Introduction of Products

Thermoelectric Generation Technology and the Applied Products

Hirokuni Hachiuma

Takahiro Murase

Daisuke Goto

Shinichi Fujimoto

Kazuya Makino

At COP 24 held in Poland in December 2018, the operation guidelines for the "The Paris Agreement" that defines the international framework for global warming countermeasures were adopted. Japanese government announced the goal of reducing greenhouse gas emissions, which are the cause of global warming, by 26% in FY 2030 compared to the FY 2013 level. In Japan, about 60% of primary energy is emitted as unused heat without being effectively utilized, and utilization of unutilized fever has become increasingly important. Thermoelectric generation has received attention in recent years as the next generation energy utilizing unused heat. Thermoelectric generation can recover electrical energy from a part of a large amount of waste heat emitted from plants, power plants, incinerators, etc. It is expected to be effective in reducing greenhouse gases.

Key Words: *Thermoelectric generation, Waste heat recovery, Thermoelectric generation module, Woody biomass stove, Energy Harvesting (EH), Time Based Maintenance (TBM), Condition Based Maintenance (CBM)*

1. Introduction

KELK Ltd. was established in 1966 as a manufacturer of applied products of thermoelectric elements, evolved from the research and development of thermoelectric semiconductors which Komatsu started in 1957. The company deals in thermo-modules (Peltier modules) using thermoelectric semiconductors for temperature control, conducting development, manufacturing, and sales of the materials, the modules, heat exchangers and the applied products, and is leading the market as the world's top manufacturer in the business of temperature controlling equipment for semiconductor manufacturing machines. It is also a leading company in thermoelectric generation which converts heat into electricity by using thermoelectric semiconductors, developing the element technologies to the applied products. It provides thermoelectric generation products with outputs ranging from button-battery-level mW to industry-level kW.

In this report, we explain thermoelectric generation technology and its applied products: "waste heat recovering unit", "thermoelectric generation stand-alone power unit", and "thermoelectric EH wireless device".

2. Principle of Thermoelectric Module

Thermoelectric conversion is the technology which directly converts heat into electricity and electricity into heat through the material called thermoelectric semiconductors. These two conversion ways are the applied technologies of the phenomena that are well-known as the Seebeck effect (Refer to **Fig. 1**) and its reverse phenomenon, the Peltier effect found in the first half of the 19th century.

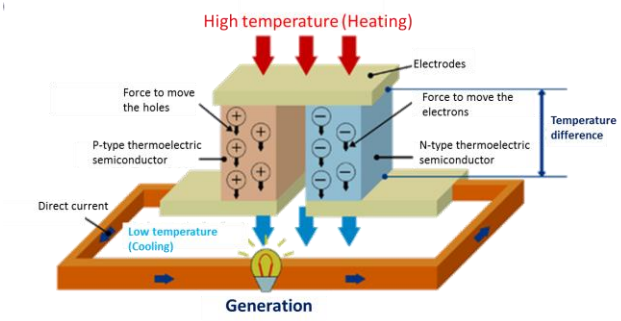


Fig. 1 Principle of the Seebeck effect

The Seebeck effect is the phenomenon that when a temperature difference occurs between the ends of a metal or a semiconductor, a difference in the concentration distribution of electrons or holes is caused to generate electromotive force (thermal electromotive force). Semiconductors in particular have an exponential increase of electrons or holes generated in proportion to the temperature in the extrinsic region, so they generate larger thermal electromotive force than metals. The thermoelectric generation module is a module in which a number of P-type and N-type thermoelectric semiconductor elements are alternatively series-connected with metal electrodes as shown in **Fig. 2**. By this structure, the thermal electromotive force of each thermoelectric semiconductor element is accumulated in the same heat flow direction, which generates larger voltage.

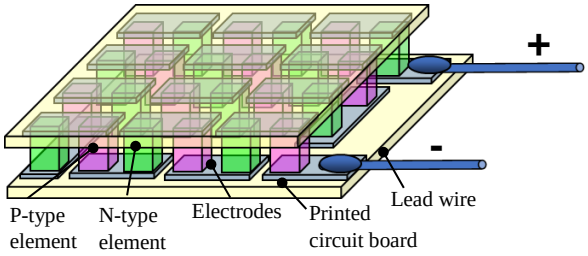


Fig. 2 Basic structure of thermoelectric module

As the thermoelectric generation module uses high temperatures, thermoelectric semiconductors for the characteristics at high temperatures have been developed. When a thermoelectric semiconductor enters from the extrinsic region where either of electrons or holes are dominant to the intrinsic region having ambipolar conduction as the temperature rises, the thermal conductivity increases (the state that a temperature difference does not occur easily) and the Seebeck coefficient decreases (the thermal electromotive force decreases), decreasing the performance of the thermoelectric semiconductor (performance index). The material for thermoelectric semiconductors which does not get ambipolar conduction easily and keeps high performance index in the region of the operating temperature has been developed.

Currently, the thermoelectric semiconductors called Bi-Te system are used for most of thermoelectric generation modules and Peltier modules. In thermoelectric generation modules, a larger temperature difference by using high-temperature thermal source is efficient in terms of the Carnot efficiency. Researches and developments have been made for a long time for many thermoelectric materials with better characteristics in the high-temperature region than those of Bi-Te system thermoelectric semiconductors, such as Silicide system, Pb-Te system, Skutterudite system, and Si-Ge (Refer to **Fig. 3-1**, **3-2**). However, in efficient thermal designs for increased power generation in actual thermoelectric generation systems, it is important to penetrate the thermoelectric generation module with a larger quantity of heat, so that the low temperature side has water cooling in most cases. In such a condition, the temperature of the high temperature side of the thermoelectric generation module inevitably decreases largely from that of the thermal source and has only a limited chance to be far above 300°C. The Bi-Te system thermoelectric semiconductors, when their compositions are optimized, show high performance indexes compared to other thermoelectric semiconductors not only in the room temperature region but also in the comparatively high temperature region around 300°C. Therefore, Bi-Te system thermoelectric semiconductors are mainly used in thermoelectric generation as well as in Peltier cooling.

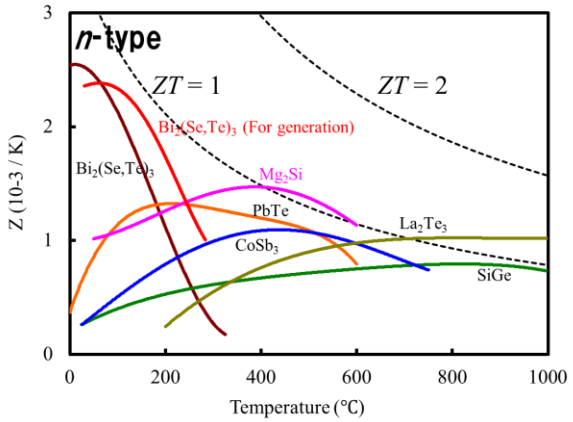


Fig. 3-1 Performance indexes of N-type thermoelectric materials

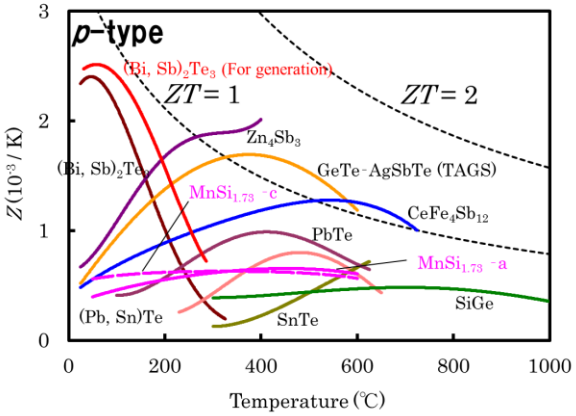


Fig. 3-2 Performance indexes of P-type thermoelectric materials

With this perspective, KELK developed "High-output thermoelectric generation module" using the Bi-Te system thermoelectric semiconductors whose high temperature side can withstand at 280°C and started its sales in 2009 (Refer to **Fig. 4**). This module shows the maximum output of 24 W and the thermoelectric conversion efficiency of 7.2% with the high temperature side at 280°C and the low temperature side at 30°C (The thermoelectric conversion efficiency of 7.2% is the world's highest in this temperature region). The module used in "Waste heat recovering unit" that is explained in the next chapter utilizes the technology of this module.

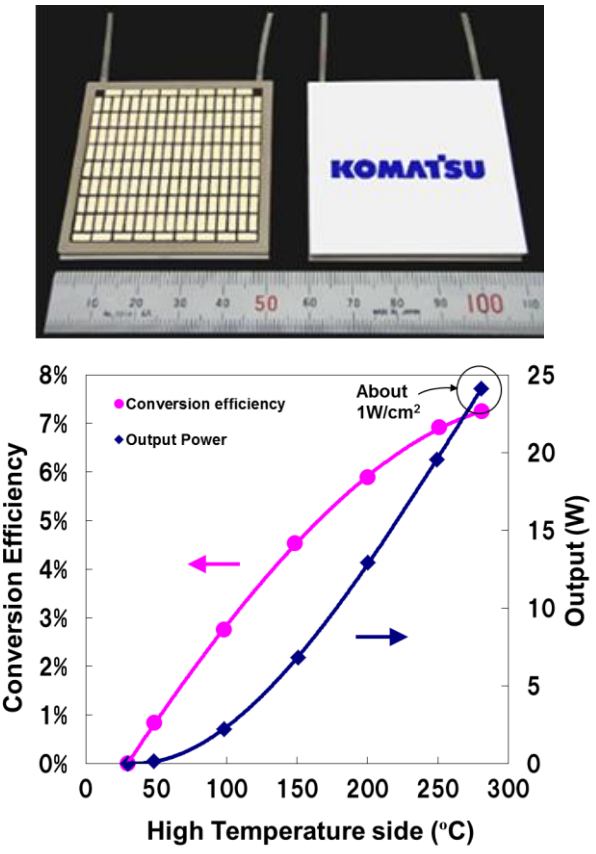


Fig. 4 Appearance and electrical characteristics of "High-output thermoelectric generation module"

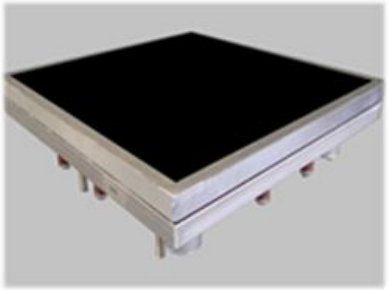
In 2018, KELK developed the Pb-free solder product to be used in the temperature region up to 250°C which causes less environmental impact, with consideration for environment. Conventionally, most of solders used in this temperature region are cheap Pb-rich solder or expensive AuSn solder. KELK newly developed the thermoelectric generation module with high durability for high temperature using comparatively cheap Pb-free solder.

3. Introduction of the Applied Products

3.1 Waste Heat Recovering Unit

For utilization of unused heat, energy recovery by the Rankine cycle, the Stirling engine, thermoelectric generation, etc. has been considered. Thermoelectric generation has the following advantages: no driving parts is necessary as the thermoelectric elements directly convert heat into electricity, the system is comparatively compact, light-weight, and resistant to the fluctuation of waste heat. Thus, it has a competitive advantage especially in power generation utilizing dispersed waste heat.

KELK developed the thermoelectric generation unit with the maximum output of 350 W, 46% up compared to our conventional product, by increasing the output density in 2018 (Refer to **Fig. 5**, the equivalent 240 W model).



Model version code	KSGU240
Size (mm)	W290 x D290 x H85
Weight	Approx. 12 kg
Rated power generation	240 W
Possible operation temperature	250°C or below by the heat receiving plate sensor
Others	Cooling water is required. The shape of the heat receiving plate varies depending on the thermal source.

Fig. 5 Appearance and specification of "Waste heat recovering unit"

KELK is conducting the verification test of "Waste heat recovering unit" utilizing waste heat from the after burner of the carburizing furnace in Awazu Plant (Refer to **Fig. 6**). Carburizing furnaces need detoxification of used flammable gas after heat treatment by combustion. They also need to keep their furnace temperature in terms of economy and stability of manufacturing conditions, making operating ratios high. KELK constructed the system that recovers combustion heat of flammable gas of a carburizing furnace which had not been utilized into electric energy by using "Waste heat recovering unit" and interconnects to electric power suppliers' distribution systems. It is the nation's first thermoelectric generation system approved by the Electric Power Safety Division of Ministry of Economy, Trade and Industry.

Fig. 6 Verification test of thermoelectric generation utilizing waste heat from the after burner of an industrial furnace

KELK is engaged on NEDO's "Strategic Innovation Program for Energy Conservation Technologies" and conducting the verification test of thermoelectric generation utilizing waste radiation heat from continuous casting facilities in a steel mill. The iron and steel industry is an energy-consuming industry having approx. 10% of the entire energy consumption of Japan and one-third of that energy is unused and disposed. With continuous casting facilities, radiation heat is emitted from high-temperature slab surfaces and disperses into the surroundings from large areas. Due to the structure of the facilities, the waste heat cannot be recovered by the Rankine cycle or the Stirling engine efficiently. On the other hand, "Waste heat recovering unit" can receive the waste radiation heat on its heat receiving surface and directly generate electricity, which is an advantage in layout. In the verification test, 56 "Waste heat recovering units" were laid out in the area of 2 m by 4 m and realized the generation of 10 kW-class electricity which is the nation's largest scale (Refer to **Fig. 7**).

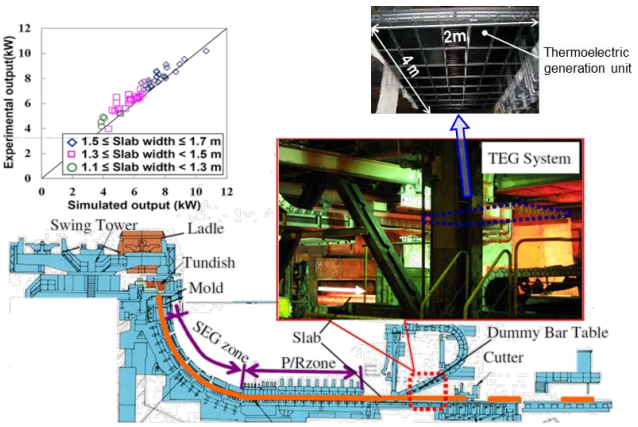
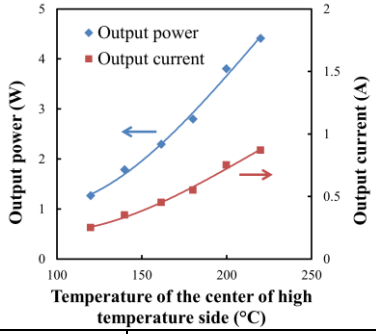


Fig. 7 Verification test of thermoelectric generation utilizing waste radiation heat from the continuous casting facility in the steel mill (Implemented with NEDO's aid)

3.2 Thermoelectric Generation Stand-Alone Power Unit

As the thermoelectric generation module functions almost permanently as a stand-alone power source without any wiring only if heat source is available, it can be applied into an alternative for batteries with output of less than 20 W. What is more, as it needs no wiring or battery, it provides more value than the unit power price of primary batteries and secondary batteries. The thermoelectric generation module has already been applied to cassette gas fan heaters and equipment for outdoor and disaster measures.

KELK developed "Thermoelectric generation stand-alone power unit" with which even people who are not familiar with the thermoelectric generation module can easily obtain some watts of electricity. "Thermoelectric generation stand-alone power unit" is the product that combines the thermoelectric generation module, the heat receiving plate, the DC-DC converter, and a fan to integrate. The thermoelectric generation stand-alone power unit "KSGU004" outputs the maximum output of 4 W with its heat receiving surface at the maximum operating temperature of 220°C (Refer to **Fig. 8**).



Model version code	KSGU004
Size (mm)	W140 x D142 x H76
Weight	Approx. 3 kg
Rated power generation	4.0 W
Possible operation temperature	120 to 220°C
Others	Output port: USB

Fig. 8 Appearance and specification of "Thermoelectric generation stand-alone power unit"

KELK developed the thermoelectric generation module with the maximum operating temperature of 200°C as thermoelectric generation stand-alone power source (Refer to **Fig. 9**) in 2015 and the module is mounted on the "Thermoelectric generation stand-alone power unit". In the comparison with high-output thermoelectric generation modules as shown in **Fig. 4**, the module is well-balanced with output and durability for high temperature and is cost effective, while being slightly inferior in performance.

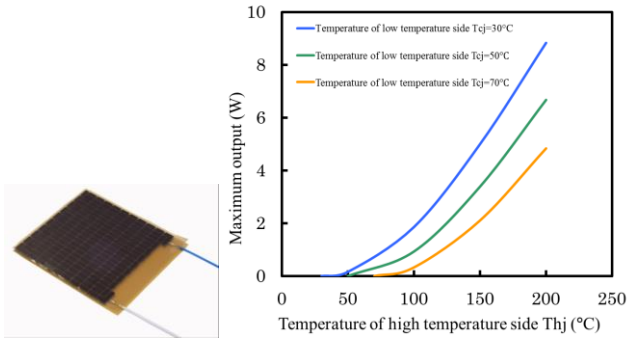


Fig. 9 Appearance and output characteristics of the 200°C thermoelectric generation module

One example of the application of "Thermoelectric generation stand-alone power unit" is power for the motors for automatic fuel supply of pellet stoves (Refer to **Fig. 10**). This system enables pellet stoves to automatically keep their heat until the fuel is run out.

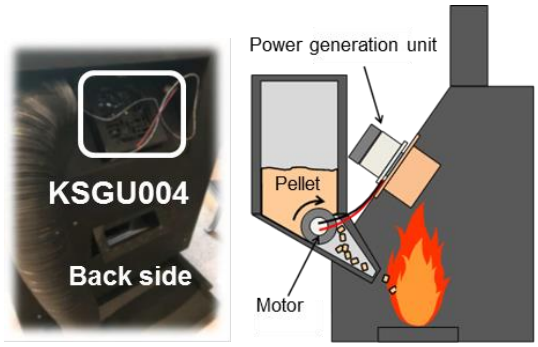


Fig. 10 Automatic fuel supply system of pellet stoves

In Europe, the number of installation of wood stoves and pellet stoves whose fuel is woody biomass has been increasing and is expected to be more than two million in 2020. On the other hand, as woody biomass stoves emit microscopic particle matter (PM) due to combustion to pollute the atmosphere, the regulatory value for PM is getting stricter year by year. The stove manufacturers promote the development of the technology to automatically control the temperature in the combustion chamber, the mixture with atmosphere, the draft of the chimney, etc. for reducing PM. In cooperation with these stove manufacturers, KELK is working on the development of the power supply by thermoelectric generation using the combustion heat for driving the automatic control system.

3.3 Thermoelectric EH Wireless Device

According to a study report on deterioration characteristics of machinery parts by a U.S. airline company, 89% of facilities have random failures of machinery parts after the decline of the initial failure rate. With general Time Based Maintenance (TBM), it is difficult to set an appropriate maintenance cycle and prevent failures that randomly occur with each facility. Therefore, Condition Based Maintenance (CBM) to give maintenance based on measurement data by the facility diagnostic technology is important. However, CBM requires installation of sensors for temperature, pressure, vibration, etc. on the monitoring section for continuous monitoring. It makes high costs for the sensors (the body, installation, and wiring), the system for collection and judgment of data, and maintenance and management, thus the CBM operation is limited to some of steel mills and plants.

KELK's "Thermoelectric EH wireless device" is expected as a device that solves this problem.

"Thermoelectric EH wireless device" is the device with wireless communication function using power by Energy Harvesting (EH) that utilizes waste heat from motors and pipes by using thermoelectric elements. "Thermoelectric EH wireless device" doesn't require wiring for power and communication or battery replacement, reducing costs for sensor installation and maintenance and management.

The interval of data transmission of "Thermoelectric EH wireless device" depends on the power generation by the mounted extremely small "Thermoelectric generation module", with the minimum of three seconds (Refer to **Fig. 11**).

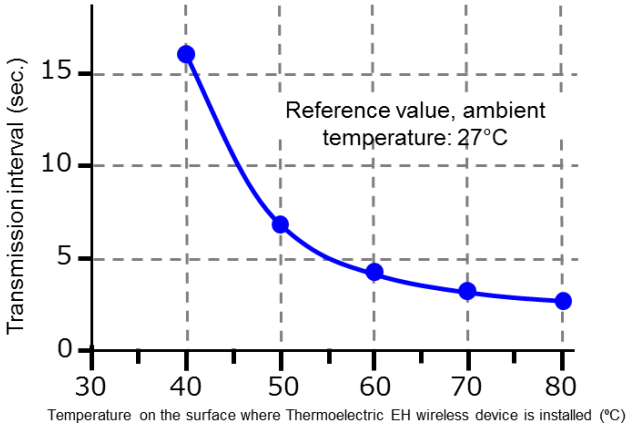


Fig. 11 Temperature of installation surface and data transmission interval

The thermoelectric generation by "Thermoelectric EH wireless device" has high robust performance with environment change, which can keep the temperature difference between the face and the back of the device to be constant even with atmosphere changing by 10°C between day and night and sudden temperature change due to rain, enabling constant power generation and transmission of the sensing data (Refer to **Fig. 12**). Moreover, the housing of the devise is designed with the consideration for outdoors use.

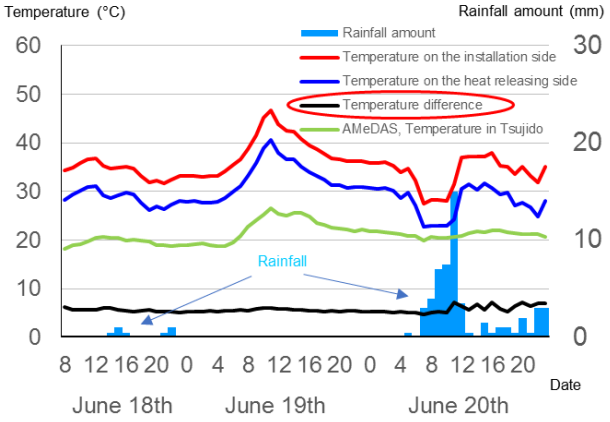


Fig. 12 Robustness to the change of ambient temperature of "Thermoelectric EH wireless device" installed outside

In 2018, KELK developed "Thermoelectric EH wireless thermocouple device" to measure temperature and "Thermoelectric EH wireless analog input device" to transmit analog output of measuring equipment. "Thermoelectric EH wireless thermocouple device" measures temperature with the thermocouple with the range between -200°C to 1500°C and wirelessly transmits the data. Analog output of 4 to 20 mA or 0 to 5 V from measuring equipment for current, flow rate, pressure, moisture, etc. installed on the facility can be input into "Thermoelectric EH wireless analog input device" and the device wirelessly transmits the data.

Table 1 Specification of "Thermoelectric EH wireless device"

Model version code	KSGD-SNA	KSGD-SNT
Type	Analog input	Thermocouple
External input	4 to 20 mA, 0 to 5 V	K, R, B thermocouple
Size (mm)	W61 x D44 x H20	
Weight	Approx. 0.1 kg	
Power supply	Self-generation with heat source	
Transmission interval	Min. 3 seconds interval (depending on the installed environment)	
Possible operation temperature	85°C or below	

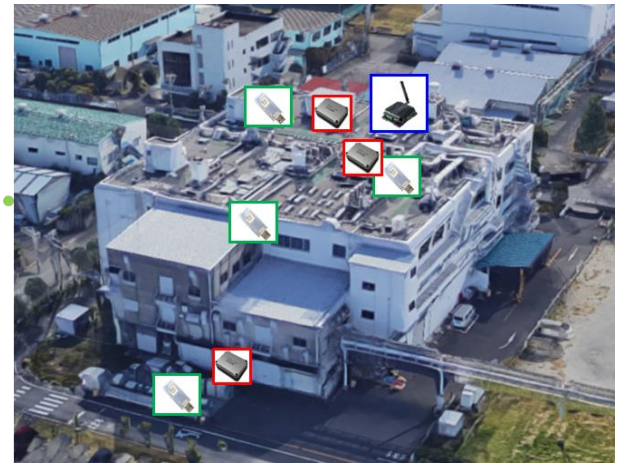
The communication system of "Thermoelectric EH wireless device" is compliant with 2.4 GHz IEEE 802.15.4. Up to a maximum of three relay transmitters can be installed to bypass obstacles for communication or extend the communication distance. The data sensed by the devise is collected and analyzed on-premises (Refer to **Fig. 13**) or on the cloud (Refer to **Fig. 14**) and can be utilized for the system which delivers a mail notification when having data out of the specified value.

Fig. 13 Example of configuration of the on-premise system

Fig. 14 Example of configuration of the cloud system

It is expected that "Thermoelectric EH wireless device" reducing the cost for sensor installation and maintenance and management and the system using rapidly progressing cloud and AI diagnosis promote the transition from TBM to more efficient CBM.

KELK installed these "Thermoelectric EH wireless devices" on the facilities in its factory and started the evaluation of the utilization for the condition monitoring and maintenance by CBM (Refer to **Fig. 15**). It also started the evaluation test for the condition monitoring using this technology with construction machinery.



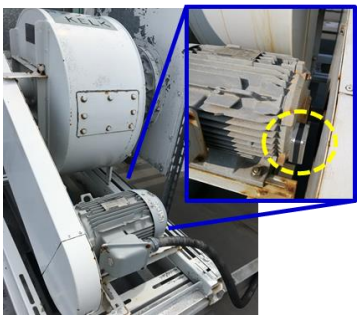


Fig. 15 KELK's factory and Thermoelectric EH wireless device installed on the motor on the rooftop

4. Conclusion

Thermoelectric generation has a competitive advantage especially in power generation utilizing dispersed waste heat. In 2017, KELK started selling of thermoelectric generation applied products in addition to the conventional products of single thermoelectric generation modules. By providing easy-to-use devices and units as the thermoelectric generation applied products, we serve more users' needs for thermoelectric conversion in more diverse scenes and environments to contribute to the construction of the energy-saving, smart society.

Introduction of the authors

Hirokuni Hachiuma
Joined KELK Ltd. in 2001.
Executive Managing Director

Takahiro Murase
Joined KELK Ltd. in 2002.
TEG Business Dept.

Daisuke Goto
Joined KELK Ltd. in 1993.
TEG Business Dept.

Shinichi Fujimoto
Joined KELK Ltd. in 2011.
TEG Business Dept.

Kazuya Makino
Joined KELK Ltd. in 1999.
TEG Business Dept.

[A comment from the authors]

Thermoelectric generation technology has evolved to be utilized as power with wide-ranging outputs from button-battery-level mW to industry-level kW. We continue to progress the product development process of market in, not product out, to proceed with the creation of the thermoelectric generation market.