A New Design of Mobile Thermoelectric Power Generation System

Hsin-Hung Chang, Jin-Lung Guan, and Ming-Ta Yang

Abstract**—**This paper presents a compact thermoelectric power generator system based on temperature difference across the element. The system can transfer the burning heat energy to electric energy directly. The proposed system has a thermoelectric generator and a power control box. In the generator, there are 4 thermoelectric modules (TEMs), each of which uses 2 thermoelectric chips (TEs) and 2 cold sinks, 1 thermal absorber, and 1 thermal conduction flat board. In the power control box, there are 1 storing energy device, 1 converter, and 1 inverter. The total net generating power is about 11W.

This system uses commercial portable gas stoves or burns timber or the coal as the heat source, which is easily obtained. It adopts solid-state thermoelectric chips as heat inverter parts. The system has the advantages of being light-weight, quite, and mobile, requiring no maintenance, and having easily-supplied heat source. The system can be used as long as burning is allowed. This system works well for highly-mobilized outdoors situations by providing a power for illumination, entertainment equipment or the wireless equipment at refuge. Under heavy storms such as typhoon, when the solar panels become ineffective and the wind-powered machines malfunction, the thermoelectric power generator can continue providing the vital power.

Keywords**—**Thermoelectric chip, seeback effect, thermo electric power generator.

I. Introduction

TRADITIONALLY, the small power generation equipment uses an engine to drive a generator to generate electricity. This type of equipment is usually heavy, bulky, noisy, and require professional adjustment and maintenance. This equipment will automatically shut down when the fuel is used up. As a result, an engine-powered generation equipment is often used as a short-term operating power equipment. In some special cases, the use of solar panels or wind turbines is a popular green energy application. However, the solar panel is suitable for used in location that has a lot of sunshine during daylights and wind turbines are only suitable for use in windy locations. Furthermore, these power units must be set up at a permanent location, take up a lot of space, lack mobility, and are easily impacted by rapidly changing weather.

Considering simplicity, mobility, energy source, and maintenance, existing small generators have inherent limitations and cannot meet all the aforementioned requirements.

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Due to advances in semiconductor technology, the compact solid thermal electric chip can directly convert heat into electrical energy. In this proposed system, TE is the core component to generate the power.

II. Background of the Thermoelectric Chip

In 1821, J. T. Seebeck (1770-1831) discovered that dissimilar metals that are connected at two different locations (junctions) will develop a micro-voltage if the two junctions are held at different temperatures. This effect is known as the "Seebeck effect"; it is the basis for thermocouple thermometers.

In 1834, Peltier discovered the inverse of the Seebeck effect, now known as the "Peltier effect": He found that if you take a thermocouple and apply a voltage, this causes a temperature difference between the junctions. This results in a small heat pump, later referred to as a thermo-electric cooler (TEC) [1].

The use of both N and P type materials in a single power generation device allows us to truly optimize the Seebeck effect. As shown in Fig. 1, the N and P pellets are configured thermally in parallel, but electrically in a series circuit. Because electrical current (i.e., moving electrons) flows in a direction opposite to that of the hole flow, the current-generating potentials in the pellets do not oppose one another, but are series-aiding. Thus, if each pellet developed a Seebeck voltage of 20mV, this combination of an N pellet and a P pellet would generate approximately 40mV rather than zero volts [2].

In truly practical TEs, many such P & N couples are employed to bring the Seebeck voltage up to useful levels. The illustration in Fig. 2 shows an example TE device (more typically, a TE has 127 couples or more).

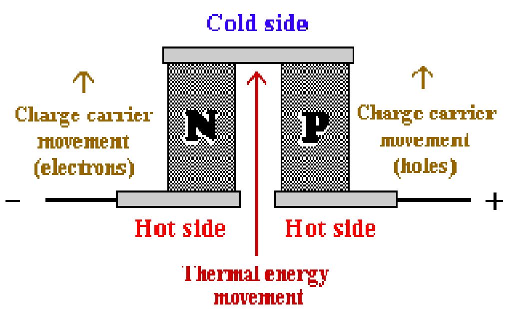

Fig. 1 Schematics of a P&N couple

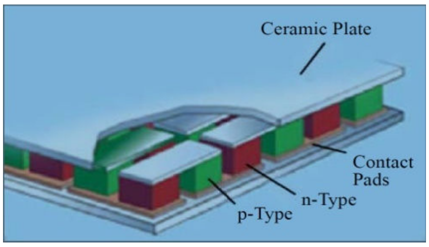

Fig. 2 P & N couples in a TE device

A thermoelectric chip (TE) consists of several N & P pellets, which are connected electrically in series and thermally in parallel and sandwiched between two ceramic substrates, as illustrated in Fig. 2. With application of a DC current of the proper polarity, heat is pumped from the bottom substrate to the top substrate, where it is dissipated to the ambient. The result is that the bottom surface becomes cold. By simply reversing the DC polarity, the bottom surface can also supply heat, thus making the top surface cold. Because TEs are light weight and efficient in cooling and heating. They are the key components in the proposed system, which contains 8 TEs.

III. The Electric Character of the Thermoelectric Chip

TEs don't work like regulated power supplies. TEs have appreciable 'internal resistance'. There is an appreciable voltage drop across this internal resistance. The electrical model for a TE can be formulated as a no-load voltage (i.e., the open-circuit voltage output of a TE) applied to a series circuit consisting of the TE's internal resistance (R_{INT}) and the electrical load (R_{Load}). As in any series circuit, the voltages will 'drop' in proportion to the resistances. As shown in Fig. 3, the most *power will be transferred* to the load when the resistance of the load *equals* the internal resistance of the voltage source.

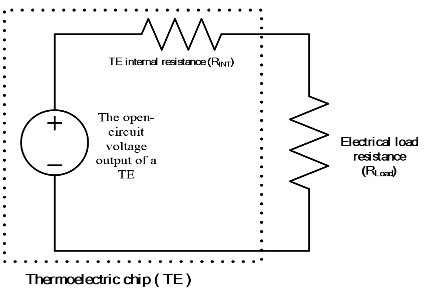

Fig. 3 The electrical model for a TE

The geometry of the thermo elements affects the power of the TE, the efficiency, and the voltage achieved [3]-[5]. When the TE is operated with a matched load, following formulations can be derived:

$$V_m = \frac{\alpha N(T_h - T_c)}{1 + 2\gamma l_c / l} \qquad (1)$$

$$I_m = \frac{\alpha A(T_h - T_c)}{2\rho(n + l)(1 + 2\gamma l_c / l)} \qquad (2)$$

$$P = V_m I_m = \frac{\alpha^2}{2\rho} \frac{AN}{(n + l)(1 + 2\gamma l_c / l)^2}(T_h - T_c)^2 \qquad (3)$$

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

where V_m is the output voltage of the TE, I_m is the output current of the TE, P is the output power of the TE, ϕ is the conversion efficiency of the TE, T_h T_c are temperatures at the hot and cold sides of the TE.

From those equations, one can observe that P is proportional to the square of the temperature difference, ϕ is proportional to the temperature difference and inverse proportional to the temperature at the hot side of the TE, and V_m and I_m are proportional to the temperature difference. It is evident that the larger the temperature differences between the hot and cold sides of the TE, the larger the power that the TE can output.

IV. The Basic Structure of the TE-Powered Generator

Fundamentally, there are four basic components in a TE-powered generator: a heat source, a TE, a 'cold-side' heat sink, and an electrical load. The system may also include a voltage regulation circuit or a fan for the heat sink. Fig. 4 shows one example of such a system.

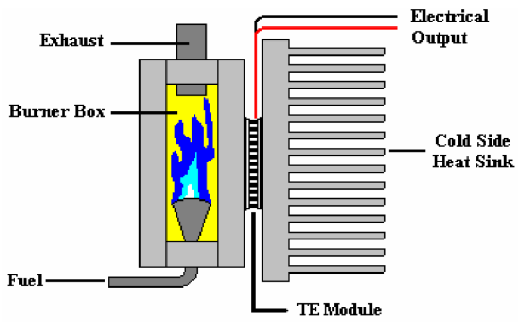

Fig. 4 An example of a TE-powered generator

To achieve low contact thermal resistance and optimal power output and to avoid metal deformation due to temperature changes and possible damage to the TE, the designed structure and mounting system must address the following issues: [6]

1. Compressive Loading
2. Thermal Expansion
3. Uniform Load
4. Overhang
5. Thermal Spreader
6. Flatness & Thermal Transfer Compound
7. Thermal Bypass

V. System Design

A. The Principles

Energy from burning butane or lumber can heat up the absorber that is at the middle of TEM. The absorbed energy is conducted to the hot side of the TE, passed through the body of TE to the cool side of TE, and finally dissipated to the air by the cold sinks.

The thermal electric power generator consisting of 4 TEMs will convert the heat energy to DC power through the Seebeck effect. The DC power will be stored at the battery and then transferred to the required electrical power for the equipment. This is the working principle of this proposed system.

B. The Structure of the Proposed System

As shown in Fig. 5, the thermo-electric generator consists of four TEMs that generate the electrical power to charge the battery in the power control box by transferring the heat energy. Then, a 12V DC output of the battery will be transferred to 110V AC or 220V AC by the inverter, be transferred to 1.25V~ 11V DC by the converter, or output the 12V DC directly.

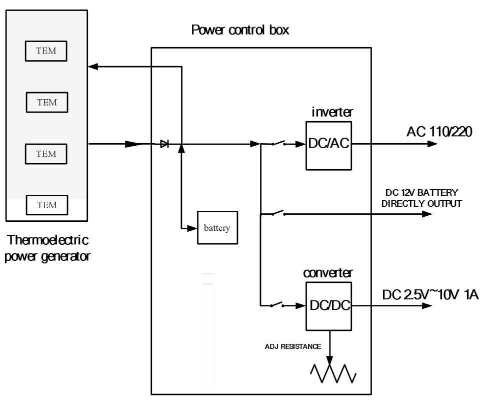

Fig. 5 The structure of the proposed system

C. *The Mechanical Design of the Thermoelectric Power Generator*

The thermoelectric power generator has four TEMs. Each TEM is composed of one thermal absorber, one thermal conduction flat board, two TEs, and two cold sinks.

1. Thermal absorber: As shown in Fig. 6, the absorber is made of aluminum with a vertical fin structure. The temperature can reach 300°C after absorbing the heat.
2. Thermal conduction flat board: As shown in Fig. 6, the flat board conducts the absorbed heat to the end of the structure. The temperature at the end point is about 200°C.
3. TEs: As shown in Fig. 7, the two TEs (size 40mm*40mm) are tightly bonded at the end of the flat board. This side is called the hot side of the TE.
4. Cold sinks: As shown in Fig. 7, the other side of the TE is the cold side, which is closely bonded to a cold sink. The cold sink uses a fan to dissipate the conducted heat of the TE by forcing the air flow. The cold sink can keep the temperature of the cold side of the TE at 60°C.

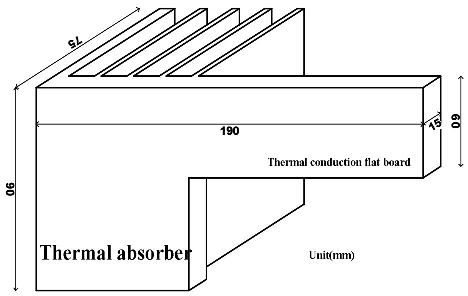

Fig. 6 Thermal absorber and thermal conduction flat board

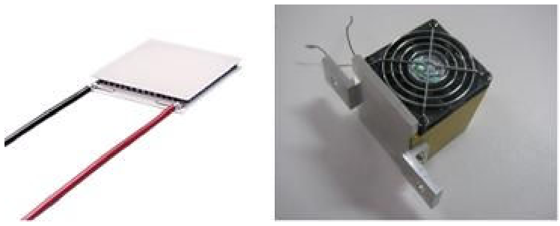

Fig. 7 TE (left) and cold sink (right)

The four TEMs make up the thermoelectric power generator, the center part of which is a heat absorber with a square fin structure. The mechanical design matches the principles defined in [6]. As shown in Fig. 8, the thermoelectric power generator is directly connected to the power control box, so the power can be transferred to the right type of power for the power devices.

Fig. 8 The thermoelectric power generator system

D. Component Selection for TEM

According of the combustion experiment for the absorber and conduction board, the temperature is about 160°C~200°C at the end of the conduction board, so the system uses the 40mm*40mm*3.3mm TE (TEC1-127.10T200) which withstand temperatures over 200°C. The TE can output an open circuit voltage Vopen = 4V with an internal resistance R_{INT} = 1.6Ω when the temperature difference is around 100°C. In general, the lower the heat sink thermal resistance, the more power the thermoelectric generator generates. However, the thermal resistance of the heat sink is inversely proportional to the air flow into the cool sink. The air flow into the cool sink is controlled by the fan speed and the fan speed is proportional to the input power therefore, the larger the fan power input, the lower the thermal resistance of the heat sink. Unfortunately, the fan power is generated by the thermoelectric generator, so you cannot get the lower thermal resistance simply by increasing the air flow.

According to the thermal resistance experiment as showed in Fig. 9, in order to simply the circuit in the system, the working voltage of the fan is only fixed at 6V DC or 12V DC. When the voltage is 6V DC, we get the current I=0.12A, the power P=V*I=0.72W, and the thermal resistance 0.45°C /W. When the voltage is 12V DC, we get the current I=0.23A, the power P=V*I=2.76W, and the thermal resistance 0.33°C/W. Even though the thermal resistance is increased from 0.33°C/W to 0.45°C/W, the power of 2.76W is much larger than 0.72W, so we select 6V DC as the fan's operating voltage.

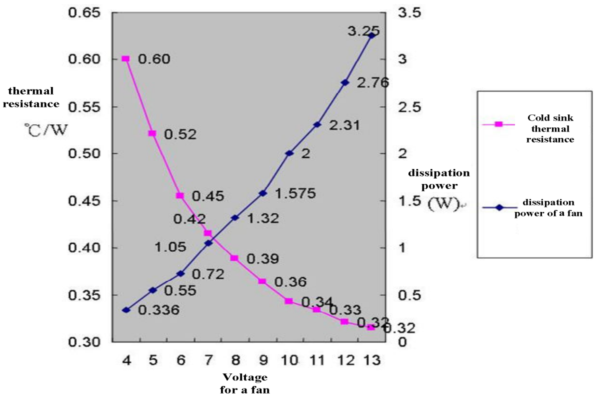

Fig. 9 The dissipation power of the fan and the thermal resistance of the cold sink

E. Generated Power and the Conversion Efficiency

The thermoelectric generator is analyzed using a thermal resistance model. Each component in the system is given a resistance in °C/W. This value tells the temperature drop through any component of the system for each watt passing through. For the system, the thermal resistances of (1) the thermal conduction board to the hot side of TE, (2) the TE body, and (3) the cold side of the TE to the cold sink, are combined and represented by a simply thermal resistance R_{module}. Fig. 10 illustrates this thermal resistance model.

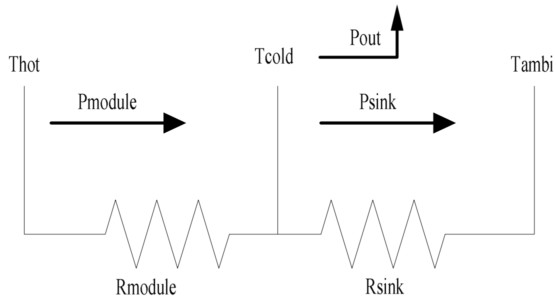

Fig. 10 The thermal resistance model of the TEM
T_{hot}: the temperature at the end of the conduction board; T_{cold}: the temperature at the cold sink; T_{ambi}: the temperature of the air inhaled by the heat sink fan; R_{module}: the total thermal resistances of (1) the thermal conduction board to the hot side of TE, (2) the TE body, (3) the cold side of the TE to the cold sink; R_{sink}: the thermal resistances of the cold sink; P_{module}: the thermal power flows from TE hot end to the cold side; P_{sink}: the thermal power flows from the cold sink to the ambience air; P_{out}: the electric power generated by TE

When the system works normally, the temperature of the hot side is T_{hot} =160°C and the cold side is T_{cold} =70°C. Therefore, the temperature difference across the TE is 90°C. The thermoelectric power generator has 8 TEs. For each TE, the open-circuit voltage is 3.7V and the internal resistance is 1.6Ω, so the total Vopen= 3.7V*8=29.6V and the total Rint = 1.6Ω*8=12.8Ω. When the generator is operated with a matching load, the load voltage is 29.6V/2=14.8V, the load current is 14.8V/12.8Ω=1.15A, and the maximum load power is 14.8V*1.15A=17W. In addition, the dissipation power of fans is 0.72*8=5.76W. Therefore, the maximum output power of the machine is about 17-5.76=11.24W. According to the "thermal resistance model" as shown in Fig. 10, the conversion efficiency of the system is calculated as below:
Given:

$$R_{sink} = 0.45\,^{\circ}C\ /W \tag{5}$$

$$T_{ambi} = 32\,^{\circ}C \tag{6}$$

$$T_{cold} = 70\,^{\circ}C \tag{7}$$

We have:

$$P_{out} = 17/8 = 2.1W \tag{8}$$

$$\begin{aligned} P_{sink} &= (T_{cold} - T_{ambi})/R_{sink} \\ &= (70-32)/0.45 \\ &= 84.4W \end{aligned} \tag{9}$$

$$P_{module} = P_{sink} + P_{out} = 86.5W \tag{10}$$

$$R_{module} = (T_{hot} - T_{cold}) / P_{module} = (160 - 70) / 86.5 = 1.04\ ^{\circ}C\ /W \quad (11)$$

and the conversion efficiency:

$$\phi = P_{out} / (P_{sink} + P_{out}) = 2.1 / 86.5 = 2.4\ \% \quad (12)$$

E. Battery

Although there is 11W of power, it can't drive any high power electrical equipment, such as household fans, television, computer, etc. Therefore, for large equipment, the ability of storing the energy in a battery is necessary. For the thermal electric generator, the open circuit voltage is 30V, the load voltage is about 15V, and the internal resistance is 12.8Ω. This resistance creates a limit of charging current for the battery to avoid damaging the battery. When the battery voltage is gradually approaching 14.5V, the charging current will be gradually reduced. The battery charging time is about 7 hours with a charging current of 0.65A, and a charging power of 9W.

VI. Experimental Result

Fig. 11 shows an example usage of the portable gas stove where a butane cartridge can burn for about 60 minutes and provide about 10Whr of power. In Fig. 12 shows another example of using dead wood. With continuous supply of dead wood or other heat source, the generator is able to continue generating electricity. Regardless of the use of a portable gas stove or wood, the system can stably output power of approximately 17W after burning for about 15 minutes. Taking into account the fan's dissipation power of 5.76W, the net power generated is approximately 11W, as shown in Fig. 13.

Fig. 11 To gen. the power with portable gas stove

Fig. 12 To gen. the power with dead wood

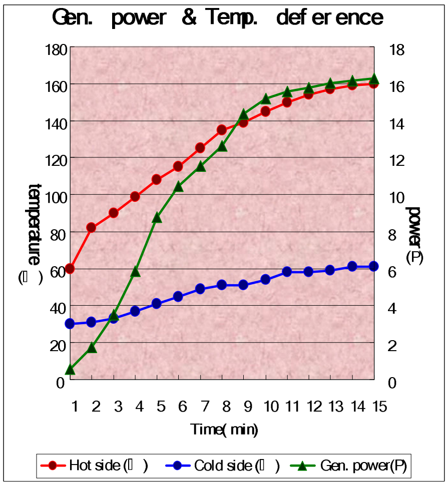

Fig. 13 The generated power & the temperature difference

For this portable generator system, the biggest benefit is to use it as an emergency power supply. Imagine a scenario that in a mountain or a remote, impoverished area, there is no electricity and the solar panels and wind turbine are already damaged. Another engine-powered generator will eventually shut down due to the lack of gasoline. Only the dead branches on the ground can be used to generate electricity.

Because of no moving part except for the fans and the use of solid TE parts, the system has good reliability, is maintenance-free, generates little noise, is small size, and has high Mobility (weight about 15 Kg). Using wood as the burning material is a green power application. Since the cost is low, it makes sense to install the system at every mountain refuge house as an emergency or life- sustaining power.

VII. Conclusion

Solid-state TE is a rather special component. Although there are already uses of TEs for some special occasions, there is a lot of room for us to explore. With the oil price approaches US$ 100 per barrel, there is an urgent need for the development of new energy or green energy. In addition, energy conservation and recycling also become important issues. In this study, the use of thermoelectric technology to produce a commercializable thermoelectric generator that can be used in mountain refuge cabins as a emergency backup power for life support equipment. It is also a portable power supply that provides great mobility. In addition, the study can be applied to heat waste recovery, in locations such as power plants, steel mills, and hot exhaust gas from automotive engines, etc.

Research and application of thermoelectric technology as an energy source is still in its infancy. With the conversion efficiency of thermoelectric technology improves, it has the potential of supplementing or even replacing the conventional power generation methods which have the drawback of polluting the environment.

REFERENCES

[1] http://www.heatsink-guidw.com/content.pnp?content=peltierinfo.shtml.
[2] http://www.tellurex.com/seebeck%20faq.pdf.
[3] Buist, Richard, Lau, Paul, "Thermoelectric Power Design and Selection from TE Cooling Module Specifications," 16th International Conference on Thermoelectric (1997), Aug 26-29 1997, Dresden, Germany, 551-554
[4] Rowe, D. M., Min, G. "Design Theory of Thermoelectric Modules for Electrical Power Generation," IEE Proceedings: Science, Measurement and Technology, Vol. 143, No 6, November 1996, 351-356.
[5] Nuwayhid, R. Y., Rowe, D. M., Min, G., "Low Cost Stove-Top Thermoelectric Generator for Regions with Unreliable Electricity Supply," Renewable Energy, Vol. 28, 2003, 205-222.
[6] Frederick A. Leavitt, Norbert B. Elsner and john C. Bass "Use, Application and Testing of Hi-Z Thermoelectric Modules" Hi-Z Technology ,Inc.