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Short communication

Development of a thermoelectric self-powered residential heating system

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ABSTRACT

Self-powered heating equipment has the potential for high overall energy efficiency and can provide an effective means of providing on site power and energy security in residential homes. It is also attractive for remote communities where connection to the grid is not cost effective. Self-powered residential heating systems operate entirely on fuel combustion and do not need externally generated electricity. Excess power can be provided for other electrical loads. To realize this concept, one must develop a reliable and low maintenance means of generating electricity and integrate it into fuel-fired heating equipment. In the present work, a self-powered residential heating system was developed using thermoelectric power generation technology. A thermoelectric module with a power generation capacity of 550 W was integrated into a fuel-fired furnace. The thermoelectric module has a radial configuration that fits well with the heating equipment. The electricity generated is adequate to power all electrical components for a residential central heating system. The performance of the thermoelectric module was examined under various operating conditions. The effects of heat transfer conditions were studied in order to maximize electric power output. A mathematical model was established and used to look into the influence of heat transfer coefficients and other parameters on electric power output and efficiency.

1. Introduction

Space and water heating equipment usually require both fuel for heat production and electricity for operating its electrical components. If the heating equipment incorporates a power generator to convert a portion of heat to electricity to drive its electrical components such as fans, blowers, pumps, and control panels, it forms a self-powered heating system that only uses fuel and needs no external electricity supply. In addition, any excess power that is generated can be used to charge batteries or be fed into the household grid to provide electricity for other electrical loads. Further, self-powered heating equipment is particularly beneficial in areas where winters are cold and long. Self-powered heating systems are more reliable in providing heat during extreme weather conditions. The heating systems can be used in remote communities where connection to the grid is not cost effective. Also, self-powered heating systems have the potential for high overall energy efficiency. Electricity is generated at essentially 100% efficiency in a self-powered heating system because the heat dissipated from the power generation is fully used for space and water heating. Consequently, energy is saved by displacing the electricity generated by the power utility. The key to realizing this concept is to develop a reliable, low maintenance and cost-effective means of generating electricity and integrate it into fuel-fired heating equipment.

Thermoelectric devices convert thermal energy directly into electricity based on the Seebeck effect. A thermoelectric power converter has no moving parts, and is compact, quiet, highly reliable and environmentally friendly. The heat to electricity converter is well suited for integrating with fuel-fired heating equipment to generate power. Table 1 illustrates the potential applications of thermoelectric power generation. However, wide application of thermoelectric power generation has been limited due to its relatively low heat to electricity conversion efficiency. In recent years, significant progress has been made in fabricating thermoelectric devices applicable to electricity generation. Self-powered central heating systems using thermoelectric power units are attracting technical attention. For this application, the required electricity share is usually small when compared with the thermal load.

The concept of self-powered heating systems using thermoelectric devices has been explored [1–5]. For instance, a residential-scale heating unit was combined with thermoelectric modules to demonstrate the self-powering operation [1,2]. The thermoelectric modules used are made from bismuth telluride-based semiconductors. One module has a power generation

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Table 1
Applications of thermoelectric power generation

Fuel-fired	Low-grade waste heat
Space (radioisotope thermoelectric power generation)	Automobile exhaust generators
Oil and gas wells (cathodic protection)	Geothermal converters
Mobile (remote or military) power supplies	Solar roof climate control (ventilation)
Telecom transmitters	Waste incinerators, power plants
Solar power backup systems	Miniature converters, e.g., watches
Self-powered central heating	Integrated cogeneration systems

capacity of 14–20 W. The electricity output from the heating equipment is 109–175 W and the thermal output is 11.0–24.0 kW. The investigations have demonstrated the merit of further developing self-powered heating and the possibility of a scale-up to a combined heat and power system with modest net electric power output. The next step would be to integrate a purposefully designed thermoelectric module into a high-efficiency residential heating system designed to address integration, compactness, and most important, more electric power output. In this study, we developed a thermoelectric self-powered residential heating system where an integrated lead tin telluride-based thermoelectric module with a radial configuration was employed. The thermoelectric module has a power generation capacity of 550 W that is capable of powering the electrical components including fans, pumps, and a control panel for a single-family central heating system. Also, modeling calculations were done to examine the influence of heat transfer coefficients and other parameters on electric power output and efficiency.

Fig. 2. Thermoelectric module.

2. Experimental

2.1. Experimental setup

Fig. 1 illustrates a thermoelectric self-powered heating system. The integrated energy system consists of a gas burner, thermoelectric power module, cooling device, flue gas heat exchanger, and a heat storage tank. The burner generates combustion heat at a rate of Q_{fuel}. Q_h is the heat input rate from the burner at temperature T_h to the thermoelectric module and Q_c is the dissipated heat rate from the thermoelectric power module to the circulating water at temperature T_c. The electric power P_{TE} is generated and supplied to the load. T_1 and T_2 are the temperatures of the hot and cold junctions, respectively. Q_{fg} is the heat remaining in the flue gases after the thermoelectric power unit. The thermoelectric module generates electricity to supply the electrical components of the entire heating system, including the air blower, fan, water pump, igniter, various valves, and the control panel. Electricity surplus could be used for other electrical loads. Circulating water is directed to the cooling system by which the unconverted heat is removed from the thermoelectric module cold junction. Exhaust gases flow through a flue-water heat exchanger in the normal fashion.

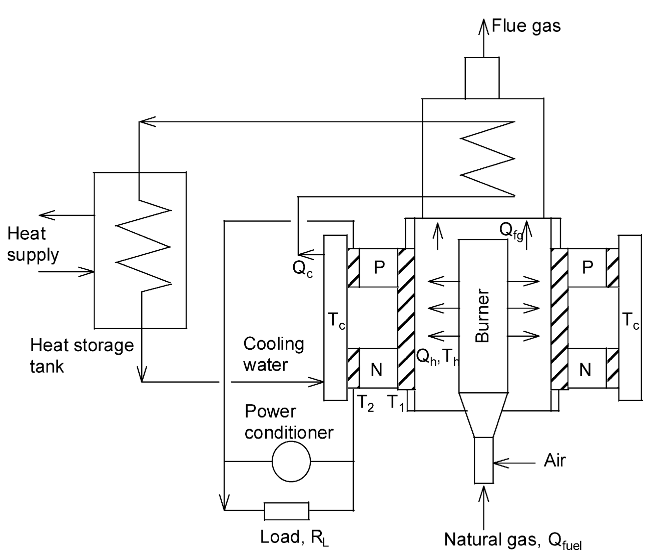

Fig. 1. Thermoelectric self-powered heating system.

The thermoelectric module is a radial type that fits in well with the burner of the furnace (Fig. 2). The thermoelectric elements in the module are made from PbSnTe doped to have either p- or n-type semiconductor properties. PbSnTe is made by means of a powder metallurgy approach. The module has 325 couples with each couple consisting of a p-type element and an n-type element. These couples are connected electrically in series and thermally in parallel. They are sealed in a hermetical enclosure that is filled with argon to eliminate any exposure to air and minimize heat transfer from the hot to cold walls. The inner wall (hot junction) is even-heated to a temperature of 500–650 °C. The outside surface (cold junction) is maintained at a low temperature by cooling water that circulates through a jacket surrounding the power unit. The nominal power output of the thermoelectric converter is 550 W for 535 °C in temperature difference between hot and cold junctions. Various measuring and control devices that included thermocouples to measure temperatures, flow meters, a voltage/current analyzer, and a data acquisition system were installed.

For a given heat input and combustion temperature, the hot junction temperature and thus the electric power output increases by enhancing heat transfer from combustion products to the hot junction of the thermoelectric module. This can be achieved by adding a number of heat-conducting fins to the inner wall of the module. The fins raise the convective heat transfer area and reduce thermal resistance from the combustion products to the inner wall,

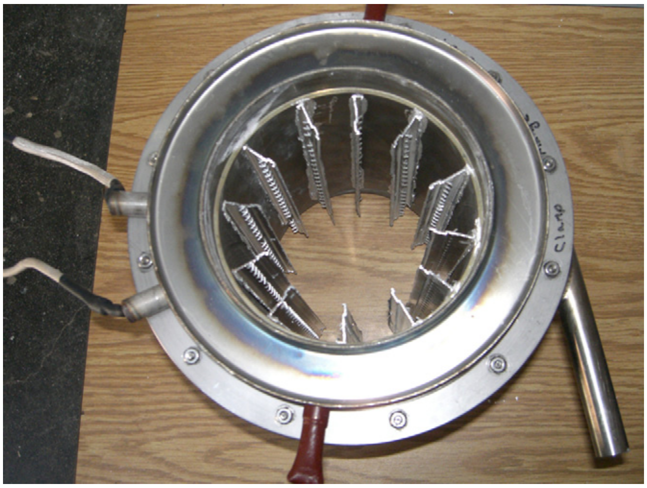

Fig. 3. Heat-conducting fins on converter inner wall to enhance heat transfer from gaseous combustion products to thermoelectric module.

and thereby increase hot junction temperature. We investigated the effect of heat-conducting fins on the temperature of the hot side surface. Fig. 3 shows the heat-conducting fins used for the heat transfer enhancement. These fins are made of a metal allay and are attached to the inner wall using special high temperature thermal grease that has a great heat conductivity to minimize thermal contact resistance.

2.2. Instrumentation and procedure

Various measuring and control devices, including thermocouples, flow meters, a voltage/current analyzer (Yokogawa Electric Corporation, Japan) and a data acquisition system (Campbell Scientific Inc., Canada) were applied. The PC based data acquisition system collected the signals from the thermocouples and gas flow meter and the output of the thermoelectric power converter. The readings were scanned and recorded every 2 s. As the generated electric current was so high that it exceeded the measurement range of the voltage/current analyzer and could not be directly recorded by the data acquisition system, the current was first converted to a corresponding voltage with a standard shunt. The shunt is rated 50 A/50 mV, so 1 mV across the shunt equals 1 A.

The power output of the thermoelectric module is calculated from the load voltage and the electric current:

$$P_{TE} = IV \tag{1}$$

where V and I are the voltage and current at given load conditions, respectively.

The power output may also be obtained from the load voltage and the load electrical resistance:

$$P_{TE} = \frac{V^2}{R_{load}} \tag{2}$$

where R_{load} is the load electrical resistance.

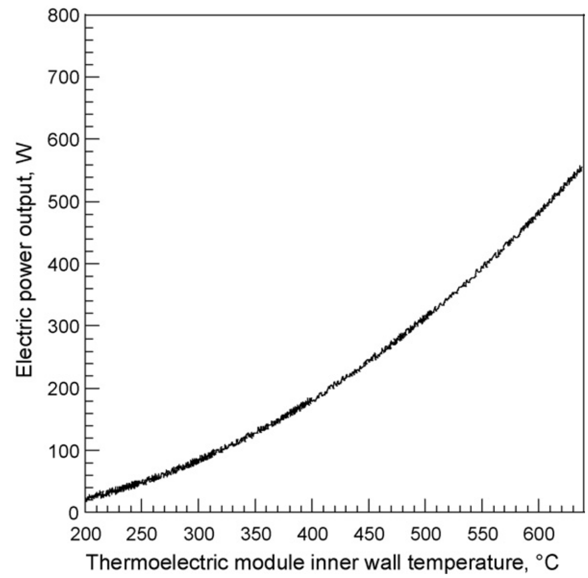

Fig. 4. Variation of thermoelectric power output with module inner wall temperature.

Basic electrical circuit theory tells us that maximum power output to a load is reached when the load resistance is equal to the internal resistance of a power source and the load voltage is one-half of the open circuit voltage. The theory is also true of a combustion-heated thermoelectric generator. However, a combustion-heated thermoelectric generator delivers maximum power and efficiency when the load voltage is slightly higher than one-half (about 55%) of the open circuit voltage (see Fig. 8).

3. Results

3.1. Combustion performance

The burner is fully aerated by mixing natural gas and air entering the burner. The premixed combustion occurs in the combustion chamber. The effects of fuel input and excess air on the combustion were examined. Table 2 illustrates the results of the burner combustion performance. The burner is made of a high temperature alloy (nickel 76 wt.%–chromium 16 wt.%–aluminum 4.5 wt.%–iron 2.5 wt.% alloy) and has a perforated structure with a wall thickness of 2.5 mm. The combustion-heated burner surface generates the desired radiation output for heating the thermoelectric module inner wall effectively.

3.2. Electric power output

Experiments were done to investigate the applicability of thermoelectric power generation to self-powered heating systems. Fig. 4 shows the power output versus the measured module inner wall temperature. The power output increases rapidly with the module inner wall temperature. The outer wall temperature was

Table 2
Experimental results of burner combustion performance

Fuel input (kW)	Excess air (°C)	Combustion load[a] ($W\,cm^{-2}$)	Burner surface temperature (°C)	Temperature of combustion products (°C)
15.6	5	31.3	993	1120
15.6	12	31.3	929	1035
17.5	5	35.1	1050	1186
17.5	12	35.1	964	1092

[a] Combustion load refers to the burner surface area.

Table 3
Results of power output characteristics at various conditions

Module inner wall temperature (°C)	Load voltage (V)	Load current (A)	Power output (W)	Open circuit voltage (V)
496	20.5	14.9	306.2	38.9
565	23.8	17.3	412.5	44.6
637	27.6	20.1	553.9	53.2

Note: The outside surface where cold junctions of thermoelectric module connect thermally is maintained below 85 °C.

maintained at 72–85 °C during the experiments. The experimental results obtained are in agreement with the Seebeck thermoelectric theory.

Table 3 summarizes the power output characteristics of the gas-fired thermoelectric power system. Under the conditions of a hot wall temperature of 637 °C and a cold wall temperature of 85 °C, the maximum power achieved by the module used in this work is 553.9 W. The power output of a thermoelectric generator depends on many factors such as the temperature difference between hot and cold junctions, the number of p and n junctions, and the properties and dimensions of thermoelectric materials. Note that the experimental results of Table 3 were obtained without using a power conditioner. Therefore, the load voltage varies with power output. If the power conditioner is used, a constant-adjustable voltage will be provided to the customer load. In practice, the power conditioner also provides an optimum load condition for the thermoelectric generator. The electricity generated is capable of powering all the electrical components for a residential heating system. Typically, a single-family heating system consumes 250–400 W electricity.

3.3. Effect of heat transfer enhancement

Although the thermoelectric power unit in the experimental setup generates a maximum of 553.9 W electricity (Table 3), we found a large temperature difference between the module's inner wall and the combustion products or burner surface (Fig. 5). This finding suggests that the heat transfer to the inner wall is inefficient. Consequently, more fuel input is required to keep the large temperature difference and maintain the thermal input (heat flux) to the module. This limits the electrical efficiency of the system. Heat-conducting fins can increase the convective heat transfer area and reduce thermal resistance from the combustion products to the thermoelectric module. Therefore, combustion load or fuel input can be reduced with the fins for a given hot junction temperature. Fig. 5 shows the variations of the inner wall temperature with combustion products temperature for both cases. That is, without heat-conducting fins and with heat-conducting fins. The use of fins increases the overall heat transfer coefficient. As shown, the same inner wall temperature is attained when lowering combustion products temperature if the heat-conducting fins are used. This suggests a more efficient heat transfer and therefore a reduction in fuel consumption.

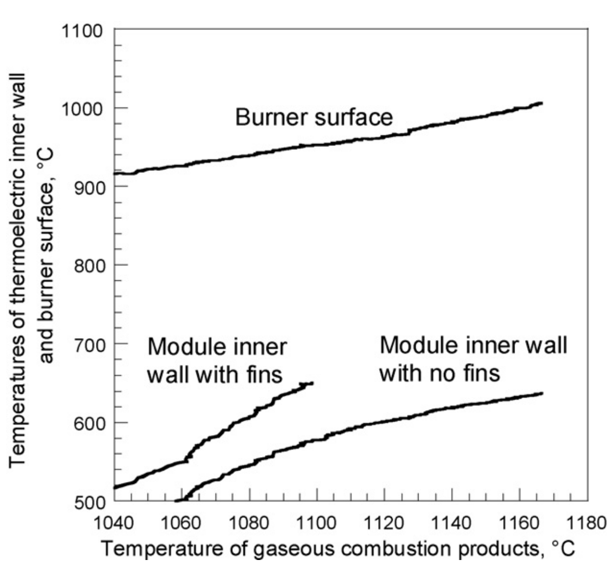

Fig. 5. Variations of temperatures of thermoelectric module inner wall and burner surface with gaseous combustion products temperature.

4. Modeling

4.1. Model description

If we assume that the burner surface and combustion products have the same temperature, T_h, the energy balance over the combustion-heated thermoelectric system may be written as

$$Q_h = K_1(T_h - T_1) + K_2(T_h^4 - T_1^4) \quad (3)$$

where K_1 is the convective heat transfer coefficient between combustion products and thermoelectric module and K_2 is the radiative heat transfer coefficient between module and burner surface. If it is further assumed that K_h is the overall heat transfer coefficient including convection and radiation, then the heat transfer from the heat source to the thermoelectric device may be estimated using the expression:

$$Q_h = K_h(T_h - T_1) \quad (4)$$

The heat transfer may also be expressed as

$$Q_h = \eta_c Q_{fuel} - K_{fg}A_E(T_h - T_0) \quad (5)$$

where η_c is the combustion efficiency, K_{fg} the heat loss flux from the burner exhaust outlet, A_E the area of the burner exhaust outlet and T_0 is the ambient temperature. Eq. (5) can be written as

$$Q_h = K_{fg}A_E(T_s - T_h) \quad (6)$$

where T_s is the temperature of the heat source when $Q_h = 0$. T_s is given by

$$T_s = \frac{\eta_c Q_{fuel}}{K_{fg}A_E} + T_0 \quad (7)$$

The power output of a thermoelectric device depends on the temperature difference between hot and cold junctions, the properties of thermoelectric materials and the external load resistance. For a given temperature difference, the Seebeck coefficient of a p–n junction, α (=dV/dT), determines the output voltage. The Seebeck coefficient of metals is usually between 0 and 50 μm K^{-1}, whereas the coefficient of semiconductors could be over 350 μm K^{-1}. According to the Seebeck effect, in a thermoelectric device, heat flux αIT_1 is absorbed by the hot junction and αIT_2 is rejected by the cold junction. In addition, there are three other effects in a thermoelectric device: Joule heating due to electric current; heat leak due to heat conduction between the two junctions; and the Thomson heat due to the temperature gradient and electric current. If the influence of the Thomson heat is negligible, the equations governing the heat input rate (Q_h) and heat rejection rate (Q_c) are obtained by considering the energy supply or removal to overcome the Peltier effects, the heat conduction, and the Joule heating [6]:

$$Q_h = \alpha_n I T_1 + K_n(T_1 - T_2) - I^2 \frac{R_n}{2} \quad (8)$$

$$Q_c = \alpha_n I T_2 + K_n(T_1 - T_2) + I^2 \frac{R_n}{2} \quad (9)$$

where K_n is the thermal conductance of the thermoelectric device consisting of n thermocouples, α_n the Seebeck coefficient, R_n the total electrical resistance of the thermoelectric device and I is the electric current. The heat removal rate from the module to the cooling medium is expressed as

$$Q_c = K_c(T_2 - T_c) \quad (10)$$

where K_c is the heat transfer coefficient between the module cold side and the cooling medium.

The electric power produced by the thermoelectric module is obtained from the energy balance:

$$P_{TE} = Q_h - Q_c = \alpha_n I(T_1 - T_2) - I^2 R_n = R_L I^2 \quad (11)$$

where R_L is the load resistance.

The electrical efficiency of the combustion-heated thermoelectric generation system is defined as

$$\eta = \frac{P_{TE}}{Q_{fuel}} = \frac{Q_h}{Q_{fuel}} \frac{P_{TE}}{Q_h} = \eta_b \eta_{TE} \quad (12)$$

where η_b (=Q_h/Q_{fuel}) is the efficiency of the combustion heat source and η_{TE} (=Q_{PE}/Q_h) is the electrical efficiency of the thermoelectric device.

For known or given thermal conductance, Seebeck coefficient and electrical resistance of a thermoelectric device consisting of n thermocouples, heat transfer coefficients and fuel combustion properties, we can solve the aforementioned equations for power output and electrical efficiency. First, in solving Eqs. (4), (6) and (8–10), we obtain the temperatures of hot and cold junctions for the thermoelectric module and the heat input and rejection rates. Then, we obtain the power output and electrical efficiency from Eqs. (11) and (12) at varying operating conditions. We also calculate the power output as a function of the ratio between load resistance and module internal resistance.

4.2. Modeling results

Figs. 6–8 present the calculated results for the gas-fired thermoelectric power system using the PbSnTe-based module having 325 thermocouples. Fig. 6 shows the electrical efficiency of the power system as a function of the combustion products temperature (heat source operating temperature) and as a function of the thermoelectric module inner wall temperature. Interestingly, as observed in Fig. 6, there is an optimum heat source temperature where the system efficiency reaches a maximum. For given heat transfer conditions, the electrical efficiency of a thermoelectric device increases with heat source operating temperature T_h with which the module inner wall temperature increases, but the heat source efficiency decreases with T_h. These combined effects lead to an optimum combustion heat source temperature.

Fig. 7 shows the variation of electrical efficiency with overall heat transfer coefficient between the hot side of the module and the combustion heat source. As expected, the efficiency increases as the heat transfer coefficient increases. For a given fuel input or a given combustion heat source temperature, the heat flux into the hot side depends on heat transfer conditions. As shown earlier, the heat transfer can be enhanced using heat-conducting fins. The fins on the hot side increase the convective heat transfer area substantially and reduce thermal resistance from combustion products to the hot side, thus increasing the hot junction temperature or power output for a given combustion load or fuel input. As a result, the electrical efficiency is increased.

Fig. 8 shows the calculated power output as a function of the ratio between load resistance and module internal resistance. The power output reaches a maximum at optimal load matching. The optimal load matching is attained when the ratio between load resistance and module internal resistance is about 1.2 or the load voltage is about 55% of the open circuit voltage. In other words, at

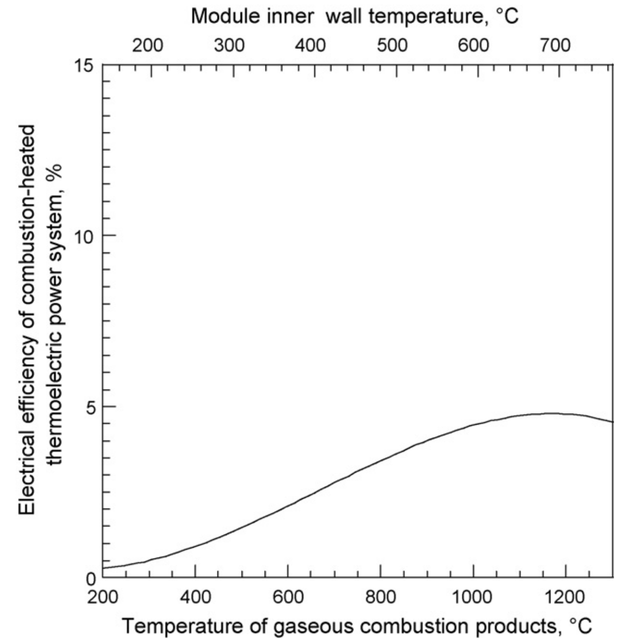

Fig. 6. Electrical efficiency of combustion-heated thermoelectric power system as a function of combustion products temperature (heat source operating temperature) and as a function of thermoelectric module inner temperature.

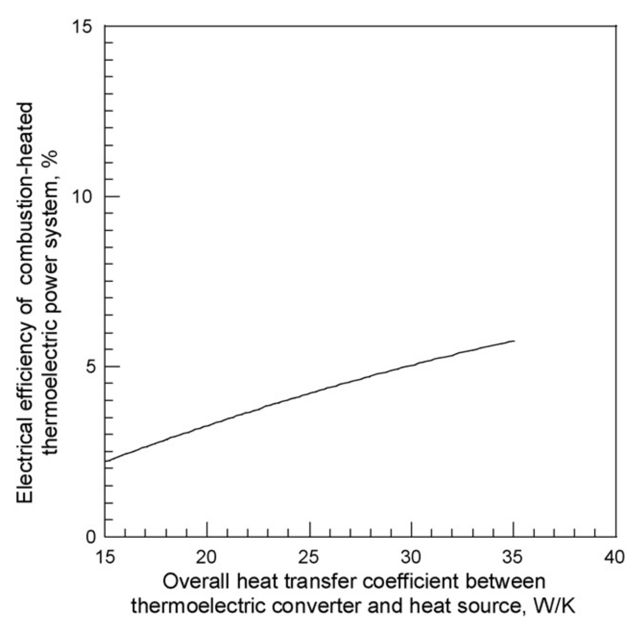

Fig. 7. Variation of electrical efficiency of combustion-heated thermoelectric power system with overall heat transfer coefficient between converter hot side and combustion heat source.

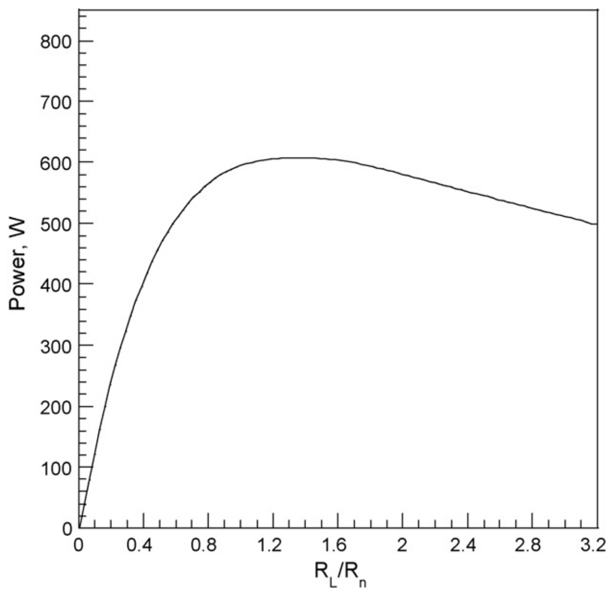

Fig. 8. Variation of power output with ratio between load resistance and internal resistance of thermoelectric module.

optimal load matching, load electrical resistance is slightly higher than module internal resistance.

5. Discussion

The theoretical energy conversion efficiency for a thermoelectric device is determined by the value of figure of merit (ZT) for a thermoelectric material. Over a long period, the value of ZT has hovered at about one; thus the efficiency of thermoelectric power generation is at relatively low levels. Since the late 1990s new thermoelectric materials have been developed and higher ZT values have been demonstrated with some promise that even greater ZT values can be obtained as development continues [7]. For instance, super lattice films, nanogranular bulk materials and point contact devices promise high ZT values. The efficiency of power generation can be significantly increased by using segmented thermoelectric elements. Both p-type and n-type thermoelectric materials are to be chosen in terms of their highest ZT for each temperature range. Established thermoelectric materials include low-temperature ($T < 500$ K) materials such as $(Bi, Sb)_2(Te, Se)_3$, mid-temperature ($550\,K < T < 850\,K$) materials such as PbTe and PbSnTe and high-temperature ($\sim$1200 K) materials such as SiGe alloys. Each material group has its optimum temperature range for high levels of heat to electricity conversion. The elements are thus constructed with a segmented structure to achieve the best average ZT over the operating temperature range for a power generation system.

Apparently, utilizing maximum ZT for specific applications and increasing ZT with new materials are primary goals in the field of thermoelectricity research. Electrical efficiency, however, is not always the most important criterion for certain applications. If a thermoelectric power unit is combined with heating equipment, then the unconverted heat can be fully utilized. In this case, the cost of the electricity generated is the cost of fuel for the equivalent heat energy. Thus, the electricity generation is essentially 100% efficient as is the case for a thermoelectric self-powered heating system where the dissipated heat is recovered for space and water heating needs. Also, the integrated energy system saves energy by decreasing the need for electricity generated by fossil fuel-fired power utilities which typically have an electrical efficiency of about 35%. Consequently, thermoelectric self-powered heating systems could be economically competitive and provide a means of reducing greenhouse gas emissions.

6. Conclusions

A thermoelectric self-powered residential heating system has been developed and a good applicability of thermoelectric power generation to the heating equipment has been demonstrated. Electricity generated by a thermoelectric module (maximum 553.9 W at a 552 °C temperature difference between the hot and cold walls) is adequate to power all electrical components for the residential central heating system, thus achieving self-powering. Excess power can be used to charge batteries or provide electricity for other electrical loads. The enhancement of heat transfer from gaseous combustion products to thermoelectric unit improves the electrical efficiency of the system. Heat-conducting fins are proven to be a useful means of enhancing heat transfer. Modeling calculations reveal the influence of various parameters on electric power output and the efficiency of the combustion-heated power system. Modeling results are useful in further system design optimization.

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