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Research, Development, and Applications of the High-Power Thermoelectric Generation Technology

[1,2] * A.J. Jin, [1]Wenbo Peng, [3]Ying Jin, [1]Dawei Liu, [1]Qiming Li

[1] Huaneng Clean Energy Research Institute, Beijing, CHINA

[2] China Huaneng Group, Beijing, CHINA

[3] Frontway Battery Ltd., Wuxi, CHINA

*ajjin@hnceri.com

ABSTRACT

Thermoelectric generation (TEG) is advantageous over traditional power production in terms of no vibration, no pollution, no noise, small volume, and long life expectancy. In this article, the authors will review the TEG, its current state of development, introduce its principal, and explore a new approach by the large-scale integration manufacturing of a high-output TEG device. By utilizing both home-made and the off-the-shelf devices, the TEG systems are constructed and tested. The TEG system is characterized. Furthermore, the authors have investigated the TEG systems in either serial or parallel configurations and demonstrated that the total power output is the simple addition of the separate systems. Based on these tests, they discuss the LSI manufacturing of TEG devices to improve its performance and cost reduction. Moreover, by utilizing LSI technology and using multi-stack TEG structure, the studies show the feasibility of producing larger output, higher density, and more efficient TEG devices than the single TEG module. Finally, based on the studies, the authors discuss how one can commercialize TEG in volume production in the future.

Keywords: *Thermoelectric power, large scale integration, TEG, China Huaneng group, Clean tech*

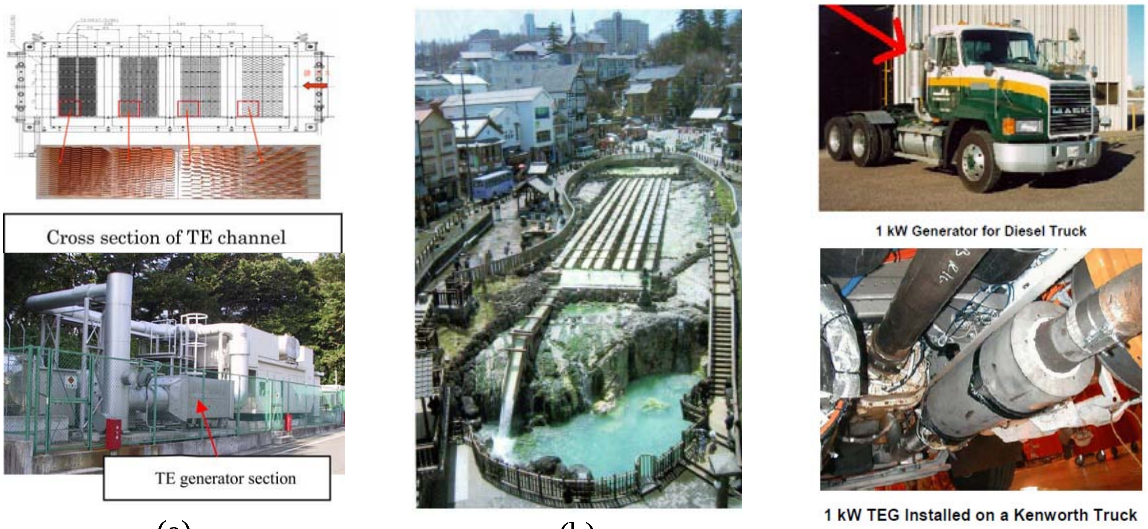
1. INTRODUCTION

In the world today, the development of renewable energy has derived strong supports to foster environmentally friendly technology in achieving sustainable energies and emission reduction. For example, China's long-term science and technology development program and national “12th Five-Year” Plan both emphasize the energy-saving, emission reduction and the development of new energy as the focus of the transition towards a green economy when the energy production is both environmental friendly and economic. The national "12th Five-Year Plan" clearly put forward the target that in the year of 2015 (Y2015) the national energy consumption per unit of GDP to reduce by 16% compared with Y2010(at Y2005 price)[1]. National long-term science and technology development program (2006 to Y2020) proposed that compared to Y2005, the amount of carbon dioxide emissions per unit of GDP decreased by 40% to 45% by Y2020[2]. Therefore, the development of new type environmentally friendly renewable energy and energy conversion technologies are important for the achievement of the Energy Security for a nation.

Thermoelectric generators (TEGS) are semiconductor devices which convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect"[3] described at below. The success of highly efficient and low cost TEGS technology is likely to have significant commercial impact. We have investigated with home-made and off-the-shelf TEG device in order to evaluate this technology as follows.

When one of its two surfaces is located in a hot or cold environment compared to the ambient, the TEGS generate some voltage. The voltage can typically be hundreds of micro-volts per degree temperature difference, and it generates electrical power when connected to a resistive load. TEG has advantages of no-vibration, no pollution, no noise, small volume, and long life expectancy. When appropriately produced, it is a green energy technology, i.e., with no carbon footprint. NASA has been using the TEG as space energy source for five decades. With technology advancement, The TEG has shown ever increasing potential for applications, that can be widely used in power generation of industrial waste heat, automobile exhaust waste heat, solar energy and other natural thermal energies. There are extremely interesting developments in the TEG area.

For example, Japan launched a series of governmental plans to study thermoelectric technology for solid waste incineration heat power generation[4]. The U.S. Department of Energy (DOE) funded the Pacific Northwest National Laboratory, and other units for the high-performance thermoelectric materials and application technology research, particularly for the utilization of industrial waste heat[5]. The U.S. DOE recently passed lump sum of three research projects by $24million US dollars in total, funding General Motors and two associate companies to carry out one research project of thermoelectric generation technology for automobile exhaust waste heat harvesting. The stated goal is to improve the fuel efficiency by 5% to 10%[6].



(a) (b) (c)

Fig. 1 of the cases illustrated high-power TE generation as follows.
(a) 1kW waste heat thermoelectric generator developed in Japan[7]
(b) Hot spring power generation system developed by Japanese, which are comprised of several 500W thermoelectric generators[4]
(c) 1kW automobile exhaust thermoelectric generator developed by BMW, GM[8], etc.

Table 1. Typical cases of the applications of high-power TE generators

SN	Manufacturer	Power W	Efficiency%	Hot side T ℃	Material	Application	Price $/W
1[6]	BMW、GM BSST、Hi-z	800	6	500	Co-Sb	automobile exhaust heat	13
2[5]	Plantec、Showa Denko、Komatsu	21.6	6.2	280	n: Ce-Co-Sb p: La-Fe-Sb	solid waste incineration heat	-
3[9]	Thermonamic	500	4.8	250	BiTe	general	<2
4[5]	Komatsu/KELK Showa Cable Systems	200	7.2	280	BiTe	boiler waste heat	-
5[5]	Komatsu	500	10~11	700	n: Co-Sb p: Mn-Si	gas turbine afterheat	-
6[10]	GM、Hi-z	1000	4.5	250	BiTe	oil turbine afterheat	11

China Huaneng Group (CHNG), the largest electric power utility company in Asian leads a frontier in the field of thermoelectric generation technology research. Upon the support of a national program [11], the CHNG has set up a project to carry out advancement and commercialization of the TEG technology. Based on nano-bulk thermoelectric materials[], the project plans to significantly increase the efficiency of thermoelectric conversion, and aim to manufacture a new generation of high-efficiency, high-power thermoelectric devices. The success of this project will enable the TEG technology be comparable to the conventional thermal power generation technologies, and reduce the TEG installed cost to 8000 RMB / kW, which will overcome the cost barrier that limit the wider application of TEG.

We have designed and constructed TE power generation device. In Section-II, we will review and discuss the technical background. Furthermore, we especially construct the TEG system(s) so that a high power output is derived. In Section-Ⅲ, experimental investigation will be presented and test data are analyzed. Finally, in Section-IV, we'll summarize the results in this article.

2. THERMOELECTRIC POWER DEVICE

2.1 Thermoelectric effects

The thermoelectric effects which underlie thermoelectric energy conversion can be conveniently illustrated in Figure 2. It can be considered as a circuit formed from two dissimilar semiconductors, P-type and N-type (thermocouple legs). If the junctions at both top and bottom

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are maintained at different temperatures T1 and T2, an open circuit electromotive force, V is developed, and given by V =α(T1-T2), in which α is the Seebeck coefficient between the P-type and N- type elements.

The basic unit of a thermoelectric (TE) generator is the thermocouple shown schematically in Figure 2. Figure 3 shows schematically a thermoelectric module, which consists of a number of the basic units connected as follows: electrically in series, thermally in parallel, and sandwiched between two ceramic plates. The generating performance of a thermoelectric module is gauged primarily by the conversion efficiency and power-per-unit-area.

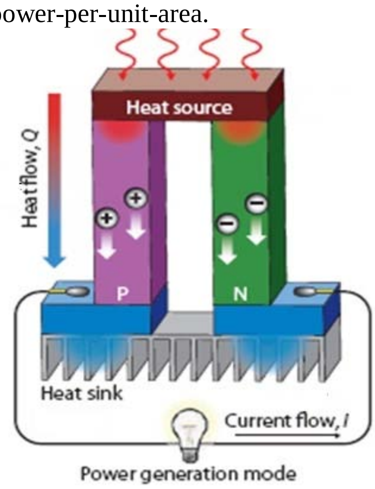

Fig. 2. Illustration of the thermoelectric generation

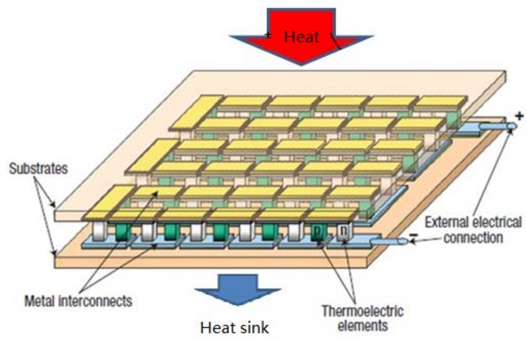

Fig. 3. Typical schematic of a thermoelectric module

A thermoelectric module is a heat engine. As it is similar to other heat engines, it obeys the laws of thermodynamics. If we initially consider the module operating as an ideal generator in which there are no heat losses, an efficiency is simply defined as the ratio of the electrical power delivered to the load to the heat absorbed at the hot junction.

The engineers could optimize the efficiency for various applications. For example, the efficiency is related to both the materials and thermal conditions as follows[13].

$$\phi_{max} = \frac{T_2 - T_1}{T_2} \cdot \frac{(1+Z\overline{T})^{1/2} - 1}{(1+Z\overline{T})^{1/2} + T_1/T_2} \qquad (1)$$

Where

$$\overline{T} = \frac{T_H + T_C}{2} \qquad (2)$$

And the figure-of-merit of the couple is as follows:

$$Z_c = \frac{\alpha_{ab}^2}{\left[\left(\frac{\lambda_a}{\sigma_a}\right)^{\frac{1}{2}} + \left(\frac{\lambda_b}{\sigma_b}\right)^{\frac{1}{2}}\right]^2} \qquad (3)$$

As shown in eq.1, the maximum thermoelectric efficiency has a positive relationship with the temperature differential ΔT and the figure-of-merit of the TE couple, Zc. For a single material, Z has an optimal temperature range. When the temperature differential increases, a single-type TE-material can't obtain maximum efficiency. It is our belief that multi-layered TE modules of optimized materials can lead to significantly higher efficiency than the single-layer TE material.

2.2 Our thermoelectric generation equipment

Figure 4a), 4b), and 4c) illustrates a variety of TEG systems that authors have constructed for the experiments. All three are similar to each other. As shown in Fig. 4a), a typical device is constructed to have heat flow upwardly from the below. The schematic illustrates many components used for their particular prototypes, etc.

Figure 4c) is a specific TEG application and this prototype is constructed as follows: where it has a copper plate [or aluminum] with high thermal conductivity, where it is coated with light-absorbing material at its lower end to supply heat, where we've coated the lower end so that it has a high absorption coefficient. where we have made the cold-side surface of the thermoelectric module with copper to ensure the best/ tight thermal interface with the heat-dissipating unit, and which is the contact-surface of an external water-cooling system. When the TEG system is constructed, its electrical output can be characterized by a programmable load-scan device shown on its right hand side[r.h.s.].

The highest temperature drop across the TEG device dictates its total power output. Therefore, it is imperative to maintain a large temperature differential as high as we can.

The thermoelectric modules were mounted on top of the copper plate, and were pressed against by the top water-cooler. The water-cooler is used to set the temperature of the cold side of the equipment, maintaining a temperature differential from the hot side (light-absorbing substrate). It is imperative to keep a high temperature differential as it determines the output power. For example, in order to prevent the heat leakage between the hot and cold ends of the equipment, a specially designed heat insulating material were fully filled by asbestos and alternating layers of foil/ fiberglass around thermoelectric modules. Its insulation can be so good as it is at least an order of magnitude lower than the air in the thermal conductivity [14]. In addition to the power output interface, the entire device also sets two-temperature interface for cold and hot side temperature test.

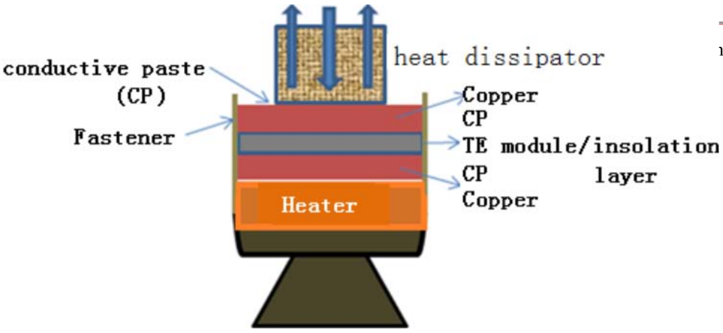

Fig. 4a). is a schematic of TEG prototype to heat upwardly from a heat source at below as shown. Heat flows through TEG, which converts into electricity from heat. The cold-side of TEG is maintained such as by means of water-cooling.

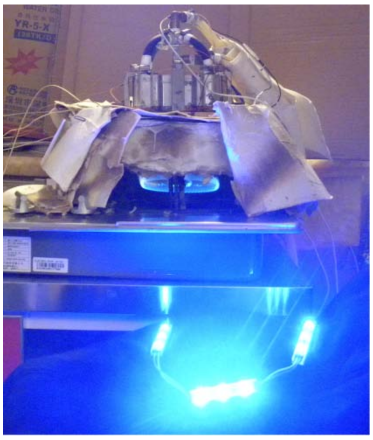

Fig.4b). illustrate a type of TEG with the hot-side attached to stove-top, and with the cold-side to a device with running water.

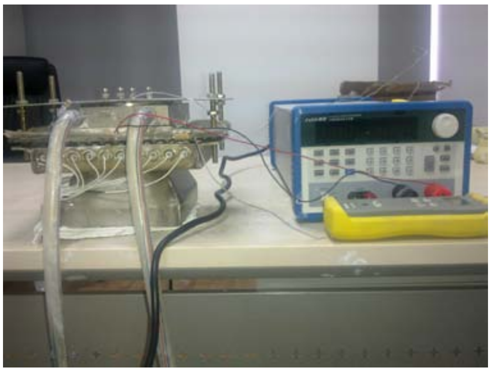

Fig.4c). TEG prototype and test platform. This illustrates a TEG prototype built with infrared irradiation as the heat source, water-cooled, and had the same of the rest components as that of Fig -4a and -4b. The variable electronic load and a multi-meter is shown on the r.h.s.

This illustrates a prototype built with infrared irradiation as the heat source, water-cooled, and had the same of the rest components as that of Fig -4a. The illustration shows a typical device that is tested as follows: Silicon Paste, Fastener, heat cooler, copper, TE devices, insulation materials, and heat source.

In order to test the output parameters of the device, a matched test platform was also built. The infrared lamp was selected as the radiation source, and the radiation, which could be adjusted by the connected transformer, was converted into heat by the light-absorbing substrate of the thermoelectric generation. The output current - voltage characteristics of this equipment was measured by a programmable DC electronic load (Faith FT6305A). And the maximum output power can be derived from the current-voltage characteristic. In addition, the OMEGA HH11B portable device was used for temperature acquisition.

3. DATA AND REPORTS

Based on the above platform, the output parameter of a small power prototype is studied at several temperature differential conditions. In the study, that resistance of an electronic load is varied which changes the output voltage. The power output is the product of both output current and output voltage. With a system configured like Fig. 4b, which is set at a maximum temperature differential, and which has BiSbTe-based TE module, the typical power output is demonstrated in Figure 5a. The authors have employed the infrared light source to set the hot-side surface temperature. By regulating a heat source of the infrared light radiation and irradiation time, the temperature of the hot side was adjusted.

In table 2, the test results under various temperature conditions are listed. When the temperature difference were 133.9℃, 212.7℃and 258.5℃, the output power of prototype increased from 7.3W to 20.7W and further increased to 27.3W. All the tests were carried out at room temperature (about 27℃).

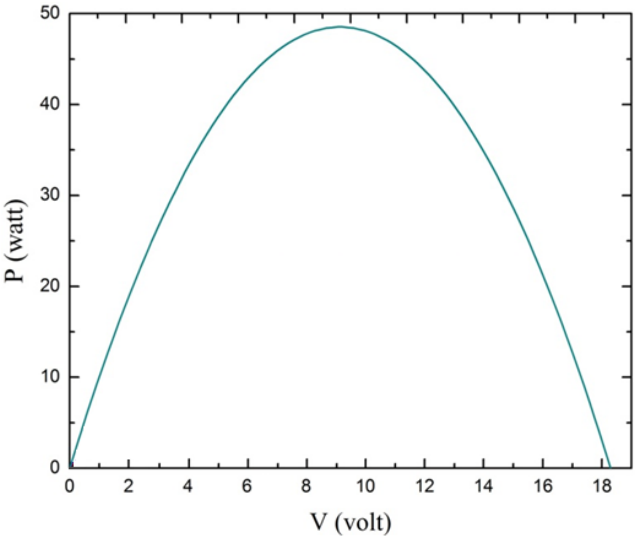

Fig. 5a): This figure illustrates the relationship of the power output and the output voltage. The figure shows that the relationship is basically parabolic.

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Table 2. Output parameters of the TEG prototype under different temperature differential conditions

Light source voltage V	Irradiation time min	Hot side temperature ℃	Cold side temperature ℃	Temperature difference ℃	Output voltage V	Output current A	Open Voltage V	Short current A	Max. Power W
100	15	196	62.1	133.9	8..66 5.99 3.99 1.98 0.41	0 1.033 1.811 2.587 3.196	8.66	3.35	7.3
150	15	300	87.3	212.7	15.81 11.98 8.98 5.98 2.97 0.64	0 1.273 2.258 3.251 4.247 4.825	15.81	5.22	20.7
160	10	361	102.5	258.5	19.08 15.99 11.98 7.98 3.97 0.76	0 0.925 2.123 3.322 4.545 5.518	19.08	5.74	27.3

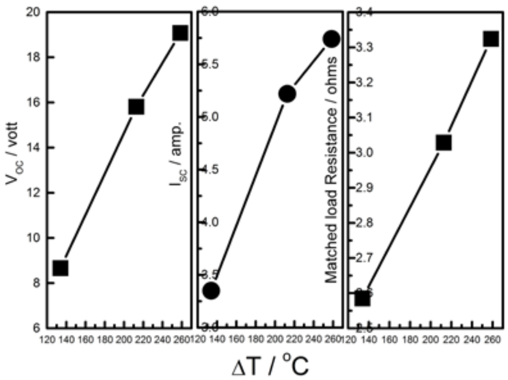

Fig.5b). The TEG prototype output parameters with the trend of temperature changes, from left to right are the open circuit voltage (V_{OC}), short-circuit current (I_{SC}) and the electrically matched load resistance.

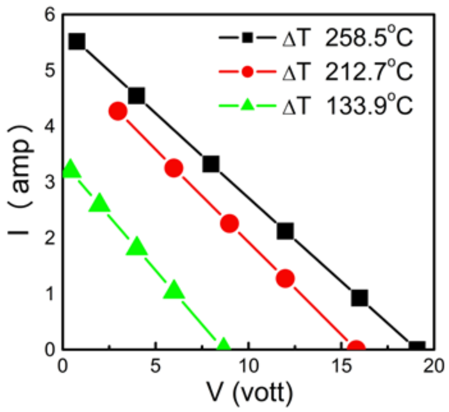

Fig.6. I-V curves of the TEG prototype at different temperature differential

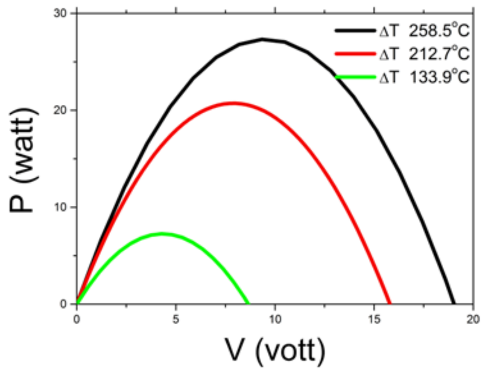

Fig.7. P-V curves of the TEG prototype at different temperature differential

Figure 5 shows the trends of each primary parameters, including the open-circuit voltage (VOC), short-circuit current (ISC) and the optimal output matching resistor, as a function of the temperature differential. Each output parameter follows nearly linear dependence upon the change of an increasing temperature differential. When the temperature differential (ΔT) reached 258.5℃, the open circuit voltage reached 19.08V, and the short circuit current reached 5.74A. Figures 6 and 7 are the I-V curves and P-V curves at various ΔT. Furthermore, we have optimized the design of the prototype, and have increased the output of TEG systems with recent prototype construction.

This paper will further report another batch of experiments conducted on two [combined] sets of TEG systems. These systems can be configured and matched closely in their thermal and electric parameters. Numerous tests are conducted for these systems in various configuration and the data are tabulated in the Table 3. Besides the separate test of set-A and set-B systems, Table 3 further shows the

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output results where set-A and -B are combined in either serial or parallel configuration. The variable data are the average temperature points T_{ave} in both the hot-side and the cold-side. Typically, there will be variation of the temperatures at either sides as illustrated in Figure 4. Table-3 is a list on a particular setting, the data was measured the open-circuit voltage Vo and the short circuit Is, and Vo * Is are tabulated in the last column.

Table 3. this lists the TEG system measurements including T_{ave}; Vo; Is: and Vo * Is from many experiments described previously.

Device Sets	T_{ave} (deg-C)		Vo	Is	Vo * Is
configured	hot-side	cold-side	(V)	(A)	(W)
Set-A	153.9	47.3	10.27	7.77	79.8
Set-B	145.0	49.6	10.57	7.36	77.8
Set-A & -B in Serial			20.85	7.53	157.0
Set-A & -B in parallel			10.44	14.98	156.4

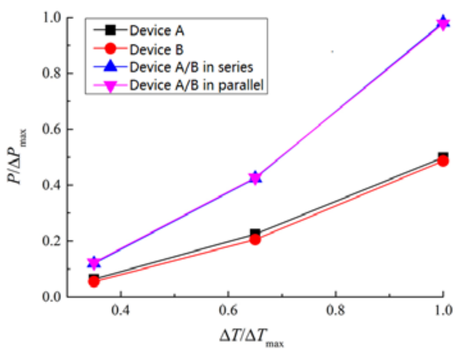

Fig. 8. Two TEG systems are assembled in either serial or parallel configuration. This figure demonstrates that the total power, P, exhibition the simple addition of separate system P1 and P2. This exhibition implies little internal loss of energy by the loop of system-1 and -2. The lines in the figure are just for eye guidance.

As a result, this article investigated the superposition of multiple systems. The Figure 8 illustrates addition of two sets of systems in the following procedures: 1) the test carefully set up their thermal electric parameters; 2) studied the electrical power output; 3) the measurement combines systems in either serial or parallel configurations. As shown, our data demonstrate that the total power output follows a simple additive law of separate systems. The simple additive law also means that the multiple systems are scalable advantageously and that we can construct TEG modules in great numbers for convenient integration. We believe that it is significant due to that the combination of various devices can meet various requirements of customers.

There are many ways to improve the performance of the TEG system. According to test results, we conclude that the output power can improve as follows:

- To use high-Z nano-bulk materials (ZT>1.5) that has better figure-of-merit, ZT, than the current ones to produce thermoelectric modules such that these materials will improve the overall system spec such as its thermoelectric efficiency.
- To match modules in serial and/or parallel configuration, where one needs to address the temperature uniformity issue needed over a large area such that the devices have well- matched output power and that the output spec can be easily customized.
- To increase delta-T by lowering the cold side temperature such that the output power can be increased
- To use multi-stack TEG structure w/ appropriate TE materials and increased window of temperature differences such that the system efficiency will be further improved.
- To miniaturize the TEG devices in a module such that one can increase the power density. In comparison with discreet bulk-TEG production approach[15], one can employ manufacturing processes such as the large scale integration (LSI) semiconductor process technology. The typical size of TE devices manufactured via LSI is approximately 25um and below.

Finally , we are exploring the high-density TEG module design for the following reasons:

- we build TEG power modules to have high-power by parallel and serial connections;
- we can build power devices by LSI methodology with beneficial integration;
- LSI processes allow us to automate production;
- scalable for manufacturing modules [LSI manufacturing] as it has been exhibited in the semiconductor industry;
- We can model, optimize, and readily produce a large array of LSI devices of TEG;
- Development of LSI work leads to the high-density semiconductor manufacturing. The combined TEG system has advantages as follows. LSI process is among the best choice of modular design to meet various output requirement.

4. SUMMARY

In summary, several TEG systems are constructed utilizing both home-made and off-the-shelf devices. Every TEG system is characterized at various temperature settings. In the performance characterization, each TEG system is constructed and fine-tuned so that this system can reach the maximum temperature differential. Based on our investigation, we are able to construct systems with output power to reach 100Watt level per system. Moreover, the TEG systems are set in either serial or in parallel configurations, and have demonstrated that the combined output follows a simple additive law of the separate output of each system.

We have developed several sets of thermoelectric generators driven by various heat sources and have measured their performance as shown in the paper. The low-cost thermoelectric power generation technology is believed to contribute to the mainstream clean tech energy market and to provide high power supply in future. One of the constraints of the large-scale application of thermoelectric generation

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technology concerns the use of rare materials, and the miniaturization of thermoelectric devices will be an effective solution to this concern. The TEG technology has covered several technological areas. It needs a wide range of technology integration, e.g., in which the industrial manufacture of micro thermoelectric modules should be emphasized and is technically challenging.

China Huaneng Group is the China's largest power generation enterprise and the leader of the scientific and technological innovation of electricity industry, and also the earliest power enterprises that start to focus on centralized thermoelectric generation. We set a mission for a team of researchers to develop the high-power thermoelectric generation technology and its product commercialization. By dedicating our resources, China Huaneng Group is going to develop in about three years a set of internationally leading thermoelectric generation technology and to in the mainstream clean tech market.

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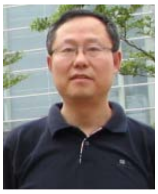
AUTHOR PROFILES

Dr. A.J. Jin has been working on the renewable energies area such as concentrated solar PV and on thermal electric power generation for several years. Dr. Jin obtained his PhD degree from University of Minnesota. His group is focused on developing renewable energy generators and is committed to create values by deploying generator with high efficiency and low cost.

Dr. Wenbo Peng obtained the PhD degree from the Chinese Academy of Science. To develop TEG power product is one of the main focuses for all authors in the China Huaneng Group. China Huaneng Group is the Chinese leading utility company which develops a wide range of power systems.



Dr. Jin Ying is an industrial veteran working in renewable energy and storage device development. He is now the managing director with [FW Battery] a company focused on the Li-battery system development for light electrical vehicles and energy storage. Jin Ying received his PhD degree from Physics Department of Peking University in 1992, and has worked in City University of Hong Kong as Research Fellow.

Dr. Dawei Liu received the Ph.D. from Tsinghua University, China, in 2011. He is a engineer in PV/TE group, Huaneng clean energy research institute. He is a project engineer who develops thermoelectric systems and modules fabrication process.

Dr. Qiming Li received his bachelor degree (2007) and doctor degree (2011) in power engineering from Tsinghua University. At present he is an engineer in Huaneng Clean Energy Research Institute. His current research and work interests include solar thermal generation, thermoelectric power, clean energy system design & optimization, heat and mass transfer

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