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Performance evaluation of thermoelectric generators under cyclic heating

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Performance evaluation of thermoelectric generators under cyclic heating

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Abstract. The effect of thermal cycling on thermoelectric generator (TEG) performance is investigated for six nominally identical samples subjected to the same heating cycle profile. All TEGs experienced performance degradation, with maximum power outputs between 28 % and 49 % of pre-cycling values and a post-cycling decrease in the dimensionless figure of merit ZT of 21 % to 49 %. Sudden significant power reductions and subsequent internal resistance increases were observed for all samples, indicative of internal damage to the structure of the TEGs arising from material interface separation and micro-crack formation.

1. Introduction

Thermoelectric generators (TEGs) are solid state semi-conductor devices which convert heat energy to electrical energy through the thermoelectric effect, with applications ranging from low power sensors, vehicle exhaust heat recovery and off-grid electricity generation. An increased temperature difference between the TEG's hot and cold surfaces, while maintained below its maximum operating temperature, results in greater voltages across the electrical terminals and subsequently higher output power. While often quoted with long lifetimes by manufacturers, actual power generation and expected lifetime can be significantly lower when subjected to thermal cycling. Despite this, limited literature exists on the effects of thermal cycling on TEGs, with no standardised method adopted for evaluating these effects.

A recent study conducted by Merienne et al. [1] investigated heating rate effects during thermal cycling on three nominally identical bismuth telluride (Bi_2Te_3) TEGs produced by a single manufacturer. Performance degradation was observed for all samples after 600 thermal cycles, with the sample subjected to the fastest heating rate experiencing the greatest degradation. Further work performed by McSweeney et al. [2] applied similar heating and cooling profiles to TEGs with comparable dimensions and quantity of p-n thermocouples but produced by a different manufacturer. The TEGs were found to have lower relative maximum power reductions after cycling when compared to those investigated by Merienne et al. [1], which the authors attributed to their higher hot side maximum operation temperature; however they experienced a sudden significant reduction in power, consistent with the 'breakdown' in performance observed by Hori et al. [3]. Scanning electron microscope (SEM) imaging post-cycling revealed separation between thermocouple pellets and conductor material with micro-cracking present, as observed by Hatzikraniotis et al. [4]. Table 1 provides a summary of the parameters and findings from a number of pertinent studies conducted on TEG thermal cycling.

The current study investigates the impact of thermal cycling on performance degradation of nominally identical TEGs produced by a single manufacturer when subjected to the same heating profile.



Table 1. Summary of TEG thermal cycling studies.

	Cycle Length [s]	Thermal Cycles Investigated	Dimensions [mm ³]	Number of Thermocouples	Number/Sample Type
Merienne et al. [1]	760 – 1,320	600	40 x 40 x 3.3	127	3 x Bi ₂ Te ₃
McSweeney et al. [2]	760 – 1,320	600	40 x 40 x 3.4	127	3 x Bi ₂ Te ₃
Hori et al. [3]	–	50 – 300	47.5 x 47.5 x 5	49	6 x Bi ₂ Te ₃
Hatzikraniotis et al. [4]	1,800	6,000	25 x 25 x 3	31	1 x Bi ₂ Te ₃
Barako et al. [5, 6]	60	45,000	–	–	–
Tatarinov et al. [7]	–	340	–	–	1 x Bi ₂ Te ₃
Park et al. [8]	180	6,000	39.7 x 39.7 x 4.16	127	1 x Bi ₂ Te ₃
Tenorio et al. [9]	900	127	40 x 40 x 3.9	127	1 x Bi ₂ Te ₃

2. Experimental Method

The experimental set-up illustrated in Figure 1 is similar in design to that employed in the work of Merienne et al. [1] and McSweeney et al. [2], consisting of a single TEG module clamped between two aluminium blocks, with heating power provided to the hot upper block via two 200 W cartridge heaters, and a recirculating chiller supplying the lower cold block with cooling water at a constant flow rate and temperature of 20 °C. Insulation of the test section with DURATEC-750 minimises heat loss, while conical spring washers accommodate pressure variations arising from thermal cycling. The apparent temperature difference across the TEG module is measured via thermocouples at the aluminium-TEG interfaces, with the modules' generated power consumed by a variable electronic load in constant current mode. Heater block and chiller setpoint temperatures are PID controlled through state machine architecture employed by a LabVIEW virtual instrument (VI) to regulate the heating and cooling times.

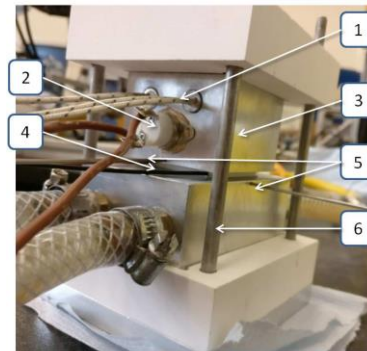
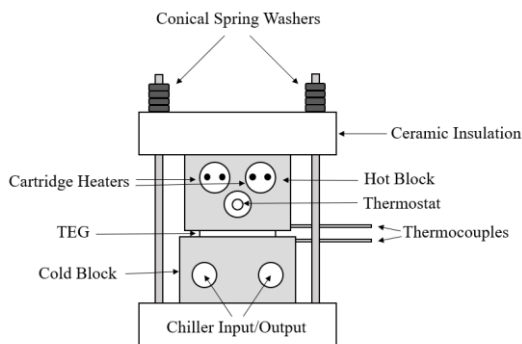


Figure 1. Experimental Set-Up: (1) Cartridge heater (2) Thermostat (3) Hot block (4) TEG (5) Thermocouples (6) Cold block. Insulation partially removed for clarity.

The performance of six 127 thermocouple 40 x 40 x 3.4 mm³ Bi₂Te₃ TEGs from European Thermodynamics (GM250-127-14-10) under thermal cycling was investigated, all with a maximum operating temperature of 250 °C. Samples were subjected to three performance evaluation tests; Harman, characterisation and thermal cycling tests. The non-destructive Harman test provides a method of pre and post-cycling material property evaluation through the determination of the dimensionless figure of merit ZT . When supplied with a 10 mA DC current, the resulting voltage across the TEG's terminals consists of resistive heating component V_{Joule} and Peltier effect-induced temperature difference component V_{Seebeck} [10]. ZT can be defined as:

$$ZT = \frac{V_{\text{Seebeck}}}{V_{\text{Joule}}} \quad (1)$$

For the characterisation test, the TEG module's internal properties are measured pre-thermal cycling and after every 50 cycles by maintaining a fixed hot and cold side temperature difference of 135 °C, and

increasing the current drawn by the electronic load from 0.5 A to 1.65 A. This current variation induces Joule heating, maintaining the hot side temperature at 165 ± 1 °C. The effective Seebeck coefficient α_{eff} is determined from TEG open circuit voltage V_{OC} and electrical resistance R as detailed by Hsu et al. [11], with TEG maximum power W_{max} determined for matching module internal and electronic load resistances. During thermal cycling testing, the TEG's hot side is repeatedly cycled between 50 °C and 165 °C with the electronic load drawing 1.4 A. The hot and cold side temperature difference is maintained for a minimum of 60 s upon reaching the maximum temperature set-point to account for fluctuations due to the Peltier, Joule and Thomson effects. TEG voltage and current, electronic load voltage and heating time are recorded, with cooling initiated when the mean and standard deviation of the hot side temperature meet required values. The average thermal cycle heating and cooling times employed during this study were approximately 154 s and 660 s respectively.

As a safety precaution, testing was terminated when W_{max} was less than half of the pre-cycling value, as all testing was automated through the LabView VI. This measure was also introduced to eliminate the TEG's recovery effect when user input is required to reinitiate thermal cycling, as observed by Merienne et al. [1].

3. Results

Characterisation test results for all samples are presented in Figure 2 in terms of TEG maximum power $W_{\text{max, norm}}$ and internal electrical resistance R_{norm} both normalised relative to their pre-cycling values, as well as the effective Seebeck coefficient α_{eff} . Pre and post-cycling characteristics for all samples are summarised in Table 2, including ZT values and their 95% confidence bounds. Despite the samples being nominally identical with very similar pre-cycling ZT values for TEGs 1-5, their performance characteristics varied significantly. Presented in Figure 2 (a) the maximum power generated decreased with increasing number of thermal cycles as expected. All samples experienced a sudden rapid output decrease, consistent with the performance 'breakdown' observed by Hori et al. [3]; however, the cycle at which this occurred varied between TEG modules, despite displaying similar initial behaviour. TEG 2's maximum generated power dropped significantly after only 200 cycles, reaching the power reduction threshold of 50 % after 350 cycles. TEG 3 and TEG 5 exhibited more extreme behaviour including power reductions of 14 % and 30 % after 150 cycles and 200 cycles respectively, with cessation of testing occurring after 300 cycles. In contrast, the power outputs of TEG 1, TEG 4 and TEG 6 were found to decline more gradually before experiencing a similar rapid decrease in performance after 300, 350 and 450 cycles respectively. This performance degradation is reflected in the modules' increased internal resistance of Figure 2 (b) and corresponding decrease in average α_{eff} of Figure 2 (c). The initial substantial resistance increase may indicate the occurrence of significant damage to the module's internal structure primarily through micro-crack formation resulting from the separation of the TEG's thermocouples and copper conducting material, previously observed in Refs. [2] and [4]. TEGs 1-5 experienced reduced post-cycling ZT values, with the greatest decrease of 49% observed for TEG 1. While a pre-cycling ZT value for TEG 6 was unavailable, a comparatively low post-cycling value indicates significant degradation to this module. Decreases in ZT were dominated by a rise in V_{Joule} and therefore increased TEG internal resistance.

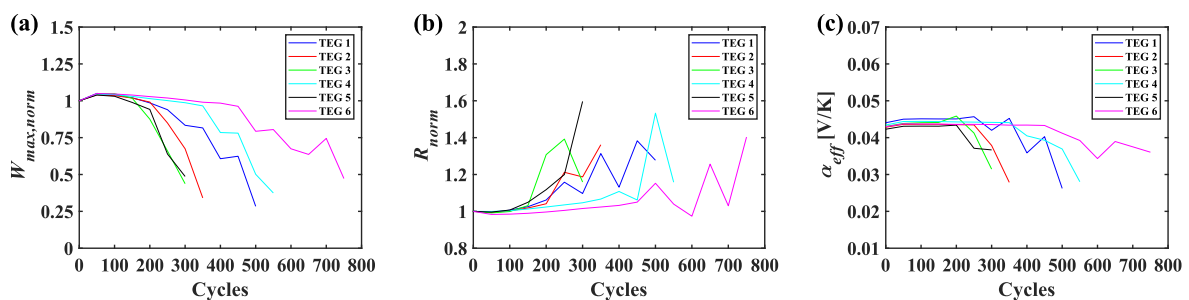


Figure 2. (a) Normalised maximum power (b) Normalised internal electrical resistance and (c) Effective Seebeck coefficient during characterisation tests for all TEG samples.

Table 2. Pre- and post-cycling characteristics for all TEG samples.

	Pre-cycling				Post-cycling			
	V_{OC} [V]	α_{eff} [V/K]	R_{pre} [Ω]	W_{max} [W]	ZT_{pre}	ZT_{post}	$ZT_{decrease}$	R_{post} [Ω]
TEG 1	5.95	0.0440	1.87	4.73	0.594 ± 0.005	0.303 ± 0.001	49 %	2.39
TEG 2	5.78	0.0428	1.90	4.40	0.580 ± 0.002	0.416 ± 0.001	28 %	2.59
TEG 3	5.81	0.0430	1.95	4.34	0.597 ± 0.002	0.471 ± 0.001	21 %	2.54
TEG 4	5.86	0.0434	1.90	4.53	0.596 ± 0.002	0.342 ± 0.001	43 %	2.20
TEG 5	5.72	0.0423	2.03	4.03	0.602 ± 0.004	0.359 ± 0.002	40 %	3.25
TEG 6	5.83	0.0430	2.01	4.21	— ^a	0.079 ± 0.001	—	2.83

^a Value for ZT_{pre} unavailable due to hardware failure.

Further indication of the substantial damage to the internal structure of the TEGs as a result of thermal cycling was evident during the characterisation tests, with the electronic load unable to draw the maximum setpoint current from the module during the final characterisation test performed. This depletion in performance is reflected in the values for R_{post} , with TEG 5 experiencing the maximum resistance increase of 60 % for all modules.

4. Conclusion

The effect of thermal cycling on the performance characteristics of nominally identical thermoelectric generator (TEG) modules when subjected to an average heating rate of 154 s was investigated in terms of maximum power output, internal electrical resistance, Seebeck coefficient and figure of merit. All samples exhibited performance degradation with increased cycles, reductions in maximum power outputs between 51 % and 72 % and increased final internal resistance values of 16 % to 60 %. A sudden ‘breakdown’ in output power was observed, occurring at thermal cycle numbers which varied between samples and was equated to significant damage in the internal structure of the TEGs, mostly likely a result of micro-crack formation due to separation of the p-n thermocouples and conducting material.

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