Research paper

A thermoelectric generator using loop heat pipe and design match for maximum-power generation

Bin-Juine Huang ^{a,*}, Po-Chien Hsu ^a, Rung-Je Tsai ^a, Muhammad Mustafa Hussain ^b^a Department of Mechanical Engineering, National Taiwan University, Taipei, 106, Taiwan^b Electrical Engineering Program, Physical Science and Engineering Division, King Abdullah University of Science and Technology (KAUST), Saudi Arabia

H I G H L I G H T S

- We develop thermoelectric generator (TEG) using loop heat pipe and design for maximum power.
- TEG uses loop heat pipe to dissipate heat without consuming power and free of noise.
- TEG using design match for maximum-power generation performs better than TEG with MPPT.

A R T I C L E I N F O

Article history:

Received 30 April 2015

Accepted 18 August 2015

Available online 5 September 2015

Keywords:

Thermoelectric generator

Thermoelectricity

Thermoelectric energy

Waste heat utilization

A B S T R A C T

The present study focuses on the thermoelectric generator (TEG) using loop heat pipe (LHP) and design match for maximum-power generation. The TEG uses loop heat pipe, a passive cooling device, to dissipate heat without consuming power and free of noise. The experiments for a TEG with 4 W rated power show that the LHP performs very well with overall thermal resistance 0.35 K W^{-1} , from the cold side of TEG module to the ambient. The LHP is able to dissipate heat up to 110 W and is maintenance free. The TEG design match for maximum-power generation, called “near maximum-power point operation (nMPPO)”, is studied to eliminate the MPPT (maximum-power point tracking controller). nMPPO is simply a system design which properly matches the output voltage of TEG with the battery. It is experimentally shown that TEG using design match for maximum-power generation (nMPPO) performs better than TEG with MPPT.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Waste heat can be used to generate electricity using thermoelectric generator (TEG). TEG utilizes the thermoelectric effect to generate electric power from a temperature difference across the device. The new material of TEG has been extensively studied in recent years. Advanced TEG material with electric conversion efficiency higher than 10% has been published, for example, El-Genk and Saber [1]. The thermoelectric generator module commercially available in the market can generate electric power at conversion efficiency about 8% and the cost is reduced quickly. This will make the TEG technology be adopted in various applications such as waste heat recovery, independent power system such as small heat-driven battery charger etc.

Many researchers [2–4] developed TEG products to charge batteries of electronic equipment. They use a DC/DC converter (charger) to boost-up the TEG output voltage to charge the battery. The TEG power generation is not optimized and may be very low.

It is known that the output current of thermoelectric generator decreases linearly with increasing voltage at fixed hot and cold side temperature, T_h and T_c . And, for a fixed T_h and T_c , there exists an optimum power output (maximum-power point, MPP) at certain output voltage. A MPP tracking control (MPPT) is thus needed to control the TEG to operate at the maximum power all the time at varying operating conditions [5,6]. This is similar to the MPPT of solar PV module.

The MPPT of a TEG is usually designed using switching power electronics circuit, a DC/DC converter. For a stand-alone TEG system, a battery is included to store the electrical energy generated, as shown in Fig. 1. Similar to solar PV module, the MPPT can be used to regulate the output of TEG (V_{TEG}) at V_{MPP} which varies with the operating conditions (T_h and T_c). However, the circuit of MPPT will

* Corresponding author. Tel.: +886 918291621; fax: +886 2 23640549.
E-mail address: bjhuang@seed.net.tw (B.-J. Huang).

Fig. 1. Schematic diagram of TEG with MPPT.

cause some system response effect between its input and output and has energy loss.

Eakburanawat and Boonyaroonate [5] developed a thermoelectric battery charger with microcontroller-based maximum-power point tracking controller to obtain the maximum power output of TEG. The MPPT uses a SEPIC (single-ended primary inductance converter) DC/DC converter controlled by a microcontroller. SEPIC is a non-inverting DC/DC converter with output voltage either above or below the input. A TEG module with 5.9 W rated output power was designed and tested [5]. The battery charge current is directly controlled by the duty cycle of the PWM (pulse-width-modulation) signal applied to the DC/DC converter to obtain the optimal power charge to the battery. The method of perturbation and observation (P.O. method) used in MPPT of photovoltaic (PV) module [7] was adopted to achieve the maximum power output by increasing or decreasing the value of the duty cycle according to the direction of consequent power change. The proposed TEG system has a maximum charging power of 7.99 W that is better than charging without MPPT by about 15%. The MPPT of TEG described above [5] can maximize the power output all the time. However, MPPT is made from power electronics circuit which has energy loss and reliability problem due to failure of the circuit.

In addition to the MPPT problem, the current commercial thermoelectric module generates power at relatively low efficiency (<8%). The majority of heat input to TEG should be dissipated. Conventional heat sink device using fins with fans will consume about 2–3 W for dissipating 100 W heat to the ambient. Hence, the net power generation of TEG system will be greatly reduced, especially for a small battery charger.

In the present study, we focus on TEG using loop heat pipe and design match for maximum-power generation to eliminate the MPPT. The loop heat pipe (LHP), a passive cooling device, is used to dissipate the heat to the ambient by free convection. A so-called “near maximum-power point operation (nMPPO)” for TEG design is developed in order to avoid the MPPT. nMPPO design is simply a system design match which properly matches the output voltage of

TEG with the battery (Fig. 2). The design concept of nMPPO is feasible if the reduction of nMPPO power generation from the MPP is less than the energy loss of the MPPT circuit. The concept of nMPPO has been successfully used in solar PV system design [8].

2. Design of TEG using loop heat pipe

2.1. Design of TEG system SYS-1

The commercial TEG module used in the present study can generate electric power at about 4% conversion efficiency. 96 W heat should be dissipated for a 4 W power output. Conventional heat sink using fins and fans will consume about 2–3 W. The net power output is very little. We utilize a low-cost loop heat pipe (LHP) [9–11], a passive cooling device, to dissipate the heat of TEG to increase the net power output. See Fig. 3 for the mechanical design of TEG.

LHP is a heat transfer device widely used in aerospace [9]. LHP consists of an evaporator, a vapor line, a condenser pipe adhered on a heat dissipating surface through a thermal connector, a liquid return line. See Fig. 4. The evaporator is attached on the cold side of the TEG module to absorb the dissipated heat. The absorbed heat evaporates the working fluid inside the LHP which flows through a bendable connecting pipe to the condenser surface. The vapor is condensed and the heat is dissipated to the ambient. The condensed liquid then returns to the evaporator through the connecting pipe by capillary effect of the wick embedded inside the evaporator. Since the pore of the wick is made in micro scale to create a large capillary force, LHP can transport large amount of heat to a long distance. National Taiwan University has developed a new manufacturing process that can make cheap LHP which has been utilized in high-power LED lighting products [10,11].

The thermoelectric generator built in the present study is denoted as “SYS-1”, which basically comprises a TEG module and two LHP. A 40 mm × 40 mm TEG module (Model STE, manufactured by TEG Power Inc.) with 100 W rated heat input was used. The rated

Fig. 2. Schematic diagram of TEG with nMPPO.

Fig. 3. TEG design using LHP.

Fig. 4. Schematic of loop heat pipe (LHP).

TEG output power is 3.84 W at 3.2 V and at $T_h = 175\text{ }^\circ\text{C}$ and $T_c = 30\text{ }^\circ\text{C}$. A cartridge-type electric heater was used to heat the TEG module. Two loop heat pipes were installed to dissipate heat in three vertical surfaces with $30\text{ cm} \times 30\text{ cm}$ each, as shown in Fig. 5. SYS-1 acts as a basic unit which can be duplicated and connected to form different TEG.

2.2. Performance test of SYS-1

The thermoelectric generator SYS-1 was tested with T_c varied. Temperatures at cold and hot sides of TEG module, T_c and T_h , and ambient temperature T_a were measured using T-type thermocouples through a Analog Measurement Device ICP-CON 7018Z (10 Channel Thermocouple Input Module) with accuracy $0.5\text{ }^\circ\text{C}$ and 16-

Fig. 5. Design of SYS-1.

bit output. The heat input to TEG is provided by a cartridge heater with DC current input. The cartridge heater is well insulated and the heat input to TEG module Q_h is then calculated from measured electrical input power. The input current I_h and voltage V_h of cartridge heater as well as the output current and voltage of TEG module (I_{TEG} , V_{TEG}) were measured by a ICP-CON 7017-A5 (High DC Voltage Input Module, 8 Channel) with accuracy 0.5% and 16-bit output. Both analog measurement devices were made by msl Measurement Systems Ltd.

It is seen from Table 1 that the best overall energy conversion efficiency of TEG is 3.18% at temperature difference $147.7\text{ }^\circ\text{C}$ ($T_h = 210.4\text{ }^\circ\text{C}$, $T_c = 62.7\text{ }^\circ\text{C}$). The SYS-1 performance measurement is carried out at various loads (different resistors). Only maximum-power-point performance at each fixed T_h and T_c is shown in Table 1. The experimental results show that the LHP performs very well and keeps the cold side temperature T_c near $60\text{ }^\circ\text{C}$ at ambient temperature $25\text{ }^\circ\text{C}$. The overall thermal resistance R_o from the cold side of TEG module to the ambient decreases with increasing heat transport [9], from 0.43 to 0.35 K W^{-1} . R_o is defined as

$$R_o = \frac{T_h - T_c}{Q_h} \quad (1)$$

Table 1
Test results of SYS-1.

T_h (°C)	T_c (°C)	P_{MPP} (W)	V_{MPP} (V)	I_{MPP} (A)	V_{oc} (V)	I_{sc} (A)	Q_h (W)	η_e (%) = P_{MPP}/Q_h	R_o , K W ⁻¹
150.2	52.1	1.91	2.35	0.81	4.45	1.61	65.6	2.91	0.425
160.6	54.3	2.12	2.47	0.86	4.77	1.68	72.4	2.93	0.417
170.8	56.6	2.41	2.63	0.91	5.10	1.75	78.2	3.08	0.417
180.0	58.1	2.72	2.80	0.97	5.53	1.85	82.9	3.28	0.413
189.8	59.5	2.98	2.88	1.03	5.74	1.94	91.4	3.26	0.390
200.7	61.1	3.28	3.23	1.02	6.12	2.03	105.1	3.12	0.355
210.4	62.7	3.57	3.21	1.11	6.42	2.10	112.2	3.18	0.347

The LHP is able to dissipate heat up to 110 W without power consumption. This is important for small TEG with several watts of power output. Another benefit of using LHP is free of noise in operation of TEG.

3. Design of TEG with MPPT

A TEG using MPPT is built for comparison test. Besides, the performance curves of TEG module is measured first for nMPPO design.

3.1. Measurement of performance curves of TEG module

The performance curves of TEG module (STE) was first measured using SYS-1 under well-controlled temperatures at the hot and cold sides. T_h was automatically regulated by controlling the input power of cartridge electric heater using a PID controller. To obtain a constant cold side temperature T_c , a fan was used to blow air onto the heat dissipation surface and the fan speed was automatically adjusted to control T_c .

The I–V curve of TEG is determined experimentally from measuring the output current I_{TEG} and voltage V_{TEG} at a given resistance load R_o . Repeating the measurement at different resistance load R_L (load line), the locus of I–V as well as P–V curve can be drawn as shown in Fig. 6.

Six power resistors (Table 2) were connected in parallel through a switching device to provide 32 different loads to TEG (Fig. 7). Six relays are connected in series to the power resistors and are turned ON/OFF individually by a microprocessor-based controller (PIC16F877A) through the Parallel Port. The 32 resistance load combinations made from this switching device is shown in Table 3.

The measurement starts when the temperatures at hot and cold sides, T_h and T_c , are kept constant using the temperature

control described previously. It takes 14 s to switch through all the 32 resistor combinations.

Fig. 8 is the measured P–V curves, at $T_c = 50$ °C. There exists a maximum power for each operating condition. The locus of maximum-power points (MPP) can be drawn as shown in Fig. 8. The maximum power occurs in the narrow voltage range $V_{TEG} = 2.3$ – 3.4 V for $T_h = 150$ – 200 °C.

3.2. Design of MPPT

In order to compare the performance of TEG using MPPT and nMPPO, a MPPT tracking controller was designed and built. The MPPT is designed using the SEPIC (single-ended primary inductance converter) DC/DC converter [5] controlled by the microprocessor PIC16F877A (Fig. 9). Since the DC/DC circuit has a dynamic effect between input (P_{TEG}) and output (P_{BAT}), the MPPT is used to track the maximum power charged to the battery (P_{BAT}), instead of the maximum power output of TEG (P_{TEG}). This will assure that the maximum power which is charged to the battery is tracked.

A current sensor is installed at the output of MPPT to measure the battery charging current I_{BAT} and to determine the charging power. The method of perturbation and observation (P.O. method) [7] was used to achieve the maximum-power charging to the battery by increasing or decreasing the PWM duty cycle (D). The feedback system block diagram of MPPT using P.O. method is shown in Fig. 10. The P.O. method is implemented using the one-step delay filter of P_{BAT} and the step-up/step-down controller.

3.3. Design of TEG with MPPT: TEG-MP1 and TEG-MP2

A TEG, denoted as “TEG-MP1”, was built using a 2.4 V/2.7 Ah lead-acid battery connected to a unit of SYS-1. The MPPT was installed. The PWM frequency of SEPIC will affect the MPPT performance. 50 kHz was chosen as the PWM frequency f_{PWM} .

To reduce the energy loss of diode, another higher voltage TEG, denoted as “TEG-MP2”, was designed using a 6 V/10 Ah lead-acid battery which is connected to two units of SYS-1. The two TEG modules are electrically connected in series, but thermally connected in parallel at the same hot side (heat source) and cold side (heat sink).

3.4. Definition of performance index

In order to evaluate the performance of TEG with MPPT, three efficiencies (η_T , η_{tk} , η_{MPPT}) are defined:

(1) Circuit efficiency η_T

Table 2
Power resistors used as TEG load combination.

Resistor	R_1	R_2	R_3	R_4	R_5	R_6
Resistance, ohm	0	1.5	3.3	8	15	33

Fig. 6. Measuring procedure of I–V and P–V curves of TEG.

Fig. 7. Switching device for I–V curve measurement.

Table 3
32 different load combinations.

Resistor combination R123456	Output of parallel port	Equivalent load R_L (Ω)	Resistor combination R123456	Output of parallel port	Equivalent load R_L (Ω)
000000	0	∞ (O.C.)	010001	17	1.43
000001	1	33.00	010010	18	1.36
000010	2	15.00	010011	19	1.31
000011	3	10.31	010100	20	1.26
000100	4	8.00	010101	21	1.22
000101	5	6.44	010110	22	1.17
000110	6	5.22	010111	23	1.13
000111	7	4.51	011000	24	1.03
001000	8	3.30	011001	25	1.00
001001	9	3.00	011010	26	0.96
001010	10	2.70	011011	27	0.94
001011	11	2.50	011100	28	0.91
001100	12	2.34	011101	29	0.89
001101	13	2.18	011110	30	0.86
001110	14	2.02	011111	31	0.84
001111	15	1.90	100000	32	0 (S.C.)
010000	16	1.50

Fig. 8. P–V curves of TEG module (STE).

$$\eta_T = \frac{P_{BAT}}{P_{TEG}} \quad (2)$$

where P_{TEG} is the output power of the TEG module; P_{BAT} is the power charged to the battery. η_T represents the efficiency of MPPT circuits.

(2) MPP tracking efficiency η_{tk}

$$\eta_{tk} = \frac{P_{TEG}}{P_{MPP}} \quad (3)$$

where P_{MPP} is the output power of the TEG module at the MPP. η_{tk} represents the tracking efficiency of the MPPT with respect to the MPP of the TEG.

Fig. 9. SEPIC (single-ended primary inductance converter) circuit in MPPT [5].

Fig. 10. Feedback control of MPPT using P.O. method.

(3) Overall MPPT tracking efficiency η_{MPPT}

$$\eta_{MPPT} = \frac{P_{BAT}}{P_{MPP}} = \eta_T \cdot \eta_{tk} \quad (4)$$

η_{MPPT} represents the overall tracking efficiency of MPPT from the theoretical maximum power P_{MPP} to the actual power charged to the battery P_{BAT} .

3.5. Test of TEG-MP1

TEG-MP1 was tested at $T_h = 210^\circ\text{C}$ and $f_{PWM} = 50\text{ kHz}$. Fig. 11 and Table 4 show that the maximum power output of TEG occurs at duty cycle $D = 60\%$ which is slightly different from the maximum power actually charged to the battery at duty cycle $D = 55\%$. This is due to the input/output response of the MPPT circuit. If MPPT is applied to the TEG output power P_{TEG} , duty cycle D should be chosen as $D = 60\%$ so that the maximum output 3.65 W is obtained. The actual power charged to the battery P_{BAT} at $D = 60\%$ will be 2.16 W which is not the maximum (2.25 W). This suggests that the maximum power tracking should be applied at the battery charge port P_{BAT} , not at the output port of TEG module. If so, about 4% more output power charged to the battery can be obtained, an increase from 2.16 W at $D = 60\%$ to 2.25 W at $D = 55\%$.

Table 4 shows that the MPPT has tracked the maximum-power point (MPP) at $D = 60\%$. However, the overall MPPT tracking efficiency η_{MPPT} is low, about 60%. This is due to the low circuit efficiency η_T resulted mainly from the energy loss of the diode (D2) in the SEPIC circuit (Fig. 9). The diode has a voltage drop 0.5 V which results in about 18% energy loss for 2.8 V battery. PWM1 is a MOSFET switching device which also loss energy.

3.6. Test of TEG-MP2

The energy loss of diode in TEG-MP1 is relatively high for low battery voltage. TEG-MP2 comprises a $6\text{ V}/10\text{ Ah}$ battery and two units of SYS-1 electrically connected in series. The two TEG modules

Fig. 11. Variation of TEG module output (P_{TEG}) and battery charging power (P_{BAT}) with duty cycle.

are thermally connected in parallel, with the same heat source and heat sink. It is seen from Table 5 that the circuit efficiency η_T reaches about 80% in which the diode energy loss is around 8% and the SEPIC circuit loss is about 12% at battery voltage 6 V . The MPPT has tracked the maximum-power point (MPP) of the TEG module. The overall MPPT tracking efficiency η_{MPPT} is around 80% over different T_h . The test results show that TEG-MP2 performs satisfactory for battery at higher voltage. The major loss comes from the diode (D2) and the circuit of SEPIC.

4. Design of TEG with nMPPO

4.1. TEG design using nMPPO

The design concept of “near maximum-power point operation, nMPPO” is illustrated in Fig. 8. The nMPPO design is simply a system design which properly matches the output voltage of TEG module close to the battery (Fig. 8). There is only one electronic component, a diode, in the circuit between the TEG and the battery for protection purpose.

Table 4Performance of TEG-MP1 ($f_{pwm} = 50$ kHz, $T_h = 210$ °C).

Duty cycle D (%)	V_{TEG} (V)	I_{TEG} (A)	V_{BAT} (V)	I_{BAT} (A)	P_{TEG} (W)	P_{BAT} (W)	P_{MPP} (W)	η_T (%) = P_{BAT}/P_{TEG}	η_{ik} (%) = P_{TEG}/P_{MPP}	η_{MPPT} (%) = P_{BAT}/P_{MPP}
10	6.54	0.00	2.72	0.01	0.03	0.02	4.17	66.3	0.7	0.5
20	6.55	0.01	2.71	0.02	0.08	0.06	3.59	70.6	2.2	1.6
30	6.52	0.02	2.72	0.04	0.16	0.12	3.61	72.4	4.4	3.2
40	5.47	0.35	2.77	0.51	1.91	1.40	3.65	73.4	52.3	38.4
45	4.77	0.58	2.80	0.69	2.78	1.95	3.65	70.1	76.2	53.4
50	4.18	0.79	2.81	0.78	3.31	2.18	3.64	65.8	90.9	59.8
55	3.61	1.00	2.81	0.80	3.61	2.25	3.65	62.6	98.9	61.9
60	3.11	1.17	2.81	0.77	3.65	2.16	3.65	59.3	100.0	59.3
70	2.28	1.46	2.79	0.62	3.33	1.73	3.65	51.9	91.3	47.4
80	1.64	1.69	2.77	0.42	2.76	1.16	3.64	41.9	75.8	31.7
90	1.13	1.86	2.74	0.21	2.11	0.56	3.64	26.7	57.9	15.4

Table 5Performance of TEG-MP2 ($f_{pwm} = 50$ kHz).

T_h (°C)	T_c (°C)	Duty cycle D (%)	V_{TEG} (V)	I_{TEG} (A)	V_{BAT} (V)	I_{BAT} (A)	P_{TEG} (W)	P_{BAT} (W)	P_{MPP} (W)	η_T (%) = P_{BAT}/P_{TEG}	η_{ik} (%) = P_{TEG}/P_{MPP}	η_{MPPT} (%) = P_{BAT}/P_{MPP}
160	52	57.8	5.27	0.82	5.94	0.59	4.32	3.47	4.36	80.3	99.2	79.7
170	55	56.9	5.59	0.87	6.00	0.64	4.87	3.86	4.92	79.3	98.9	78.5
180	57	55.9	5.87	0.90	6.05	0.69	5.28	4.19	5.28	79.3	100.0	79.3
190	59	54.7	6.10	0.91	6.07	0.73	5.55	4.44	5.61	80.0	99.0	79.2
200	61	53.8	6.31	0.93	6.08	0.78	5.87	4.72	5.90	80.4	99.5	80.0
210	63	53.8	6.51	0.96	6.13	0.82	6.25	5.01	6.32	80.2	98.9	79.3

By careful matching the specifications of TEG module and battery, we can achieve an nMPPO design which will perform close to that of MPPT.

4.1.1. Design of nTEG-1

SYS-1 built for the experiments of MPPT includes a TEG module (Model STE) with rated output power 3.84 W at $V_{TEG} = 3.2$ V and $T_h = 175$ °C. The voltage of a 2.4 V/2.7 Ah lead-acid battery varies between 2.1 V and 3 V. Hence, combining a single unit of SYS-1 with a 2.4 V lead-acid battery will form a design of nMPPO, denoted as “nTEG-1”.

nTEG-1 includes a 2.4 V lead-acid battery which operates at the range 2.1–3 V. The diode voltage loss V_{diode} is 0.5 V. Therefore, the resultant voltage across the TEG module is $V_{TEG} = V_{BAT} + V_{diode} = 2.6$ –3.5 V which matches the MPP range of TEG module (2.3–3.4 V, Fig. 4).

The mismatch of nMPPO with the MPPT will result in energy generation loss. This mismatch loss is acceptable if it is less than the energy loss of MPPT circuit, usually 10–20% for small TEG.

Using the P–V performance curve of TEG module shown in Fig. 8, we can calculate the voltage of TEG at 95% and 90% (or 5% and 10% loss) of the maximum power P_{MPP} at different T_h and T_c , denoted as V_{MPP95} and V_{MPP90} . Table 6 shows the voltage range of a single TEG module, V_{MPP95} and V_{MPP90} at different T_h (ranging from 1.75 to 4 V). The shaded area in Fig. 8 represents the TEG operating voltage $V_{TEG} = V_{BAT} + V_{diode}$ (=2.6–3.5 V) after taking into account the diode voltage drop. For TEG operating at the voltage range of

Table 6Voltage of nTEG-1 at 95% and 90% of maximum power at $T_c = 50$ °C.

T_h (°C)	P_{MPP} (W)	V_{MPP} (V)	V_{MPP95} (V)	V_{MPP90} (V)
150	1.91	2.25	1.75–2.75	1.54–2.96
160	2.15	2.41	1.87–2.95	1.65–3.17
170	2.39	2.56	1.99–3.13	1.75–3.36
180	2.62	2.72	2.12–3.32	1.87–3.57
190	2.81	2.82	2.19–3.44	1.94–3.70
200	3.01	2.94	2.28–3.59	2.01–3.86
210	3.19	3.04	2.36–3.72	2.08–4.00

V_{MPP90} shown in Table 6, the energy generation loss is less than 10% for $T_h = 180$ –210 °C since V_{MPP90} covers the TEG operating voltage $V_{TEG} = V_{BAT} + V_{diode}$ (=2.6–3.5 V). For $T_h < 180$ °C, the energy generation loss can be less than 10% if the TEG operates at a low operating voltage, near 2.6 V. This can be achieved from carefully designing the battery storage. Similarly, as seen from the range of V_{MPP95} , the energy generation loss less than 5% can be obtained for all T_h , if the TEG operates at a low operating voltage, near 2.6 V.

4.1.2. Design of nTEG-2

The circuit efficiency η_{diode} can be increased relatively by increasing the battery voltage. Hence, we designed another higher voltage TEG, denoted “nTEG-2”, using two units of SYS-1 connected with a 6 V/10 Ah lead-acid battery. The two TEG modules are electrically connected in series. The measured P–V performance curves of two TEG modules in series are shown in Fig. 12. The cold side temperature T_c was not fixed during the tests but varies with the heat dissipation load. The TEG voltage at MPP is in the range 5.0–6.4 V for $T_h = 150$ –210 °C.

Fig. 12. Measurement of two TEG modules in series (nTEG-2).

Table 7
Voltage of nTEG-2 at 95%, 90% and 85% of maximum power.

T_h (°C)	T_c (°C)	P_{MPP} (W)	V_{MPP} (V)	V_{MPP95} (V)	V_{MPP90} (V)	V_{MPP85} (V)
150	51	3.87	4.64	3.61–5.67	3.18–6.09	2.85–6.42
160	52.7	4.33	4.88	3.80–5.96	3.35–6.41	3.01–6.75
170	54.4	4.82	5.21	4.05–6.36	3.57–6.84	3.20–7.21
180	56.5	5.24	5.52	4.30–6.75	3.79–7.26	3.40–7.65
190	58.6	5.75	5.78	4.50–7.07	3.96–7.60	3.55–8.01
200	60.2	6.23	6.04	4.70–7.39	4.14–7.94	3.71–8.37
210	62.3	6.59	6.27	4.88–7.66	4.30–8.24	3.86–8.68

The operating voltage of the 6 V lead-acid battery is between 5.3 V and 7.2 V. The diode voltage loss V_{diode} is 0.5 V. Therefore, the resultant voltage across TEG is $V_{TEG} (=V_{BAT} + V_{diode}) = 5.8–7.7$ V which covers the MPP range of the TEG (5.0–6.4 V).

Using the measured P–V performance curve in Fig. 12, we can calculate the voltage range of nTEG-2 at 95%, 90% and 85% (or 5%, 10%, and 15% energy generation loss) of the maximum power P_{MPP} at different T_h and T_c , denoted as V_{MPP95} , V_{MPP90} , and V_{MPP85} .

The shaded area in Fig. 12 represents the TEG operating voltage $V_{TEG} = V_{BAT} + V_{diode} (=5.8–7.7$ V) after taking into account the diode voltage drop. For TEG operating at the voltage range of V_{MPP90} shown in Table 7, the energy generation loss is less than 10% for $T_h = 200–210$ °C since V_{MPP90} covers the TEG operating voltage $V_{TEG} = V_{BAT} + V_{diode} (=5.8–7.7$ V). For $T_h < 200$ °C, the energy generation loss can be less than 10% if the TEG operates at a lower operating voltage, near 6.0 V. This can be achieved from carefully designing the battery storage. Similarly, as seen from the range of V_{MPP95} , the energy generation loss less than 5% can be obtained for all T_h , if the TEG operates at a lower operating voltage, near 5.8 V. The above estimated energy generation loss by using nMPPO design is a conservative result.

4.2. Performance index for TEG design using nMPPO

In order to experimentally evaluate the performance of TEG with nMPPO design, three efficiencies (η_{diode} , η_{otk} , η_{nMPPO}) are defined:

- (1) Circuit efficiency η_{ot}

$$\eta_{ot} = \eta_{diode} = \frac{P_{BAT}}{P_{TEG}} \quad (5)$$

Where P_{TEG} is the power output of the TEG module; P_{BAT} is the power charged to the battery. η_{diode} is the efficiency of the circuit in nMPPO which has only a component, diode.

- (2) MPP tracking efficiency η_{otk}

$$\eta_{otk} = \frac{P_{TEG}}{P_{MPP}} \quad (6)$$

Where P_{MPP} is the power output of TEG module at MPP (maximum-power point). η_{otk} is the tracking efficiency of the nMPPO design with respect to the MPP of the TEG.

- (3) Overall nMPPO tracking efficiency η_{nMPPO}

$$\eta_{nMPPO} = \frac{P_{BAT}}{P_{MPP}} = \eta_{diode} \cdot \eta_{otk} \quad (7)$$

η_{nMPPO} is the overall tracking efficiency of the nMPPO design from the maximum power output of TEG, P_{MPP} , to the actual power charged to the battery P_{BAT} .

4.3. Test of nTEG-1

The performance of nTEG-1 is measured and compared to TEG with MPPT. The test is thus conducted at different battery voltages to evaluate the performance of nTEG-1.

The performance test results of nTEG-1 with 2.4 V/2.7 Ah battery are shown in Table 8. The cold side temperature T_c was not fixed during the tests but varies with the heat load. This reflects the actual operation of a TEG. For battery voltage V_{BAT} between 2.49 V and 2.54 V, the MPP tracking efficiency η_{otk} of nTEG-1 is larger than 96% at $T_h > 170$ °C. This means that the design of nMPPO causes only about 4% energy loss of the maximum power generation. The measured circuit efficiency η_{diode} is around 85% or the energy loss of the diode about 15%. The overall nMPPO tracking efficiency η_{nMPPO} is between 78% and 84% which is larger than that of TEG-MP1 (η_{MPPT} around 62% as shown in Table 4).

For battery voltage at 3.00–3.10 V, the MPP tracking efficiency η_{otk} is larger than 90% at $T_h > 170$ °C. The measured circuit efficiency η_{diode} is around 87%. The overall nMPPO tracking efficiency η_{nMPPO} is between 65% and 82% which is larger than that of TEG-MP1 (η_{MPPT} around 62% due to large energy loss in circuits as shown in Table 4). The diode voltage drop is 0.5 V. η_{nMPPO} can be further improved if the diode is changed using a better one.

4.4. Test of nTEG-2

The performance test results of nTEG-2 with 6 V/10 Ah battery are shown in Table 9. It is seen that the MPP tracking efficiency η_{otk} is larger than 96% at $T_h > 170$ °C for low battery voltage around 5.8 V. The design of nMPPO causes only about 4% energy loss of the maximum-power generation. The measured circuit efficiency η_{diode} is around 91%. The overall nMPPO tracking efficiency η_{nMPPO} of nTEG-2 is around 89% which is larger than that of TEG-MP2 (η_{MPPT} around 80% shown in Table 5).

For TEG operating at high battery voltage around 7.1 ± 0.5 V, the MPP tracking efficiency η_{otk} is reduced and the overall nMPPO tracking efficiency η_{nMPPO} are about the same as η_{MPPT} of TEG-MP2.

The experimental results suggest that the design of nMPPO causes small energy generation loss if the TEG operated at low battery voltage. This can be achieved from carefully designing the battery storage. The diode voltage drop is 0.5 V. η_{nMPPO} can be further improved if the diode has a lower voltage drop.

5. Discussions

5.1. Comparison of TEG design using MPPT and nMPPO

The TEG module (STE) used in the present study is designed to work at $T_h < 210$ °C with temperature difference around 150 °C, i.e. T_c around 60 °C. We can compare the performance of the four TEG systems (TEG-MP1, TEG-MP2, nTEG-1, nTEG-2) and find out the feasibility of the design using nMPPO. Table 10 summarizes the test results at $T_h = 200$ and 210 °C for different battery voltages. It is seen that the MPP tracking efficiencies of TEG-MP1 and TEG-MP2, η_{tk} , are higher than 98.9%. On the other hand, the MPP tracking efficiencies of nTEG-1 and nTEG-2, η_{otk} , are also higher than 97.2% for battery running at lower voltage as shown in the highlights of Table 10. At higher V_{BAT} , η_{otk} are between 92.1% and 95% which is still satisfactory.

η_{MPPT} of TEG-MP1 is the lowest (61.9%) since it uses a 2.4 V battery which results in a relatively large energy loss from the

Table 8

Performance test of nTEG-1.

T_h (°C)	P_{MPP} (W)	V_{TEG} (V)	I_{TEG} (A)	V_{BAT} (V)	I_{BAT} (A)	P_{TEG} (W)	P_{BAT} (W)	$\eta_{otk} (\%) = P_{TEG}/P_{MPP}$	$\eta_{diode} (\%) = P_{BAT}/P_{TEG}$	$\eta_{nMPPO} (\%) = P_{BAT}/P_{MPP}$
150	1.91	2.82	0.62	2.41	0.62	1.75	1.50	91.6	85.5	78.3
160	2.11	2.90	0.69	2.47	0.69	2.01	1.71	94.9	85.3	80.9
170	2.41	2.93	0.79	2.49	0.79	2.31	1.96	96.1	84.8	81.5
180	2.72	2.97	0.88	2.51	0.88	2.63	2.22	96.5	84.4	81.4
190	2.98	3.00	0.99	2.52	0.99	2.97	2.50	99.7	84.0	83.7
200	3.28	3.03	1.08	2.54	1.08	3.28	2.75	99.8	83.8	83.6
150	1.91	3.42	0.41	3.00	0.41	1.41	1.25	73.8	88.6	65.3
160	2.11	3.42	0.51	3.02	0.51	1.74	1.54	82.3	88.1	72.7
170	2.41	3.45	0.60	3.03	0.60	2.07	1.81	86.0	87.5	75.2
180	2.72	3.52	0.70	3.07	0.70	2.46	2.15	90.4	87.2	78.9
190	2.98	3.56	0.78	3.09	0.78	2.78	2.42	93.1	86.9	81.0
200	3.28	3.58	0.87	3.10	0.87	3.12	2.71	95.0	86.7	82.4

Table 9

Performance test of nTEG-2.

T_h (°C)	T_c (°C)	P_{MPP} (W)	V_{TEG} (V)	I_{TEG} (A)	V_{BAT} (V)	I_{BAT} (A)	P_{TEG} (W)	P_{BAT} (W)	$\eta_{otk} (\%) = P_{TEG}/P_{MPP}$	$\eta_{diode} (\%) = P_{BAT}/P_{TEG}$	$\eta_{nMPPO} (\%) = P_{BAT}/P_{MPP}$
160	50.5	4.36	6.27	0.63	5.80	0.63	3.95	3.66	90.6	92.5	83.9
170	52.7	4.92	6.33	0.73	5.83	0.73	4.63	4.27	94.1	92.2	86.7
180	54.7	5.24	6.38	0.79	5.85	0.79	5.06	4.65	96.6	91.8	88.7
190	56.7	5.61	6.42	0.85	5.87	0.85	5.44	4.97	97.0	91.4	88.7
200	58.7	5.90	6.46	0.89	5.89	0.89	5.74	5.24	97.2	91.3	88.7
210	60.6	6.32	6.49	0.95	5.91	0.95	6.19	5.64	98.1	91.1	89.3
160	50.6	4.36	7.06	0.49	6.63	0.49	3.43	3.22	78.6	93.9	73.8
170	53.0	4.91	7.32	0.55	6.87	0.55	4.02	3.78	81.8	93.9	76.8
180	55.1	5.24	7.56	0.59	7.11	0.59	4.52	4.20	86.3	92.8	80.1
190	57.1	5.60	7.85	0.62	7.38	0.62	4.96	4.58	88.6	92.2	81.7
200	59.5	5.90	7.96	0.65	7.47	0.65	5.44	4.85	92.1	89.3	82.2
210	61.4	6.31	8.11	0.69	7.62	0.69	5.91	5.23	93.6	88.5	82.9

Table 10

Performance comparison.

	T_h (°C)	T_c (°C)	V_{TEG} (V)	I_{TEG} (A)	V_{BAT} (V)	I_{BAT} (A)	P_{TEG} (W)	P_{BAT} (W)	P_{MPP} (W)	$\eta_T (\%) = P_{BAT}/P_{TEG}$	$\eta_{tk} (\%) = P_{TEG}/P_{MPP}$	$\eta_{MPPT} (\%) = P_{BAT}/P_{MPP}$
TEG-MP1	210	62	3.61	1.00	2.81	0.80	3.61	2.25	3.65	62.6	98.9	61.9
TEG-MP2	200	61	6.31	0.93	6.08	0.78	5.87	4.72	5.90	80.4	99.5	80.0
TEG-MP2	210	63	6.51	0.96	6.13	0.82	6.25	5.01	6.32	80.2	98.9	79.3
	T_h (°C)	T_c (°C)	V_{TEG} (V)	I_{TEG} (A)	V_{BAT} (V)	I_{BAT} (A)	P_{TEG} (W)	P_{BAT} (W)	P_{MPP} (W)	$\eta_{diode} (\%) = P_{BAT}/P_{TEG}$	$\eta_{otk} (\%) = P_{TEG}/P_{MPP}$	$\eta_{nMPPO} (\%) = P_{BAT}/P_{MPP}$
nTEG-1	200	59	3.03	1.08	2.54	1.08	3.28	2.75	3.28	83.8	99.8	83.6
nTEG-1	200	60	3.58	0.87	3.10	0.87	3.12	2.71	3.28	86.7	95.0	82.4
nTEG-2	200	59	6.46	0.89	5.89	0.89	5.74	5.24	5.90	91.3	97.2	88.7
nTEG-2	200	60	7.96	0.65	7.47	0.65	5.44	4.85	5.90	89.3	92.1	82.2
nTEG-2	210	61	6.49	0.95	5.91	0.95	6.19	5.64	6.32	91.1	98.1	89.3
nTEG-2	210	61	8.11	0.69	7.62	0.69	5.91	5.23	6.32	88.5	93.6	82.9

diode voltage drop (0.5 V). TEG-MP2 uses a 6 V battery and has a higher η_{MPPT} around 80%. However, the η_{MPPT} of both TEG-MP1 and TEG-MP2 (61.9–80%) are all less than the η_{nMPPO} of nTEG-1 and nTEG-2 (82.2–89.3%) at different battery voltage. This indicates that the reduction of nMPPO power generation from the MPP is less than the energy loss of the MPPT circuit. The TEG design using nMPPO is more efficient and feasible.

Only two kinds of battery specifications (2.4 V and 6 V) were used in the present study. In some applications, the different combination of TEG modules can be used to fit the arbitrary battery specification, for example, 3.6 V, 12 V or 24 V, using the nMPPO design method.

5.2. Advantages of TEG using loop heat pipe

The TEGs built in the present study use LHP (loop heat pipe) as the passive cooling device which consumes no power and free of noise. LHP also requires no maintenance since it has no moving parts. The net power output can be kept high. For example, for TEG-

MP1 running at $T_h = 210$ °C, the power output of TEG, P_{TEG} , is 3.61 W (Table 10). The fan power consumption of an active cooling device will be around 2 W in dissipating about 110 W heat for TEG-MP1. This will reduce about 55% of the TEG power output. The use of LHP is thus important for small TEG with several watts of power output, as in some commercial battery charging devices.

The thermal resistance of the present LHP cooling device can be further reduced by using a larger heat dissipating surface or exposing to an environment with natural wind. This will increase the power output of the TEG.

5.3. Efficiency improvement of MPPT and nMPPO

The diode used in the SEPIC circuit of MPPT and in the nMPPO circuit causes a voltage drop (0.5 V) as well as energy loss. The diode loss is relatively large for a low-voltage TEG. This loss can be reduced if using a lower voltage drop diode such as Schottky diode, says, <0.3 V. Another way to improve the overall efficiency is to

adopt a higher-voltage battery TEG system, for example, 12 V or 24 V.

6. Conclusion

The conversion efficiency of current thermoelectric generator is low. This means that 96 W heat should be dissipated for a 4 W power output of TEG. Conventional heat sink device using fins with fans will consume about 2–3 W to dissipate the heat and cause the net power generation of TEG greatly reduced. The present study propose a TEG design using loop heat pipe (LHP), a passive cooling device, to dissipate heat to the ambient by free convection. The heat is transported to a large surface at a distance and dissipated without power consumption and noise. The experiments for a TEG with rated power 4 W show that the LHP performs very well with thermal resistance 0.35 K W^{-1} , from the cold side of TEG module to the ambient.

For TEG, a MPPT (maximum-power point tracking controller) is necessary in order to maximize the power generation. However, it has energy loss in the circuit and reliability problem due to hardware failure. In the present study, we develop a so-called “near maximum-power point operation (nMPPO)” method for the design of TEG to eliminate the MPPT. nMPPO is simply a system design which properly matches the output voltage of TEG at the battery voltage.

Two TEG (nTEG-1 and nTEG2) were designed and built using nMPPO design. The test results were compared with the performance of TEG-MP1 and TEG-MP2.

It is found that the MPP tracking efficiencies of TEG-MP1 and TEG-MP2, η_{tk} , are higher than 98.9%. The MPP tracking efficiencies of nTEG-1 and nTEG2, η_{otk} , are also higher than 97.2% for battery running at lower voltage V_{BAT} . At higher V_{BAT} , η_{otk} are between 92.1% and 95% which is still satisfactory.

The η_{MPPT} of both TEG-MP1 and TEG-MP2 (61.9–80%) are all less than the η_{nMPPO} of nTEG-1 and nTEG-2 (82.2–89.3%) at different battery voltage. This indicates that the reduction of nMPPO power generation from the value of MPP is less than the energy loss of the MPPT circuit. The TEG design using nMPPO is better.

Acknowledgements

This publication is based in part on work supported by Award No. KUK-C1-014-12, made by King Abdullah University of Science and Technology (KAUST), Saudi Arabia.

Nomenclature

D	duty cycle of PWM signal in the SEPIC circuit, %
I_{BAT}	current charged to the battery, A
I_{MPP}	maximum-power-point current of TEG module, A
I_{sc}	short-circuit current of TEG module, A
I_{TEG}	output current of TEG module, A
Q_h	heat input at hot-side of TEG module, W

MPP	maximum-power point at which maximum power is generated from the TEG module
T_c	cold side temperature of TEG module, °C
T_h	hot side temperature of TEG module, °C
P_{BAT}	power charged to the battery, W
P_{TEG}	actual power generated from the TEG module, W
P_{MPP}	power generated from the TEG module at the MPP, W
R_o	overall thermal resistance from the cold side of TEG module to the ambient, K W^{-1} , Eq. (1)
R_L	equivalent resistance load connected to the TEG, Ohm
V_{MPP}	maximum-power-point voltage of TEG module, V
V_{MPP95}	voltage of TEG at 95% of the maximum power P_{MPP} , V
V_{MPP90}	voltage of TEG at 90% of the maximum power P_{MPP} , V
V_{MPP85}	voltage of TEG at 85% of the maximum power P_{MPP} , V
V_{oc}	open-circuit voltage of TEG module, V
V_{TEG}	output voltage of TEG module, V
η_{diode}	efficiency of the circuit of the nMPPO (diode)
η_e	energy conversion efficiency of TEG = P_{MPP}/Q_h
η_{MPPT}	overall MPPT tracking efficiency ($=P_{BAT}/P_{MPP} = \eta_T \eta_{tk}$), Eq. (4)
η_{nMPPO}	overall nMPPO tracking efficiency ($P_{BAT}/P_{MPP} = \eta_{diode} \eta_{otk}$), Eq. (7)
η_{otk}	MPP tracking efficiency in nMPPO ($=P_{TEG}/P_{MPP}$), Eq. (6)
η_T	circuit efficiency of MPPT or nMPPO ($=P_{BAT}/P_{TEG}$), Eq. (6) or (5)
η_{tk}	MPP tracking efficiency ($=P_{TEG}/P_{MPP}$), Eq. (3)

References

- [1] M.S. El-Genk, H.H. Saber, High efficiency segmented thermoelectric uncouple for operation between 973 and 300K, *Energy Convers. Manag.* 44 (2003) 1069–1088.
- [2] Anders Killander, J.C. Bass, A stove-top generator for cold areas, in: *Proc IEEE 15th International Conference on Thermoelectric*, 1996, pp. 390–393.
- [3] R. Mahmudur, S. Roger, Thermoelectric power-generation for battery charging, in: *Proc IEEE Conference on Energy Management and Power Delivery*, 1, 1995, pp. 186–191.
- [4] W. Roth, Grid-independent power-supply for repeaters in mobile radio networks using photovoltaic/thermoelectric hybrid systems, in: *Proc 16th International Conference on Thermoelectric*, 1997, pp. 582–585.
- [5] J. Eakburanawat, I. Boonyaroonate, Development of a thermoelectric battery-charger with microcontroller-based maximum power point tracking technique, *Appl. Energy* 83 (2006) 687–704.
- [6] Chuang Yu, K.T. Chau, Thermoelectric automotive waste heat energy recovery using maximum power point tracking, *Energy Convers. Manag.* 50 (2009) 1506–1512.
- [7] C. Hua, C. Shen, Study of maximum power tracking techniques and control of dc/dc converters for photovoltaic power system, in: *Proceedings of 29th Annual IEEE PESC*, IEEE Computer Soc. Press, New York, USA, 1998, pp. 86–93.
- [8] B.J. Huang, F.S. Sun, R.W. Ho, Near-Maximum-Power-Point-Operation (nMPPO) design of photovoltaic power generation system, *Sol. Energy* 80 (8) (2006) 1003–1020.
- [9] Y. Maydanik, Review loop heat pipes, *Appl. Therm. Eng.* 25 (5&6) (2005) 635–657.
- [10] B.J. Huang, H.H. Huang, C.W. Chen, M.S. Wu, Development of high-power LED lighting luminaries using loop heat pipe, *J. Light Vis. Env.* 32 (2) (2008) 148–155.
- [11] B.J. Huang, C.H. Wang, T.T. Lin, H.H. Huang, Y.Y. Yeh, Development of a low-cost LHP for commercial application, in: *13th International Heat Pipe Conference (13th IHPC)*, Shanghai, China, September 21–25, 2004.