Optimisation of thermoelectric module geometry for 'waste heat' electric power generation

Gao Min
Kunming Institute of Physics, Kunming (China)

D. M. Rowe*
School of Electrical, Electronic and Systems Engineering, University of Wales College of Cardiff, P.O. Box 904, Cardiff CF1 3YH (UK)

(Received July 26, 1991; in revised form September 23, 1991)

Abstract

In this paper the 'performance' of a commercially available thermoelectric module (Peltier cooler) is investigated when operated in the Seebeck mode as a generator, to convert low temperature 'waste heat' into electrical power. Calculations based upon a realistic theoretical model of a single couple 'generator', which takes into account contact effects, indicate that a significant increase in the electrical power output from a module can be achieved by modifying the geometry of the thermoelements. The increase in power output is not accompanied by a significant reduction in conversion efficiency. Measurements on three commercial modules with the same number of thermocouples and with the same thermoelement cross-sectional area but different thermoelement length confirmed the predicted improvement in output power when the hot side of the module was attached to a simulated heat source at 120 °C with the cold side maintained at ambient. A decrease in the length of the thermoelements by 55% was accompanied by an increase of 48% in the electrical power output while the conversion efficiency was reduced by less than 10%. This improvement in 'performance' will be less in an actual generating system where the heat is derived from a flow of water. Nevertheless, it is concluded that in principle thermoelectric generators, when used over a long period of time (20–25 years), can provide on-site electrical power from low temperature waste heat at cost which is competitive to that generated by conventional utilities.

Introduction

In a recent United Kingdom Department of Energy publication the problem of converting low temperature 'waste heat' into electrical power was addressed [1]. Low temperature heat was considered to be heat at a temperature below 240 °C. Typical sources of low temperature heat are geothermal, hot dry rock, cooling water from large industrial utilities, solar ponds, ocean thermal energy, and hot water from decommissioned oil wells. Most heat from these sources is at a temperature considerably below the 140 °C required to drive a steam turbine. However, low temperature heat can be converted into electrical power using an organic Rankine cycle or thermoelectric generators. Thermoelectric generators are less efficient than Rankine engines but they

*Author to whom correspondence should be addressed.

0378-7753/92/$5.00

do offer a number of advantages not the least of which are that they are extremely reliable and environmentally friendly. Although thermoelectric generators are extensively used in a number of specialised applications [2] the wider application of this method for generating electrical power has previously been thought uneconomic. The concept of large scale thermoelectric generation has been discussed previously in general terms [3] but the only reported experimental data relate to a system based on ocean thermal energy conversion (OTEC). In OTEC the thermoelectric generator utilises the temperature differences which exist between the warm surface waters and the cold deep water of a number of tropical seas [4].

Thermoelectric convertors are usually designed for use in the Peltier mode, as refrigerating devices, although it has been reported that commercially available Peltier devices would operate as generators at the highest efficiencies that thermoelectrics can currently attain at temperatures up to about 500 K. This is because the thermoelements are fabricated from materials which possess their highest figures of merit over this temperature range of operation [5]. However, whether the thermoelectric convertor is used as a generator or a refrigerator, the geometry of the elements of commercially available modules has been optimised for the device to operate at maximum efficiency or to attain the largest temperature difference.

In large scale thermoelectric generation using 'waste heat' as the heat input, conversion efficiency is not an overriding consideration. Consequently the thermoelement geometry should now be optimised to maximise the electrical power output. The resulting increase in power from a module with 'modified geometry' is accompanied by a significant reduction in the 'cost per watt'. However, transferring this benefit to an operating system where the heat is derived from a water flow is not straightforward and involves a more complicated optimisation procedure. In this paper the conditions which maximise the power output from a module are investigated and the factors which influence the optimisation of an actual generating system discussed.

Theoretical model

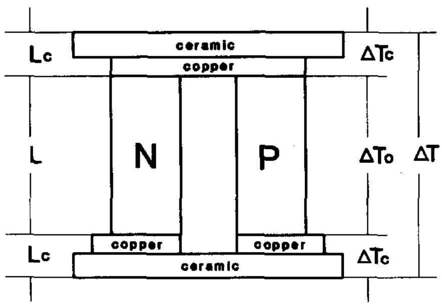
A single couple thermoelectric module is shown in Fig. 1. It consists of an n-type and a p-type semiconductor thermoelement which are connected by electrically conducting copper strips and supported by two plates of high thermally conducting but electrically insulating aluminium oxide. When contact effects are neglected the power output P_i of this 'ideal' generator is given by [6]

$$P_i=\left(\frac{\alpha^2}{\rho}\right)\left(\frac{\Delta T^2}{2}\right)\left(\frac{A_0}{L_0}\right) \qquad (1)$$

where α is the Seebeck coefficient, ρ the bulk electrical resistivity of the thermoelements, ΔT the temperature difference across the thermoelements and A_0/L_0 is the ratio of cross-sectional area to length of the thermoelements. This expression indicates that the power output approaches infinity as the length of the thermoelements goes to zero. However, in an actual device this limit cannot be realised because of the finite electrical and thermal resistance associated with the contacting layers.

A more realistic model which takes into account these contact effects can be formulated and is given by:

$$P_c=P_i(A/A_0)(L/L_0+(\rho_c/\rho)/L_0)^{-1}(1+2(\lambda/\lambda_c)(L_c/L))^{-2} \qquad (2)$$



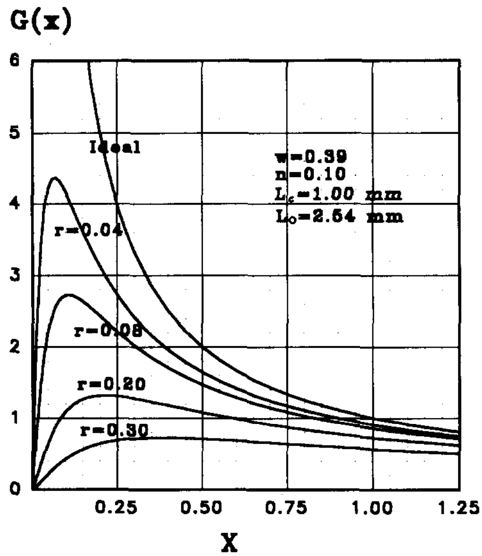


Fig. 1. Single couple thermoelectric module.

Fig. 2. Theoretical power output of thermoelectric module vs. length of thermoelement.

where ρ_c is the contact electrical resistivity, λ_c the contact thermal conductivity, L_c the thickness of the contact layer and A/L the ratio of the cross-sectional areas to length of the modified thermoelements. The change of the power output of the generator as a function of the length and cross-sectional area of the thermoelements can be obtained from the equation:

$$G(x) = (P_c/P_i) = ax^2\ (x + n/L_0)^{-1}(x + 2rw)^{-2} \qquad (3)$$

where $a = A/A_0$, $n = \rho_c/\rho$, $r = \lambda/\lambda_c$, $w = L_c/L_0$, and $X = L/L_0$.

It can be seen that the power output increases with an increase in the cross-sectional area of the thermoelements and with a decrease in their length. Evidently an increase in the former is accompanied by an increase in device volume and consequently in the amount of semiconductor material; both of which are undesirable. A decrease in thermoelement length results in a beneficial reduction in volume and amount of material.

In Fig. 2, the fractional change in power output is expressed as a function of the fractional change in thermoelement length. The power output increases with a decrease in thermoelement length until it reaches a maximum and then decreases with a further decrease in the length of thermoelement. It is also evident that the power output is affected by the properties of the contacts. A prerequisite for a large power output is that the ratio of the bulk electrical conductivity and thermal conductivity to that of the contact should be low.

Experimental

Performance predictions based upon the theoretical model were investigated by experiment. Three commercial modules designated CP 1.4-127-10L, CP 1.4-127-06L and CP 1.4-127-045L were obtained from MELCOR, USA. The three modules were identical apart from having thermoelements which differed in length as indicated in Table 1.

A temperature difference was established across each module by attaching an electric heater to the 'hot side' of the module and a heat sink to the 'cold side'. The open circuit voltage V_{op} and the short circuit I_{sc} were measured and the output power calculated using $P = V_{op}I_{sc}/4$.

Results

The power output from the three modules is displayed in Fig. 3. Evidently the power output increases with a decrease in the thermoelement length. The fractional increase in power output of the modules obtained from the experimental data together with the corresponding theoretical fractional increase obtained from curve $r = 0.20$ in Fig. 2 are also reported in Table 1.

It was anticipated that the increase in power output would be accompanied by a substantial reduction in conversion efficiency; this proved not to be the case. The

TABLE 1

Length dependence of power output of thermoelectric modules

Modules	Length (mm)	L/L_0	P_c(W)	F_e (%)	F_t (%)
CP 1.4-127-10L	2.54	1.00	1.36	0	0
CP 1.4-127-06L	1.52	0.60	1.72	26	30
CP 1.4-127-045L	1.14	0.45	2.01	48	50

$L_0 = 2.54$ mm; P_c were measured under temperature difference 100 K; F_e and F_t are fractional increases in power outputs obtained from the experiment and theory, respectively.

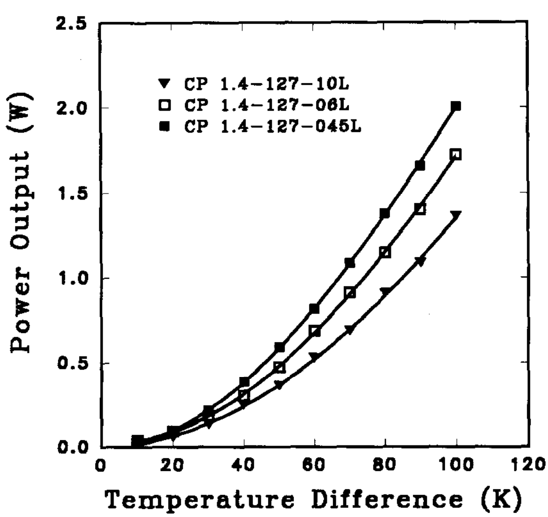


Fig. 3. Experimental power output of thermoelectric modules as a function of temperature difference and length of thermoelements.

reduction in conversion efficiency with decrease in thermoelement length is shown in Fig. 4. Decreasing the length from 2 to 0.5 mm is accompanied by a reduction in efficiency of only 8%.

Discussion and conclusions

A simple realistic theoretical model of a single couple thermoelectric module has been formulated and employed to investigate the dependence of electric power output on thermoelement geometry. Good agreement has been obtained between the theory and experimental data. The results indicate that a reduction in thermoelement length from 2.54 to 0.5 mm results un an increase in power of ~75%. This increase in power is accompanied by an acceptable decrease in conversion efficiency of about 8%.

This increase in output power has significant economic benefits if carried over to an operating system. Currently available Peltier coolers of the type investigated generate about one watt(e) when operating at a temperature difference of around 100 K and cost about 20$ a unit. This cost reduces to around 10$ a unit for orders of several thousand. The calculated cost of generating electrical power using thermoelectrics is displayed in Fig. 5. It is evident that electricity can be generated over 20 years at a cost of around 6 cents per kW h. Employing a module with shorter thermoelements (producing 1.75 W) reduces the cost to about 3.5 cents per kW h. The modules will be the most costly items in any large scale thermoelectric generating system, consequently doubling the generating cost would overestimate the cost of the total system. Nevertheless the total generating cost of around 7 cents per kW h would compare very favourably with the price of between 5 and 7 cents paid for electricity generated by conventional methods [7].

However in an actual conversion system where the heat input is provided by a flow of water the temperature difference across the thermoelements will be subtantially less than that maintained across a module when in intimate contact with a simulated heat source at the same temperature. Optimisation of the system now involves taking

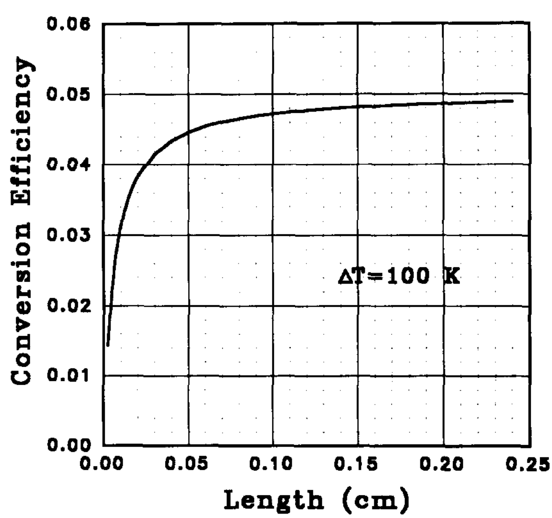


Fig. 4. Conversion efficiency vs. length of thermoelement of the modules.

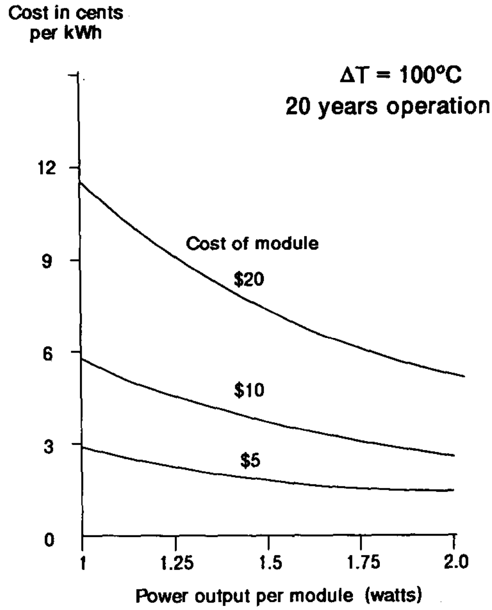


Fig. 5. Cost of electricity as a function of module cost and power output per module.

into account the heat transfer coefficient between the water and the thermoelements. This results in a different optimum thermoelement geometry but preliminary calculations indicate that for a water flow at 120 °C and the cold side at ambient the output power per module would maximise at around 1.4 W(e). As is evident from Fig. 5 the increase in the cost per kW h will be marginal.

Acknowledgements

The Kunming Institute of Physics, China, is acknowledged for Gao Min's one year's leave of absence at the University of Wales College of Cardiff. The British Council is thanked for funding the collaboration programme between U.W.C.C. and K.I.P.

References

1 Watt Committee Report, Profiting from low grade heat, presented at The Institution of Mechanical Engineers, Feb. 26, 1991.
2 D. M. Rowe and C. M. Bhandari, *Modern Thermoelectrics*, Holt, Rinehart and Winston, New York, 1983, ISBN 0-03-910433-8.
3 D. K. Benson and T. S. Jaydev, *Proc. Third Int. Conf. Thermoelectric Energy Conversion, Arlington, TX, USA, Mar. 12–14, 1980*, pp. 27–57.
4 K. T. Matsuura, *IEE Japan*, 1987, 107-B, No. 6, pp. 307–314.

5 E. J. Burke and R. J. Buist, *Proc. Fifth Int. Conf. Thermoelectric Energy Conversion, Arlington, TX, USA, Mar. 14–16, 1984*, pp. 91–94.
6 A. F. Ioffe, *Semiconductor Thermoelements and Thermoelectric Cooling*, Infosearch Ltd., London, 1957.
7 J. Crook, Some uses of low grade heat, in *Power Generation Technology*, Sterling Pulications International Ltd., London, 1992, to be published.