A 1KW THERMOELECTRIC POWER GENERATION SYSTEM FOR MICRO-COGENERATION

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Abstract. A combustion-driven thermoelectric power generation system was developed for potential micro-cogeneration applications. Thermoelectric modules with a total power capacity of 1000 W were integrated into a gas-fired furnace. The performance of the thermoelectric modules in the power generation system was investigated at various operating conditions. Different heat transfer strategies were examined in order to maximize electric power output. A mathematical model was established that considered various irreversibilities in the thermal to electric energy conversion process. The technology was demonstrated to offer the potential for applications in certain situations.

1. Introduction

A thermoelectric generator has no moving parts, and is compact, quiet, highly reliable and environmentally friendly. Thermoelectric power generation technology can be applied to self-powered heating appliances and micro-cogeneration systems in which fuel-fired heating equipment incorporates a power generator to convert a portion of heat to electricity. These integrated heat and power systems provide a means of providing on site power and energy security. The thermal efficiency of the heating equipment would be the same with or with no thermoelectric generation, since the heat dissipated from the power generation unit is fully used for space and water heating. In this study, a natural gas-fired thermoelectric generation system was constructed and tested. PbSnTe-based thermoelectric modules with a power capacity of 1000 W were integrated into a gas-fired furnace. A mathematical model for the combustion-driven power system was established.

2. Experimental

Figure 1 illustrates the gas-fired thermoelectric generation setup being investigated in this study. Two thermoelectric modules were employed in the experimental setup. The thermoelectric module is of a radial type (Figure 2). The thermoelectric elements in the module are made from PbSnTe doped to have either p or n-type semiconductor properties. One thermoelectric module has 325 couples with each couple consisting of a p-type element and an n-type element. Natural gas-fired burner heats the inner surface wall (hot junction) of the thermoelectric module. The burner is made of a high temperature alloy. The outside surface (cold junction) of the module is maintained at a low temperature by cooling water that circulates through a jacket surrounding the power unit. The two modules were arranged in tandem. The lower one has a flat heat transfer surface at the hot side while the upper one contains a number of heat-conducting fins to increase convective heat transfer from the flue gases to the thermoelectric module (Figure 3).

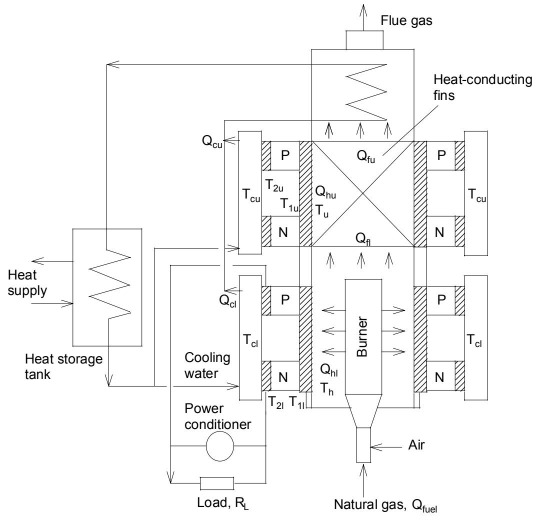

Figure 1. Gas-fired micro-cogeneration system using two thermoelectric modules

Figure 2. Thermoelectric module

Figure 3. Heat-conducting fins on module's inner wall to enhance heat transfer from gaseous combustion products to thermoelectric module

3. Experimental results

Table 1 illustrates the power output characteristics of the two thermoelectric modules in the gas-fired power system at various operating conditions. The power output was observed to increase markedly with module inner wall temperature. The electric power output of the upper module is somewhat lower than that of the lower module due to the more effective radiation heat transfer between the burner and the lower module. The total power output of the integrated system reached 1017.1W.

The premixed gas combustion in the burner first heats the hot side of the lower thermoelectric module. This involves two heat transfer processes. One is convective heat transfer between the combustion products and the module inner surface. The other is radiation heat transfer between the metal burner surface and the module inner surface. Heat is transferred from the flue gases to the upper thermoelectric module primarily through convective heat transfer. The convective heat transfer on the hot side is enhanced by adding heat-conducting fins to the module inner wall. The fins increase convective heat transfer area and reduce thermal resistance from the combustion products to the inner wall, thus increasing hot junction temperature.

The electricity generated in this system is capable of powering all the electrical components for a residential central heating system. Typically, a single-family space and water heating system consumes 200-450 W electricity. In addition to self-powering the electrical components of a heating system, excess electricity can charge batteries or be fed into the household grid. The thermoelectric power unit can integrate into a hybrid energy system (e.g. with a solar photovoltaic system).

Table 1 Results of power output characteristics at various conditions

Heat source (burner) operating temperature, ºC	TE module	Module inner wall temperature, ºC	Cold side temperature, ºC	Open circuit voltage, V	Load voltage, V	Load current, A	Power output, W
959	Upper module	566	78	43.1	23.7	17.7	423.7
	Lower module	605	80	49.8	25.9	19.6	506.5
1053	Upper module	591	78	47.5	24.8	18.7	464.3
	Lower	630	82	53.2	27.1	20.4	552.8

4. Modeling

4.1 Model description

The gas-fired thermoelectric power system is shown in Figure 1. If we assume that the burner surface and combustion products have the same temperature, T_h, the energy balance between the burner and the lower thermoelectric converter may be written as:

$$Q_{hl} = K_1(T_h - T_{1l}) + K_2(T_h^4 - T_{1l}^4) \qquad (1)$$

where K_1 is the convective heat transfer coefficient between combustion products and thermoelectric converter and K_2 is the radiative heat transfer coefficient between converter and burner surface. If it is further assumed that K_{hl} is the overall heat transfer coefficient including convection and radiation, then the heat transfer from the heat source to the thermoelectric device can be calculated from the following expression:

$$Q_{hl} = K_{hl}(T_h - T_{1l}) \qquad (2)$$

The heat transfer may also be expressed as:

$$Q_{hl} = \eta_c Q_{fuel} - K_{fl} A_E (T_h - T_0) \qquad (3)$$

where η_c is the combustion efficiency, K_{fl} is the heat flux from the burner exhaust outlet, A_E is the area of the burner exhaust outlet and T_0 is the ambient temperature. Equation (3) can be written as:

$$Q_{hl} = K_{fl} A_E (T_s - T_h) \qquad (4)$$

where T_s is the temperature of the heat source at the conditions of $Q_{hl} = 0$. T_s is given by

$$T_s = \frac{\eta_c Q_{fuel}}{K_{fl} A_E} + T_0 \qquad (5)$$

For the upper thermoelectric module, the heat transfer from the flow gases to the module may be calculated from the following expression:

$$Q_{hu} = K_{hu}(T_u - T_{1u}) \qquad (6)$$

where Q_{hu} is the heat transfer rate from the flow gases at temperature T_u to the upper thermoelectric module, and K_{hu} is the heat transfer coefficient. Equation (6) may also be written as:

$$Q_{hu} = K_{fu} A_E (T_h - T_u) \qquad (7)$$

with K_{fl} being the heat loss flux from the exhaust flow gases outlet.

The equations governing the heat inputs and heat rejections for the two modules are obtained by considering the energy supply or removal to overcome the Peltier effect, the heat conduction and the Joule heating:

$$Q_{hl} = \alpha_n I_l T_{1l} + K_n (T_{1l} - T_{2l}) - I_l^2 \frac{R_n}{2} \quad (8)$$

$$Q_{hu} = \alpha_n I_u T_{1u} + K_n (T_{1u} - T_{2u}) - I_u^2 \frac{R_n}{2} \quad (9)$$

$$Q_{cl} = \alpha_n I_l T_{2l} + K_n (T_{1l} - T_{2l}) + I_l^2 \frac{R_n}{2} \quad (10)$$

$$Q_{cu} = \alpha_n I_u T_{2u} + K_n (T_{1u} - T_{2u}) + I_u^2 \frac{R_n}{2} \quad (11)$$

where K_n is the thermal conductance of the thermoelectric device consisting of n couples, α_n is the Seebeck coefficient, R_n is the total electrical resistance of the thermoelectric device and I_l and I_u are the electric currents generated by the lower module and upper module, respectively. The heat removal rates are expressed, respectively, as

$$Q_{cl} = K_c (T_{2l} - T_{cl}) \quad (12)$$

$$Q_{cu} = K_c (T_{2u} - T_{cu}) \quad (13)$$

where K_c is the overall heat transfer coefficient between the cold side and the cooling medium (heat sink).

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

$$P_{TE} = P_{TEl} + P_{TEu} = Q_{hl} - Q_{cl} + Q_{hu} - Q_{cu} = R_L (I_l + I_u)^2 \quad (14)$$

where R_L is the load resistance. The electrical efficiency of the combustion-heated thermoelectric generation system is defined as:

$$\eta = \frac{P_{TE}}{Q_{fuel}} \quad (15)$$

We can solve above equations for power output and electrical efficiency at various operating conditions.

4.2 Modeling results

Figure 4 illustrates the electrical efficiency of the power system as a function of the burner operating temperature. There is an optimum heat source temperature where the efficiency reaches a maximum. The reason is, for given heat transfer conditions, the electrical efficiency of a thermoelectric device increases with heat source operating temperature T_h, but the heat source efficiency decreases with T_h. These combined effects lead to an optimum combustion heat source temperature.

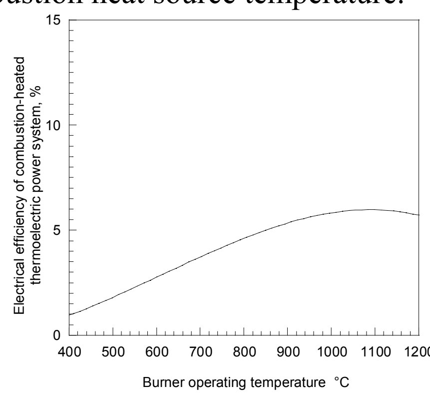

Figure 4. System electrical efficiency vs burner (heat source) operating temperature

The combustion-driven thermoelectric power systems offer the potential for applications in certain situations in spite of a relatively low electrical efficiency. For instance, if a thermoelectric power unit is combined with fuel-fired heating equipment, then the unconverted heat can be fully utilized. In fact, the electricity generation is essentially 100% efficient for a thermoelectric self-powered heating system or micro-cogeneration where the dissipated heat is recovered for space and water heating needs. This is superior to conventional fuel-fired heating equipment.