variation of TEG surface temperature differences and power output with respect to the cold fluid flow rates

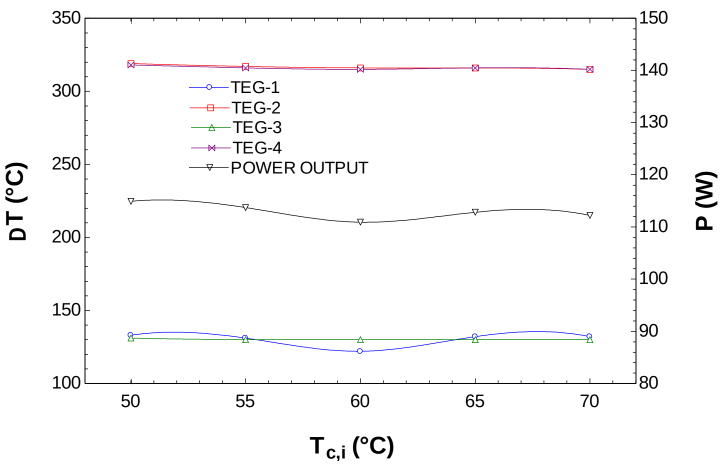

Figure 8: Variation of TEG surface temperature differences and power output with respect to the cold fluid inlet temperatures

Conclusions

In this study, a thermoelectric self-powered heating equipment has been simulated and investigated for a reduction in electric power consumption. The study analyzed temperature differences between TEG surfaces, the influences of three different operating conditions, which are the hot fluid low rate, the cold fluid low rate and the cold fluid inlet temperature. Simulation results show good applicability of thermoelectric power generation to natural gas-fired heating appliances. In this model, total power output of 140 W was obtained from fourteen thermoelectric modules. In the simulation Bi2Te3-based on thermoelectric modules were integrated into the heat cell of a condensing combi boiler. In this model, radiation was taken into account. The simulation results imply that total power output of fourteen thermoelectric modules can reach 140 W for the maximum hot fluid flow rate, when the cold fluid flow rate and inlet temperature are fixed at 295 g/s and 60 °C, respectively. Therefore, sufficient power could be generated due to the fact that the boiler needs approximately a power of 120 W.

Acknowledgements

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