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Evaluation of thermoelectric modules for power generation

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Abstract

A procedure is developed to assess the potential of thermoelectric modules when used for electrical power generation. The generating performance of a thermoelectric module is evaluated in terms of its power output, conversion efficiency and reliability, while the potential for improving its performance is investigated based upon the power-per-area, cost-per-watt and manufacture quality factor. The methods employed in determining these parameters are described and used to evaluate several commercially available modules. The results show that a thermoelectric module is a promising device for low temperature waste heat recovery.

Keywords: Thermoelectric modules; Heat recovery; Power generation

1. Introduction

The relatively low conversion efficiency of thermoelectric modules (∼5%) has been a major factor in limiting their applications in electrical power generation and has restricted their use to specialised situations where reliability is a major consideration [1]. However, one exception is the thermoelectric recovery of waste heat when it is unnecessary to consider the cost of the thermal input [2]. Consequently, the low conversion efficiency is not a serious drawback. The primary consideration in this application is to optimise the thermoelectric module to provide maximum power output. A previous investigation has shown that the power output of thermoelectric modules can be improved by optimising the thermoelement length [3]. Accompanying recent progress in this field is an urgent need for reliable information on the generating performances of thermoelectric modules. Generally, the power output and conversion efficiency provide a rough estimation of module performance when operating in the generating mode. However, additional information such as the power-per-unit-area, cost-per-watt, quality of module fabrication and reliability is required to evaluate its commercial potential for its intended application and to identify areas of further improvement in module performance. Furthermore, this information would also facilitate a direct comparison of currently available modules of different design and assembled using different fabrication processes.

2. Maximum power output and conversion efficiency

Two types of commercially available multicouple thermoelectric modules are shown schematically in Fig. 1a–b. Type A was originally designed for cooling applications and possesses significant inter-thermoelement separation. In this type of module, *n*- and *p*-type semiconductor thermoelements are connected electrically in series by highly conducting metal strips and sandwiched between thermally conducting but electrically insulating plates. Type B has been developed recently for power generation and is densely constructed with very small inter-thermoelement separation. However, the conducting metal strips in the latter module are not insulated and the module cannot be attached directly to electrical conductors, such as an aluminium heat sink.

Maximum power output of a thermoelectric module is defined as the power output generated when the module resistance matches the load resistance. In principle, the maximum power output of a thermoelectric module can be measured readily when it has a temperature difference across it. However, in practice, accurate measurement of power output requires an appropriate circuit which minimises the problems associated with the very low thermoelectric module resistance and fluctuations in signal mea-

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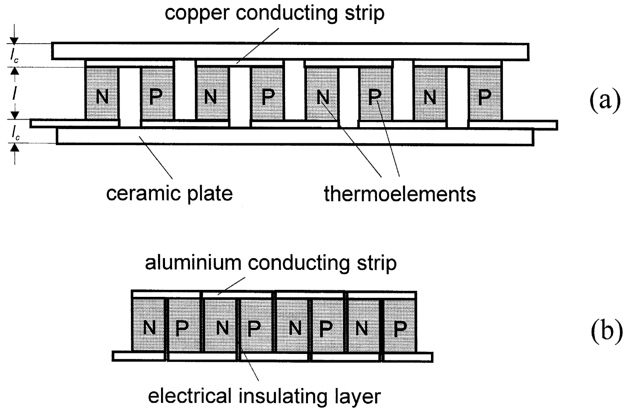

Fig. 1. Schematic diagrams of multicouple thermoelectric modules. (a) Type A configuration with ceramic insulating plates and large inter-thermoelement separation; (b) Type B configuration without ceramic insulating plate and with very small inter-thermoelement separation.

surements due to the Peltier effect. In Fig. 2 is shown a circuit designed to overcome these problems, which enables an accurate measurement to be made of the thermoelectric module maximum power output. When a temperature difference is established across the module, voltages V_1 and V_2 are measured at terminals a and b when the switch is open and closed, respectively. The maximum power output of the module can be calculated using

$$P_{\max} = \frac{V_1^2}{4R_L(V_1/V_2 - 1)} \quad (1)$$

where, R_L is the load resistance which includes contributions from all the wires and connections in the circuit. The electrical resistance of a module (R_m) can also be obtained from,

$$R_m = R_L\left(\frac{V_1}{V_2} - 1\right) \quad (2)$$

Fig. 3a–b display the maximum power output as a function of temperature difference for modules which possess different geometry as listed in Table 1. The modules denoted ‘I’ indicate that they possess 127 thermocouples having a thermoelement cross-sectional area of about 1.4×1.4 mm^2 (Fig. 3a). While those denoted ‘II’ and ‘III’ possess 33 thermocouples with a cross-sectional area of about 4.5×4.5 mm^2 and 50 thermocouples with a cross-sectional area of 5.0×5.0 mm^2, respectively (Fig. 3b). It can be seen that the maximum power output increases parabolically with an increase in temperature difference. For a given temperature difference, there is a significant variation in maximum power output for different modules due to variation in thermoelectric materials, module geometry and contact properties. However, as shown in Fig. 3a, the maximum power output follows a clear trend and increases with an decrease in thermoelement length for a given cross-sectional area.

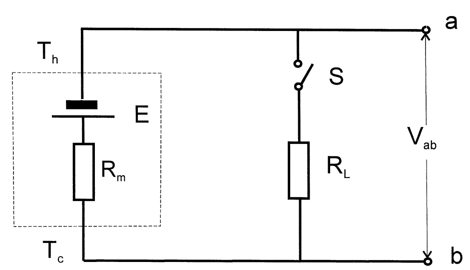

Fig. 2. Circuit for measuring the maximum power output and resistance of thermoelectric modules.

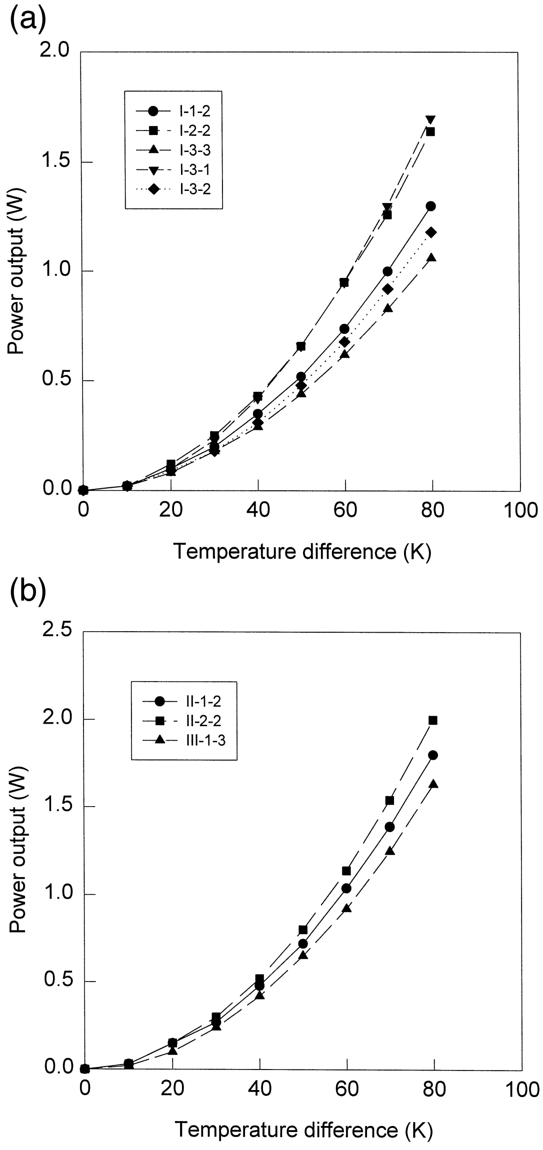

Fig. 3. Maximum power output as a function of temperature differences. (a) Modules with 127 thermocouples and a cross-sectional area of 1.4×1.4 mm^2; (b) Modules denoted II possess 31 thermocouples and a cross-sectional area of 4.5×4.5 mm^2. Module denoted III possesses 49 thermocouples and a cross-sectional area 5.0×5.0 mm^2.

Measurement of the conversion efficiency of a thermoelectric module presents difficulties because it requires an

Table 1
Thermocouple number (N), cross-sectional area (A) and thermoelement length (l) of several commercially available modules

Modules	N	A (mm^2)	l (mm)	A/l (mm)
I-1-2	127	1.35×1.35	1.53	1.19
I-2-2	127	1.47×1.47	1.47	1.47
I-3-1	127	1.40×1.40	1.14	1.72
I-3-2	127	1.40×1.40	*2.03*	*0.96*
I-3-3	127	1.40×1.40	2.54	0.77
II-1-2	31	4.30×4.30	1.52	12.16
II-2-2	31	4.50×4.50	1.67	12.12
III-1-3	50	5.00×5.00	3.00	8.33

accurate determination of the heat input absorbed at its hot side. However, a realistic estimate of the module conversion efficiency can be made which is based upon the maximum power output and its relationship to the contact properties. When consideration is taken of the effects of thermal and electrical contact resistances, the power output per unit area ($p = P/NA$) and the conversion efficiency of a module are given by [3],

$$P = \frac{\alpha^2}{2\rho}\frac{NA\Delta T^2}{(l+n)(1+2rl_c/l)} \tag{3}$$

$$\phi = \left(\frac{T_h - T_c}{T_h}\right)\left\{(1+2rl_c/l)^2\left[2 - \frac{1}{2}\left(\frac{T_h - T_c}{T_h}\right) + \frac{4}{zT_h}\left(\frac{l+n}{l+2rl_c}\right)\right]\right\}^{-1} \tag{4}$$

where, α, ρ and z are the Seebeck coefficient, electrical resistivity and figure-of-merit respectively of the thermocouple material; N the number of thermocouples in a module; A the cross-sectional area of thermoelements; T_h and T_c are the respective temperatures at the hot and cold sides of the module; l_c the thickness of the insulating ceramic layers; $n = \rho_c/\rho$ and $r = \lambda/\lambda_c$, where ρ_c and λ_c are the electrical and thermal contact resistivities. The contact parameters n and r of a given thermoelectric module can be determined from the maximum power output using a method described previously [4]. The conversion efficiency, ϕ, can then be estimated using Eq. (4). In Fig. 4 is shown the conversion efficiency, together with the corresponding maximum power output, as a function of thermoelement length for different temperature differences at $n = 0.1$ mm and $r = 0.2$ (both are typical values for the type A commercially available modules). It can be seen that a conversion efficiency of 3% can be achieved for modules with a thermoelement length around 1.5 mm and operating at a temperature difference of about 80 K with the cold side at 300 K. The conversion efficiency of the modules can be improved by operating at a larger temperature difference and/or increasing the thermoelement length. However, the maximum power output will be reduced if a longer thermoelement is employed. Consequently, thermoelement length is usually a compromise between that required for the maximum power output and that for maximum conversion efficiency and should be optimised to obtain minimum cost (£/kWh) taking into account the cost of heat sources [5].

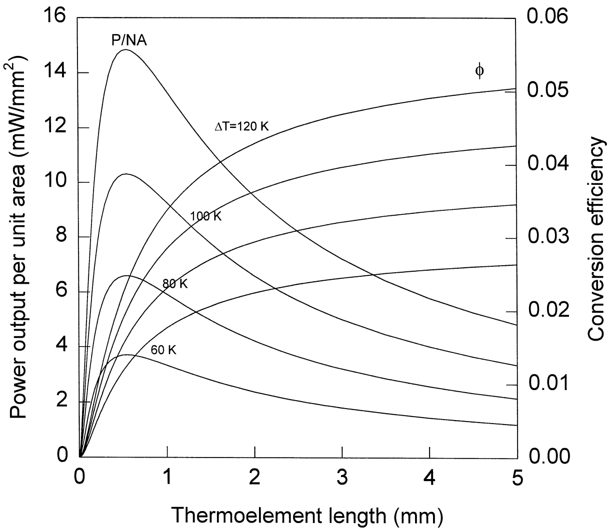

Fig. 4. Power output per unit area and conversion efficiency as a function of thermoelement length.

3. Manufacture quality factor (MQF)

Maximum power output and conversion efficiency of a thermoelectric module provide useful information on its performance as a generator. However, as indicated by Eqs. (3) and (4), both the maximum power output and conversion efficiency depend upon temperature difference, thermocouple materials, module geometry and contact parameters, the latter being closely associated with the module fabrication process. The performance of a module, having thermoelements with a fixed geometry, fabricated from a given materials and operated in a given temperature regime, will be determined by its quality of manufacture. Manufacture quality includes selection of contact materials and formation of electrical junctions and thermal contact layers. In order to quantify the manufacture quality, the influence of the temperature difference and module geometry has to be separated from those factors associated with the manufacturing process. Rewriting Eq. (3) as,

$$P = F \cdot N\Delta T^2\left(\frac{\alpha^2}{2\rho}\right)\left(\frac{A}{l}\right) \tag{5}$$

where

$$F = \frac{1}{\left(1+\frac{n}{l}\right)\left(1+\frac{2rl_c}{l}\right)^2} \tag{6}$$

or

$$F = \frac{P}{N\Delta T^2 \left(\frac{\alpha^2}{2\rho}\right)\left(\frac{A}{l}\right)} \tag{7}$$

where F is referred to as the manufacture quality factor (MQF). It can be seen from Eq. (6) that F approaches unity when the electrical and thermal contact resistances are negligible and/or the thermoelement length approaches infinity. The maximum power output and conversion efficiency then approached those predicted by the 'ideal' model [6]. However, in practice, a relatively short thermoelement should be employed to obtain large power output. Consequently, a large F can only be obtained by reducing the thermal and electrical contact resistances. In Fig. 5 is plotted F as a function of thermoelement length for different contact resistances. It can be seen that for modules with the same thermoelement length, any variation in F indicates differences in the quality of manufacture. Furthermore, it is noted that each curve in the figure represents a group of modules which possess identical contact properties (determined solely by the manufacturing process), although their thermoelement lengths may be different. Consequently, the module manufacture quality for different thermoelement lengths can be compared by identifying their corresponding curves. Evidently, F is a useful parameter which measures manufacturers' ability to fabricate high-quality modules based upon the available materials and it can also be used as a pointer for improving module performance.

The F of commercially available thermoelectric modules can also be estimated experimentally using Eq. (7) and the results are displayed by solid circles in the figure. It is apparent that the module manufacture quality for the majority of the manufacturers is quite similar with F values ranging between 0.6 to 0.8 for a thermoelement length of around 1.5 mm. However, module III-1-3 exhibits a significantly poorer MQF because of different contacts and manufacturing process. Evidently, this result also indicates that the performance of module III-1-3 can be increased significantly by improving its MQF.

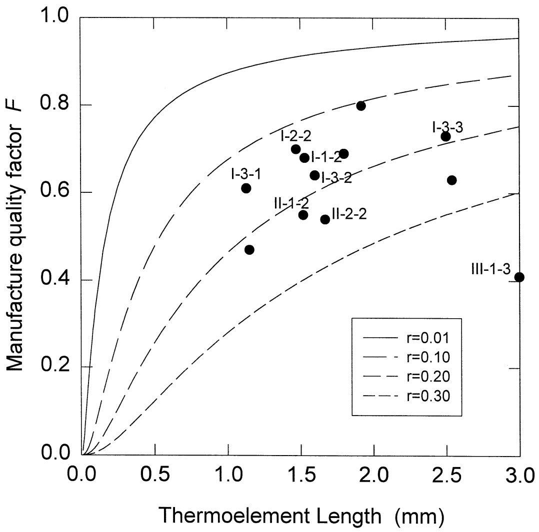

Fig. 5. Manufacture quality factor F as a function of thermoelement length for $n = 0.1$ mm and $l_c = 1$ mm.

4. Power-per-area and cost-per-watt

The power-per-area of a module is defined as the ratio P/A_m, where P is the power output and A_m the area of the module, while the power per area of thermoelements is defined as the ratio $P/2NA$, where A is the cross-sectional area of a thermoelement and N the number of the thermocouples employed in a module. There are basically two types of commercially available thermoelectric modules. Modules denoted I and II in Table 1 possess a type A configuration, while the module denoted III is type B. In Table 2 are compared the power-per-area for both types of modules from several different manufacturers. It can be seen that type A possesses a significantly larger $P/2NA$ than that of type B, which may result from different fabrication techniques. However, P/A_m of type A is only slightly larger than that of type B because of the significant separation between the thermoelements in type A. These results indicate that the ratio P/A_m of type A can be increased by reducing the inter-thermoelement separation. It is estimated that the ratio of $2NA/A_m$ can readily be increased from about 0.35 to 0.50 for type A, which results in an increase of about 40% in the power-per-area. Although the inter-thermoelement separation is very small for type B, the thermoelement power-per-area ($P/2NA$) is low compared with that of type A. As indicated in Section 3 using MQF, type B possesses relatively poor contact properties.

In Table 2 are also collected the price and cost-per-watt of currently available modules from several manufacturers. It can be seen that the cost-per-watt for different modules differs significantly, although these modules display much less diversity in their power output. In general, the cost of

Table 2
Comparison of the power output per unit area, p, for different modules at temperature difference $\Delta T = 65$ K. A_m is module area, A the thermoelement cross-sectional area, N the number of thermoelements in the module, P the maximum power output per module

Modules	I-1-2	I-2-2	I-3-1	II-1-2	III-1-3
A_m (mm^2)	1600	1600	1600	3025	2704
$2NA$ (mm^2)	463	549	489	1136	2500
$2NA/A_m$	0.29	0.34	0.31	0.38	0.92
P (W)	0.9	1.1	1.1	1.6	1.1
$P/2NA$ (W/m^2)	1940	2000	2210	1410	440
P/A_m (W/m^2)	560	680	690	530	406
Cost (£)	13.3	19.3	5.3	31.2	103.3
£/W	14.8	17.6	4.8	19.5	93.9

thermoelectrically producing electricity mainly consists of the running cost and module cost. The running cost is determined by its conversion efficiency, while the module cost is determined by the cost of its construction to produce the required power output. Since the conversion efficiency of a module is comparatively low, thermoelectric generation using waste heat is an ideal application. In this case, the running cost is negligible compared with the module cost because the fuels cost very little or nothing. Consequently, an important objective in thermoelectric power generation using waste heat is to reduce the cost-per-watt of the modules. It can be seen from Table 2 that a figure of about £4/W can readily be obtained from module I-3-1, which is comparable to that of the state-of-art solar cell [7]. The low cost-per-watt of the module is attributed to its Chinese origin and associated low manufacturing costs. Furthermore, cost-per-watt can be reduced by optimising the module geometry, improving the manufacture quality and simply by operating the module at a larger temperature difference. For instance, if the ratio of $2NA/A_m$ of a module such as I-3-1 is increased to 0.5 and thermoelement length reduced to 0.7 mm, the corresponding increase in the power output of the module will be about 70% and 10%, respectively, as a result of an increase in the ratio A/l and thermoelement length optimisation [5]. However, the resulting increase in module cost is unlikely to be significant. In addition, further doubling in the power output can be achieved by increasing the temperature difference of module's operation from the 65 K employed in the present work to 100 K [5]. Consequently, the cost-per-watt can be reduced to about £1/W.

5. Reliability and failure mechanisms

The cost-per-watt of a module provides a measure of its economic performance to some extent. However, the ultimate cost of the electricity generated using a thermoelectric module is a function of the operating period and consequently, related to its reliability. In general, the cost of electricity generated thermoelectrically using waste heat is given by,

$$£/\text{kWh} = \frac{\text{Cost per watt}}{\text{Mean time between failure}} \quad (8)$$

In Fig. 6 is shown the cost of electricity as a function of the operating period for several modules at a temperature difference of 65 K with the cold side at 300 K. UK domestic electricity consumption cost of about £0.08/kWh is also given as a comparison. It should be noted that the estimated price shown in Fig. 6 neglects the system construction cost. Nevertheless, the results indicate that a highly reliable module is required for thermoelectric generation to be economically competitive. For commercially available modules, a mean-time-between-failure of over 10 years is probably the minimum requirement.

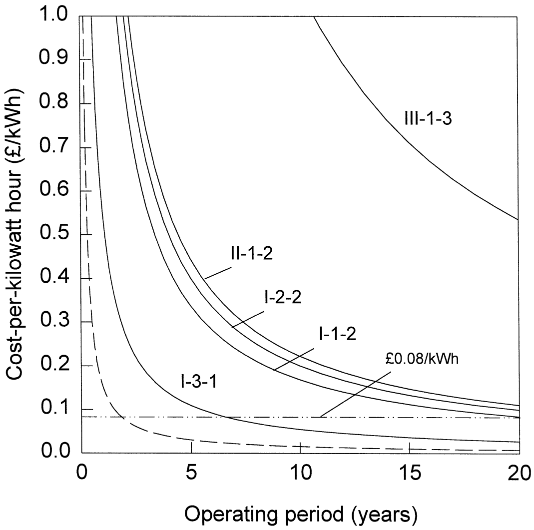

Fig. 6. Cost of electricity as a function of operating periods. Solid lines represent commercially available modules operated at $\Delta T = 65$ K. Dashed lines indicates the predicted cost for a module with improved power-per-area operated at $\Delta T = 100$ K.

It has been reported that commercially available modules are very reliable when used as coolers and operated at temperatures below room temperature [8]. However, the results of a recent reliability study indicated that these modules may be less reliable when operated above room temperature as generators [9]. Preliminary results showed that a significant change in the electrical resistance of the modules is mainly responsible for the degradation of module performance, while degradation in the Seebeck coefficient is less significant. Consequently, the electrical resistance can be used as a indicator for module degradation. In Fig. 7 is shown the change in AC resistance of modules as a function of time. It can be seen that the electrical resistance of modules increased by about 20% after a test

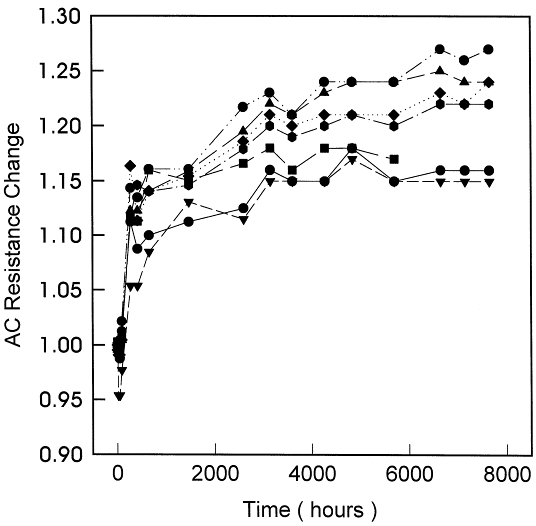

Fig. 7. AC resistance of modules as a function of operating period at temperature 100°C.

period of 7600 h at a temperature of 100°C. A significant increase in the electrical resistance of about 15% occurred during first 300 h, while the degradation is much less during the following 7300 h. Evidently, the reliability of commercially available modules needs to be improved for ‘high’ temperature operation.

Preliminary failure mechanisms analysis indicated that the module’s design and fabrication significantly affect the reliability of the thermoelectric modules [9]. The degradation rate is related to the melting point of the solder and the thickness of nickel barriers. Scanning electron microscopy analysis also showed that the module degradation is mainly related to the compositional and structural changes in the vicinity of junctions. Further investigation is necessary in order to improve the module reliability for ‘high’ temperature operation.

6. Conclusions

Thermoelectric modules which were originally developed for cooling applications also exhibit a promising performance for electrical power generation using waste heat in the temperature range 300–400 K. The results reported in this paper show that a cost-per-watt of about £4/W can readily be obtained using commercially available modules with an appropriate thermoelement length. A detailed analysis of module performance indicated that a further reduction in cost-per-watt can be obtained using optimised geometry with improved MQF. The power-per-area can also be significantly improved by reducing the inter-thermoelement separation. Although the inter-thermoelement separation may not affect most cooling applications, its reduction will significantly increase the power-per-area of a module when it is used in generating mode. The development of modules which operate reliably at ‘high’ temperatures is crucial in application of thermoelectric waste heat recovery. If currently available modules had a mean-time-between-failure of 10 years, they could produce electricity from a warm water flow ($\Delta T = 60$ K) at a cost of £0.08/kWh. Implementation of module improvements outlined in this paper would reduce the cost to a realistic estimate of £0.02/kWh. The cost of integrating a module into a generating system is unlikely to exceed the cost of the modules. Consequently, a generating system employing a large number of improved modules would produce electricity at £0.04/kWh, a price which compares very favourably with that charged by major electric utilities.

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