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RECENT ACTIVITY ON THERMOELECTRIC POWER GENERATION TECHNOLOGY IN JAPAN

Thermoelectric power generation(TEPG) technology in Japan has been noticed as one of the innovative energy technologies in order to contribute to the establishment of comfortable society and individual life in the real world in the near future due to push-forward by globally environmental issues and serious energy problems (3E + S). Several R&D projects on TEPG technology in Japan have been actively ongoing such as 1) Thermal Management, Materials and Technology Research to utilize unused heat in the social environment, 2) Development of TEPG Application to a Gas Carburizing Furnace, 3) Development of Thermoelectric Generation Using Waste Heat in Steel Works, 4) Development of Tubular Thermoelectric Generator (TTEG), 5) Development of Solar Powered Desalination Using Thermoelectric Power Generation, 6) Practical Development of Rare-Metal-Free Thermoelectric Generator for Automotive Waste Heat Recovery, 7) Practical-use of Multilayer type Thermoelectric Generator for Self-powered Wireless Sensor Network Node supported by government and /or private enterprise funds. As the future prospects several aspects, such as advanced nano-structured TE materials, organic/hybrid TE materials, durability science, safety engineering including hazard analysis have been discussed aiming the smooth promotion of TEPG applications to the real world.

Key words: thermoelectric power generation, nano-structured TE, thermoelectric generation.

Introduction

Reflecting the Paris agreement for United Nations climate change framework convention No.21 (COP21) and Japan's No.5 Science & Technology basic plan (2016 – 2020), Japan has to be challenge to conquer the serious energy problems on so-called ($3E + S$) which stands for Energy security, Environmental preservation, Economic activation and Safety because of poor fossil energy resources, small country and keeping enormously gross domestic product and enhancement of safety consciousness to health and hazards [1]. Overall energy efficiency for total energy system in Japan has been around only 34 %. It means 66 % of supplied energy is rejected into the environment as low graded thermal energy. Therefore, it is strongly recognized to be more important that advanced thermal technologies on the basis of 3 R (Reduce, Reuse and Recycle) should be urgently established. In these circumstances TEPG technology has been noticed as one of the innovative energy technologies in order to contribute to the establishment of comfortable society and individual life in the world in the near future. Therefore, the government organizations such as Ministry of Economy, Trade and Industry (METI), Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Ministry of the Environment (MOE), and various industrial fields such as steel, chemical plant, information, energy etc. are going to pay attention to R&D on various kinds of TEPG applications. Many R&D projects on TEPG technology in Japan have been ongoing, such as:

1. Thermal Management, Materials and Technology Research to utilize unused heat in the social environment;
2. Development of TEPG Application to a Gas Carburizing Furnace;
3. Development of Thermoelectric Generation Using Waste Heat in SteelWorks;
4. Development of Tubular Thermoelectric Generator (TTEG);
5. Development of Solar Powered Desalination Using Thermoelectric Power Generation;
6. Practical Development of Rare-Metal-Free Thermoelectric Generator for Automotive Waste Heat Recovery;
7. Practical-use of Multilayer type Thermoelectric Generator for Self-powered Wireless Sensor Network Node, etc.

In this paper, the recent activity on thermoelectric technology in Japan is overviewed and the future prospects to commercialization of TEPG applications are also discussed.

Several current topics on R&D activity in JAPAN.

Thermal Management, Materials and Technology Research (TherMAT)

This is a 10-year fully government-supported R&D project aiming to provide new, highly efficient systems that can achieve significant reductions in energy consumption and finally promoting to realize the energy conservation in many aspects of the social systems [2]. TherMAT has been carried out under the leadership by H. Obara, National Institute of Advanced Industrial Science & Technology (AIST) since FY2013, which has 8 Major Development Field-Divisions such as:

1. Heat Storage Technology;
2. Heat Shielding Technology;
3. Heat Insulation Technology;
4. Thermoelectric Conversion Technology;
5. Waste Heat Recovery Technology;
6. Heat Pump Technology;
7. Heat Management Technology;
8. Basic Energy Technology.

The R&D budget in FY2015 was about 15.4 M $ in all including around 1.7 ~ 2.0 M $ for thermoelectric conversion technology division.

The goal of the thermoelectric conversion technology division is as follows: The final goal in 2023 is:

1. The establishment of TEPG module technology of $ZT = 4$ using inorganic material systems;
2. The establishment of TEPG module technology of $ZT = 2$ for organic materials systems including hybrid ones.

In order to achieve the final goal the intermediate goal is to achieve the advanced TEPG materials systems based on the inorganic materials of $ZT = 2$, and the organic materials of $ZT = 1$ by 2018.

Six domestic private companies, AIST and several universities have joined in TEPG group. The following 8 R&D sub-items on the TEPG project such as:

1. High Efficient thermoelectric materials and devices on the basis of nano- and/or layered-structured technology by AIST;
2. Thermoelectric device and materials based on conducting high polymer by AIST and Osaka Univ;
3. Thermoelectric device using carbon system such as CNT, graphite etc. by AIST, as shown by a sample of carbon nanotube based flexible thermoelectric devices fabricated by printing process in Fig. 1;

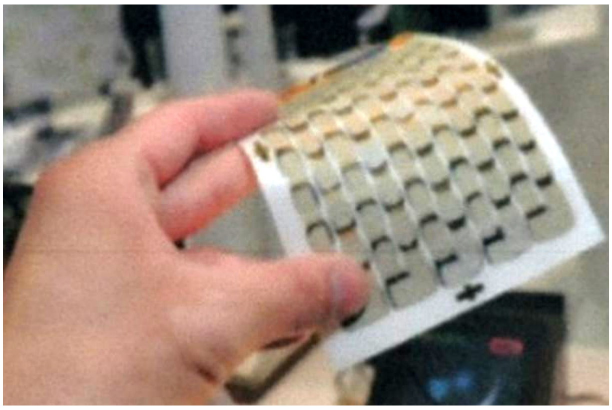

Fig. 1. Carbon nanotube based flexible thermoelectric device.

4. Thermoelectric device based on durable skutterudite materials establishing $ZT > 1.1$, i.e. 8 % in conversion efficiency by FURUKAWA, as shown by the experimental results on the durability of the skutterudite thermoelectric modules in Fig. 2;

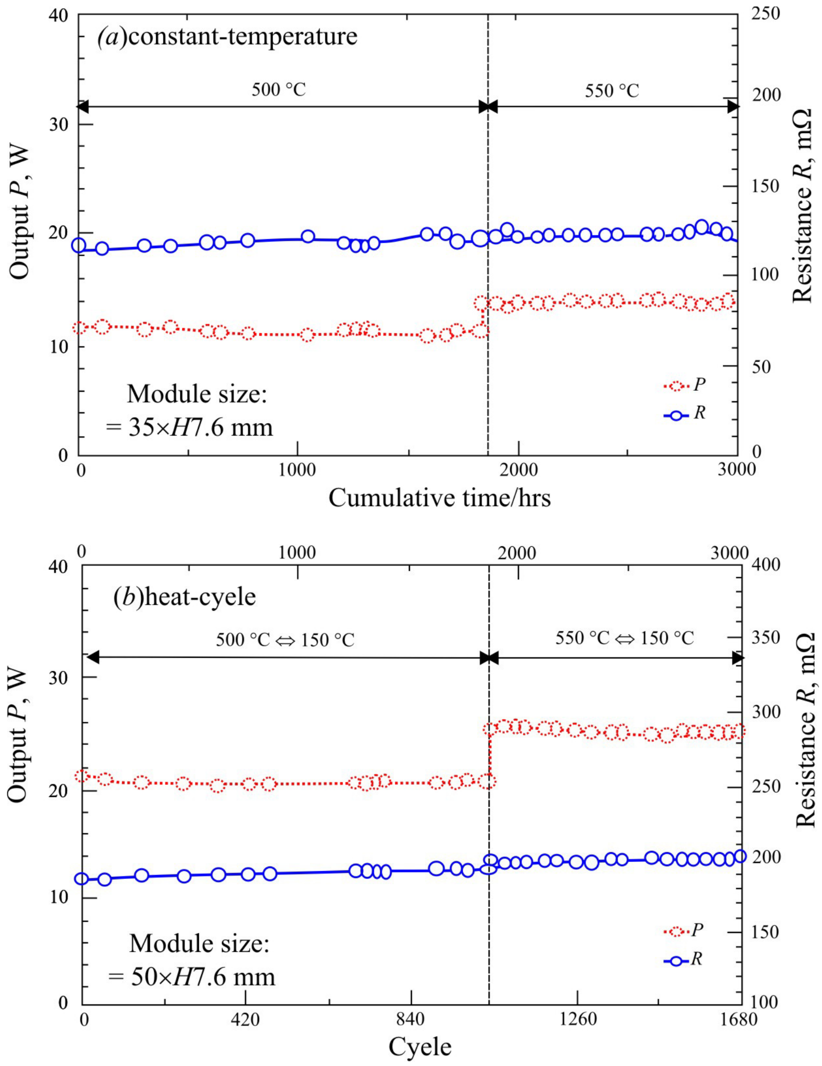

Fig. 2. Durability test result for skutterudite thermoelectric modules for (a) Constant temperature mode and (b) Heat cycle mode.

5. Waste heat recovery system of 5 – 10 kW class using thermoelectric power generating technology by HITACHI;
6. Flexible organic thermoelectric materials and devices controlling the orientation and distribution of CNT and developing the advanced hybrid of nano-particle technology by FUJIFILM;
7. High efficiency sintered Clathrate device in connection to electrode bonding technology for practical use by FURUKAWA DENKO;
8. Silicide thermoelectric materials, devices and optimal systems for automobile application by Yamaguchi University and Nippon Thermostat Inc.

Development of thermoelectric power generation (TEPG) system using waste heat recovery from Steelmaking system

The steel industry in Japan has achieved the significant reduction of energy consumption to produce high-quality steel and has been pursuing to establish a further more efficient process. It has been recognized that the waste heat recovery technologies in each section for steelworks is very important. Thermoelectric power generation system has been favorably paid attention from the viewpoints of reliability, compactness and environmental friendly way.

The demonstration experiment for 10 kW class TEPG system installed in the JFE's continuous casting line has been carried out aiming the commercialization of large-scale 100 kW class TEPG application base on the established Bismuth-Telluride TEPG module by KELK, as shown in Fig. 3.

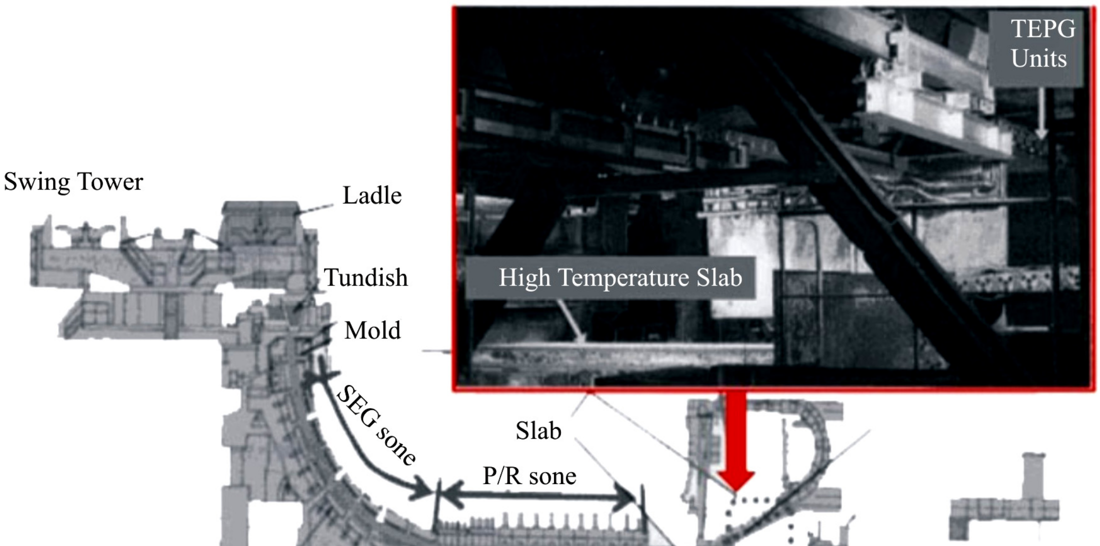

Fig. 3. JFE's continuous casting line installed with TEPG units.

This project has been achieved by the team of JFE, KELK and Hokkaido University partially supported by NEDO, and individual fund after finishing NEDO project [3]. The high temperature heat source is radiation heat from the slab flow, of which temperature is around 1073 K ~ 1273 K, while the low temperature is factory water of around room temperature. The overall TEPG system is 2 m wide and 4 m long in size consisting of 56 TEPG units, as shown in Fig. 4 in order to generate about 10 kW in D.C. electricity, and also has installed an emergency countermeasure apparatus.

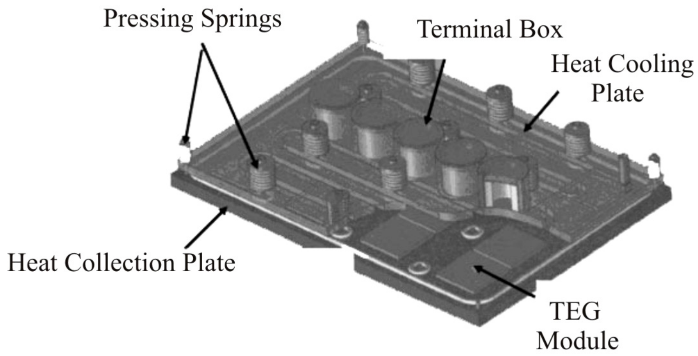

Fig. 4. Components of TEG unit (Size:400 mm × 280 mm) constituted of 16 commercial high-efficiency TEG modules of 50 mm × 50 mm × 4.2 mm by KELK.

The output power from this thermoelectric power generation system is about 9 kW (i.e., 1.7 kW/m^2 for module-base) at 1188 K in slab temperature for 1.7 m in slab width. The experimental results have been satisfactorily consistent with the estimated values from the system simulation analysis as shown in Fig. 5.

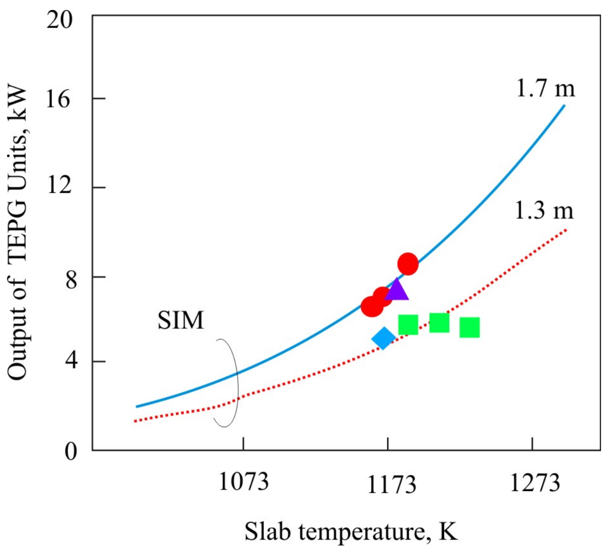

Fig. 5. Experimental results of power output versus slab temperature for JFE's TEPG system in comparison with their simulations:
1. ● – slab width = 1.7 m, Experiment; 2. ▲ – slab width = 1.6 m, Experiment;
3. ◆ – slab width = 1.4 m, Experiment; 4. ■ – slab width = 1.3 m, Experiment;
5. ▬▬ – slab width = 1.7 m, Simulation; 6. ■ ■ ■ ■ ■ – slab width = 1.3 m, Simulation.

The power output will surely obtain greater values than the present ones in the future by development of the durable TEPG modules against temperature higher than the upper temperature limit for the *Bi – Te* modules. Because at the present stage the surface temperature for *Bi – Te* based TEPG modules is constrained to be lowered to avoid thermal degradation.

R&D of solar powered desalination system using thermoelectric power generation

The shortage of the supply of fresh water is one of the biggest social issues all over the world in the near future. It is urgently established the economical desalination system technology combined with renewable energy sources such as solar power without large amount of consumption of fossil fuel resources.

From the viewpoints of easy and continuous operation, maintenance-free, high quality of fresh water, the concept of a solar powered Multi-Effect Desalination and Reverse Osmosis (MED-RO) hybrid desalination system using thermoelectric power generation system has been proposed by TDS-conference constituted of several private companies and universities under the leadership of Prof. Y.Horita, Tokyo Institute of Technology (TITech) with international cooperation since 2010 [4]. The proposed system is composed of a concentrated solar thermal power plant with high temperature (around 850 K) thermal energy storage, novel TESG (Thermoelectric and Steam Generator), and two kinds of desalination systems (MED (Multi-Effect Desalination and RO (Reverse Osmosis)) as main sub-systems, as shown in Fig. 6. For the TESG the hot side of TEPG devices is heated by the high temperature molten salt from the thermal storage unit powered by a concentrating solar power unit and the cold side of TEPG devices is cooled by the large latent heat of continuously supplied water to produce low temperature steam which is used by the first stage of MED unit. All of the discharged thermal energy used to cool TEPG devices in the TESG system is effectively and steadily utilized in the system, while for TEPG systems as usual the water that cooled the cold side of TEPG devices is rejected from the system to the environment. It is clarified with the feasibility study for cost evaluation that this proposed desalination system has the good potentiality to be the most cost-competitive solution at least in the Middle and Near East area.

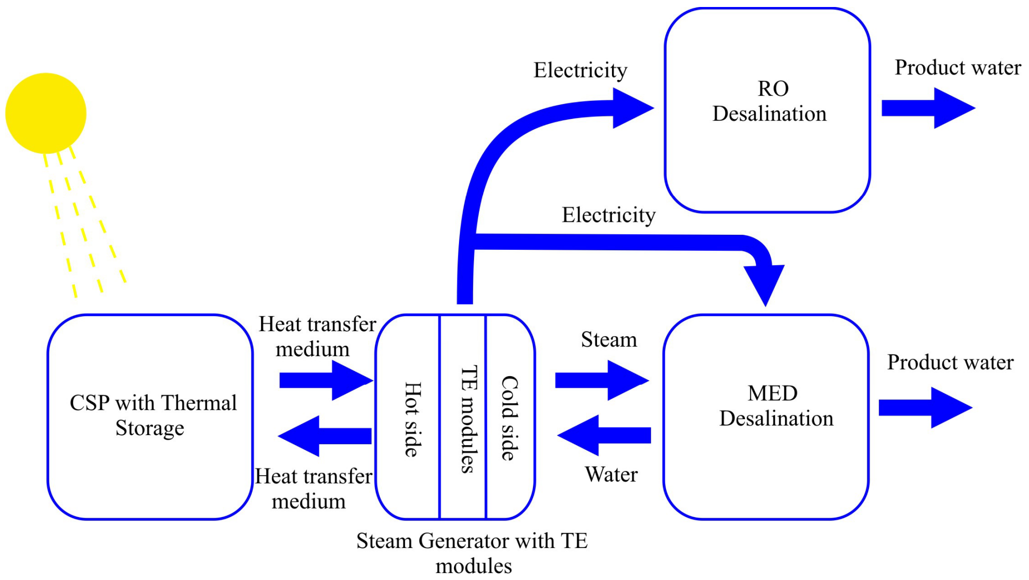

Fig. 6. Concept of the solar powered desalination system using thermoelectric power generation.

Fig. 7. Proof-of-concept experimental facility.

A small scale proof-of-concept experiment for TESG system as the most important key component has been carried out in order to confirm the system characteristics, such as static heat balance, dynamic mass balance response, which are needed for accurate design of the proto-type solar desalination system combined with TEPG system. The experimental facility is shown in Fig. 7.

Practical-use of Multilayer type Thermoelectric Generator for Self-powered Wireless Sensor Network Node

Murata Manufacturing Co., Ltd has developed TEPG device aiming to establish energy harvesting TEPG device for self-powered wireless sensor network node for practical use by its own fund applying the existing MLCC (Multi-layered Ceramic Capacitor) facilities to the TEPG device production [5]. Thermoelectric device consists of composite of $Ni_{0.9}Mo_{0.1}$ and $Ni_{1-x}Mo_x$ for *p*-type, and $(La_ySr_{1-y})TiO_3$ for *n*-type. For a couple of TE device *p*-type and *n*-type are directly bonded to each other without electrode metal. An insulator of the thin layer composed $(Yb, Zr)\,O_2$ is inserted between them. These materials were selected because of having the same performance of thermal expansion coefficient to reduce thermal stress among them. A sample of the TEPG device is shown in Fig. 8. The commercial proto-type TEPG-integrated wireless sensor node device has been installed, as shown in Fig. 9, and was attached at the steel pipe line in the factory as shown in Fig. 10.

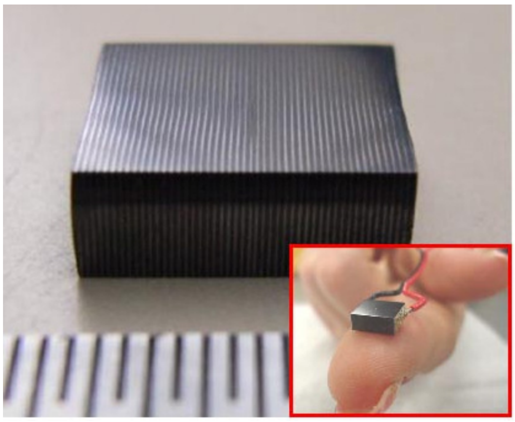

Fig. 8. Sample of multilayered type TEPG module for energy harvesting TEPG device.

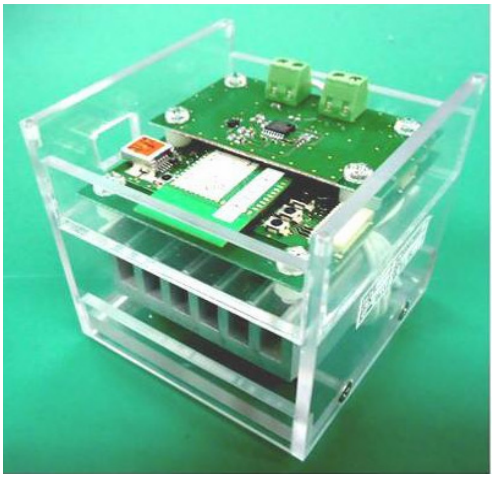

Fig. 9. Commercial proto-type TEPG-integrated wireless sensor node device.

Fig. 10. Installation of TEPG-integrated wireless sensor node device to a pipe.

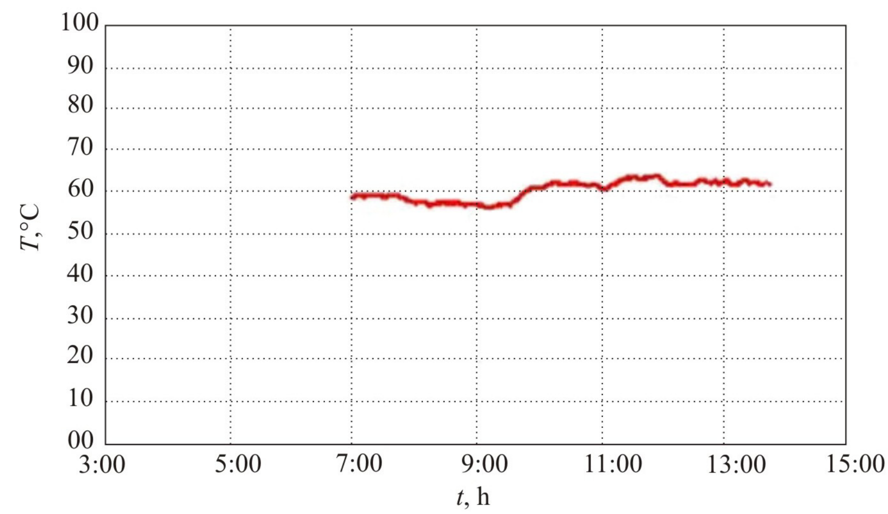

Fig. 11. Demonstration result of the monitor of pipe temperature.

The power characteristics for the thermoelectric device of 50 couples and 6.0 mm × 6.9 mm × 2.7 mm in size are as follows: the open circuit voltage and maximum power output are 52.3 mV and 105 μW at 10 K in temperature difference respectively. The demonstration run has been successfully carried out for over 12 months to monitor the temperature every 20 seconds, as shown in Fig. 11.

Future prospects

We have been proceeding a lot of R&D works to mature TEPG technology for practical use as the following in parallel with the above-mentioned developments for academia and industry sector supported by METI, NEDO, MEXT, JST and/or private enterprise funds:

- Sophisticated nano-structured TE technology for enhancement of high ZT by bottom-up approach ($ZT > 4$);
- Development of advanced Organic/Hybrid TE materials;
- Progress of durability science, and safety engineering in terms of TEPG field;
- Establishment of international standardization for TEPG measurement.

The sophisticated nano-structured TE device approach is based on the fact that nano-structure for the *Mg* – doped *PbTe* could be found not to degrade the electrical properties such as the Seebeck coefficient and electrical conductivity, but to reduce of the lattice thermal conductivity independently by AIST [6]. Therefore, for the optimum nano-structured TE device of *Mg* – doped *PbTe* – 4 % *Na* the maximum value of *ZT* could be enhanced to be 1.8 at 810 K as compared with the maximum value of *ZT* of 1.1 at 710 K for non-doped one, as shown in Fig. 12.

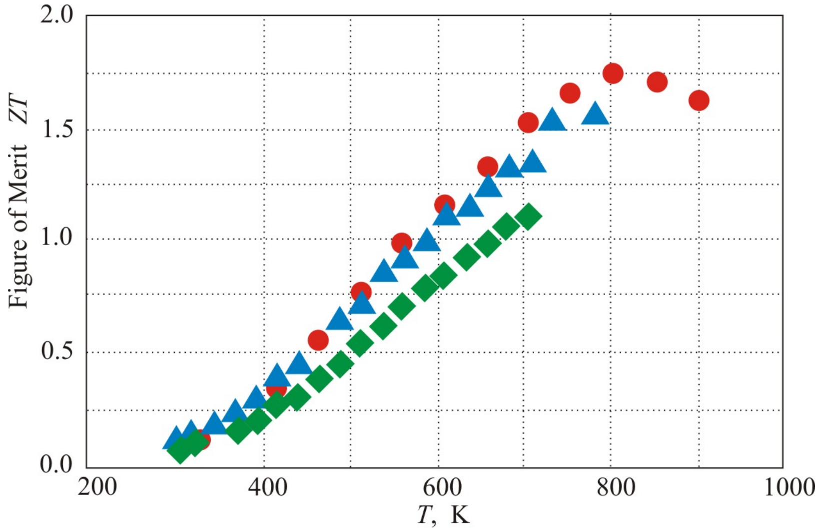

Fig. 12. Effect of the enhancement of ZT due to the nano-structured processfor PbTe – 4 %Na system:
1. ● – Mg – doped PbTe – 4 % Na sintered;
2. ▲ – Mg – doped PbTe – 4 % Na melted;
3. ◆ – PbTe – 4 % Na melted.

A sample of TE module made of eight couples of nano-structured *p*-type *Mg* – doped *PbTe* – 4 % *Na* sintered leg and *n*-type *PbTe* – 0.2 % PbI_2 sintered leg has been successfully fabricated to generate 3.55 W at 570 K in temperature difference (high temperature: 873 K, and low temperature: 303 K at the electrode respectively). It is recognized to be important that controlled nano-structure processing approaches should be established in the shape, size, density, components, and so on for all of thermoelectric material systems.

Polymer thermoelectrics have received a remarkable attention due to several advantages, such as low cost, easiness of assembly, light weight, and feasibility of efficient bottom-up approach to expand the TE application fields recently. Ternary organic-inorganic hybrid systems consisting of a conducting polymer (*Ni* – ethylenetetrathiolate: *Ni* – PETT), PVC (polyvinyl chloride) and CNT (Carbon nano-tube) have been researched to obtain notable experimental results of *ZT*: 0.28 at 340 K in comparison with the performance for PEDOT-PSS (poly 3, 4 – ethylenedioxythiophene-poly styrenesulfonate) film and PEDDOT-TSS/CNT film, as shown in Fig. 13 by Toshima's group [7, 8]. It can be said that recent experimental results and research on various kinds of organic thermoelectric materials including hybrid systems will be promising in the future.

Environmentally friendly thermoelectric materials are considered to be very important for the contribution of thermoelectric applications to the real world. There are many R&D works on *Te* – free TE materials such as Silicide, Oxide, Sulfide systems including Colusites [9], Heusler systems including Half-Heusler, Skutterudite, Clathrate, etc in Japan.

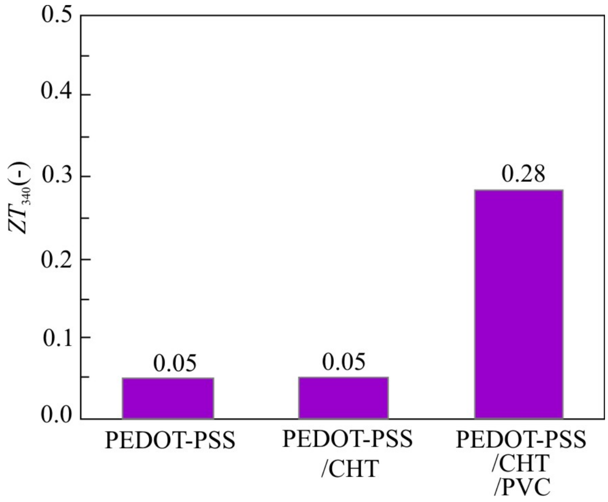

Fig. 13. Effect of the performance enhancement of ZT for a ternary organic-inorganic hybrid system in comparison with PEDOT-PSS and PEDOT-PSS/CNT systems.

In order to penetrate the thermoelectric power generation technology to the real world smoothly, it is inevitable to get the social acceptance in advance. It means that we have to show the evidence of risk management for TEPG systems in parallel with the development of durability science [10] and safety engineering in terms of TEPG field [11]. It is necessary to achieve the hazard analysis and include the countermeasure design in TEPG system even at the demonstration phase. For the hazard analysis the three kinds of hazard are classified due to functional stress for sub-systems and components, time dependence in operation and interface among components for three major sub-systems; main power generation system, power transmission-transformation, and heat sources & rejection systems. Practically, a 10 kW class TEPG demonstration plant using waste heat from steel works at JFE and TEPG units set up on each carburizing furnace at Awazu gear manufacturing plant, Komatsu Ltd., have been installed some emergency sub-units in order to protect the main system as the first priority and also TEPG systems from the serious troubles in operation. It can be emphasized to be important that market- oriented TEPG systems should be raised to the social life step by step.

Finally, it can be said that the human resource is the most important power for the establishment of a new technology such as thermoelectrics into the real world. The number of members of the Thermoelectrics Society of Japan (TSJ) is increasing year and year to be more than 500 in 2015. The activity of thermoelectric R&D in Japan has been kept to be high. For example, the number of the attendee was about 150 at International Conference on Organic and Hybrid Thermoelectrics (ICOT2016) held in Kyoto on January 2016.

Concluding Remarks

On the one hand, several R&D efforts of the enhancement of TE performance for various TE material systems have been steadily progressed on and on. The distinguished experimental results for several TE materials such as sulfide, self-assembled and forced nano-structured TE materials, and hybrid organic TE materials have been presented year and year.

On the other hand, the demonstration run of the TEPG systems using $Bi-Te$ based modules has been connected to the power grid to prove its reliability for 500 W class and 10 kW class systems. They have been able to give us the prospect the realization of the practical-use for TEPG system over more than 100 kW class system. The TEPG-Integrated Wireless Sensor Node has been established for practical-use stage as the TEPG application to energy harvesting field.

TEPG systems have been approached to the advanced stage for practical TEPG system. For this stage the durability science, the safety engineering and various assessments will be highly required. It can be believed that a TEPG technology should be able to become the indispensable core technology in the near future to build the high-efficiency energy system in the world.

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