Introduction of Products

Thermoelectric Generation Unit KSGU400: Generating 10 kW of Power within an Area of 1.5 m × 1.5 m

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At the 2021 Climate Summit, the Japanese government vigorously expressed their goal that they would reduce the total emission of greenhouse effect gas by 46% in FY2030 compared to 2013; to achieve the carbon neutrality in 2050. In February 2023, the Cabinet decided the "The Basic Policy for the Realization of Green Transformation (GX)" which includes the promotion of thorough energy conservation, structural transformation of the manufacturing industry, and making renewable energy the main power source. In Japan, approx. 60% of primary energy is discharged as unused heat without being used effectively. Utilization of unused heat is becoming more important. The method of thermoelectric generation can utilize local-unused heat discharged from iron and steel mills, power plants, incinerators, etc. to regenerate electric energy; and is expected to be effective in reducing greenhouse gas effect.

KELK Ltd. (hereinafter referred to as KELK) is developing applied products of thermoelectric generation, and has developed "KSGU400," a thermoelectric generation unit that generates electricity of 10 kW, in area conversion of 1.5 m × 1.5 m, from the large quantity of waste heat obtained from large-scale facilities like iron and steel mills. They have also developed "KSGD-SV10," a battery-less vibration sensor device that operates from a temperature differential of 3 °C caused by a minute heat source and has a transmission range of 500 m. Their development allows to handle the measurement of sustainable equipment conditions, optimize the equipment maintenance timing, and support preventing sudden failures; thereby improving the productivity of equipment maintenance activities. These applied products of thermoelectric generation contribute to the reduction of greenhouse effect gas through their energy-saving effects. In this paper, these products are introduced.

Key Words: *Carbon neutrality, Energy conservation, Thermoelectric generation, Waste heat recovery, Thermoelectric generation module, Energy harvesting (EH), IoT, Condition based maintenance (CBM)*

1. Introduction

KELK was established in 1966 as a manufacturer of the applied products of thermoelectric elements succeeding to the research and development section which Komatsu launched in 1957 focusing on the thermoelectric conversion elements (thermoelectric elements). The company systematically deals with the development, manufacturing, and selling of Peltier modules, from raw material to applied equipment, that use thermoelectric elements for temperature control. We are a global leading manufacturer of the temperature control equipment used in semi-conductor manufacturing devices. As for thermoelectric generation using the Seebeck effect of thermoelectric elements, we produce thermoelectric generation modules with the world's highest efficiency of 7.2% (temperature differential power generation at the temperature of 280°C on the heat receiving side and 30°C on the heat dissipating side). In this paper, the thermoelectric generation technology and their applied products "thermoelectric generation units" and "thermoelectric energy harvesting (EH) radio devices" are explained.

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 semi-conductors. These two conversion ways are the applied technologies of the phenomena that are well-known as the Seebeck effect (**Fig. 1**) and its reverse phenomenon, the Peltier effect found in the first half of the 19th century.

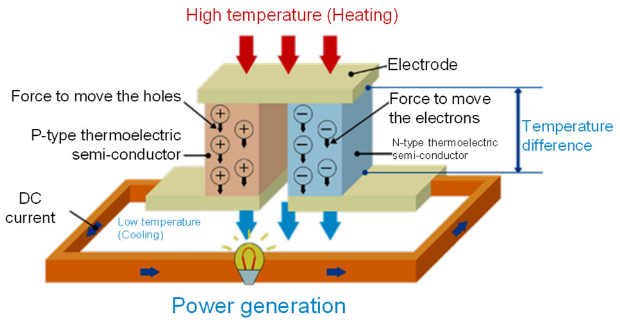


Fig. 1 Principle of the Seebeck effect

The Seebeck effect is a phenomenon that when a temperature difference occurs between the ends of a metal or a semi-conductor, a difference in the concentration distribution of electrons or holes is caused to generate an electromotive force (thermal electromotive force). Semi-conductors in particular have a 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 consists of a number of P- and N-type thermoelectric semi-conductor elements that are alternatively series-connected with metal electrodes as in **Fig. 2**. By this structure, the thermal electromotive force of each thermoelectric semi-conductor element is accumulated in the same heat flow direction, which generates larger voltage.

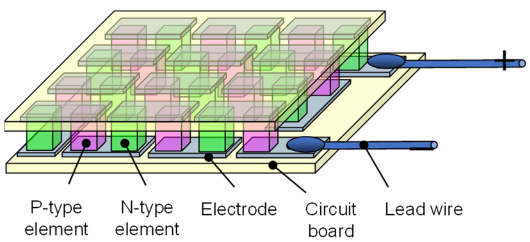
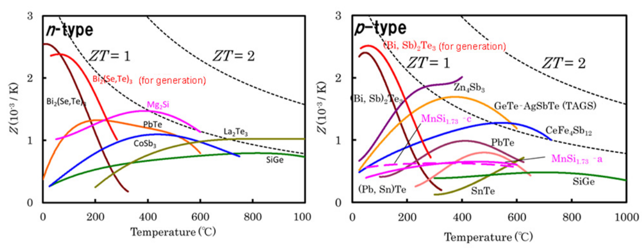


Fig. 2 Basic structure of thermoelectric module

As the thermoelectric generation module uses high temperatures, thermoelectric semi-conductors for the characteristics at high temperatures have been developed. When a thermoelectric semi-conductor 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).

Currently, the thermoelectric semi-conductors called Bi-Te system are used for most of thermoelectric generation modules and Peltier modules.

When designing an efficient thermoelectric generation system that increases electric power generation, a thermal design that allows a larger quantity of heat to penetrate the thermoelectric generation module is effective, and water cooling is often adopted on the cooling side to increase the temperature differential. Because of this, the temperature on the high temperature side of the thermoelectric generation module significantly lowers than the heat source temperature; and the situation where the temperature rises significantly above 300℃ shall be extremely limited. The Bi-Te system thermoelectric semi-conductors show higher performance indexes compared to other thermoelectric semi-conductors not only in the areas with room temperature but also in the areas with comparatively high temperature around 300℃ by optimizing the material composition. Therefore, Bi-Te system thermoelectric semi-conductors are mainly used in thermoelectric generation.



Left: N-type thermoelectric material performance index
Right: P-type thermoelectric material performance index

Fig. 3 Performance indexes of various thermoelectric materials

From the mentioned perspective above, KELK developed, and produces "High-output thermoelectric generation module" (**Fig. 4**) using the Bi-Te system thermoelectric semi-conductors which withstand the temperature of 280 °C at the high temperature side. 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).

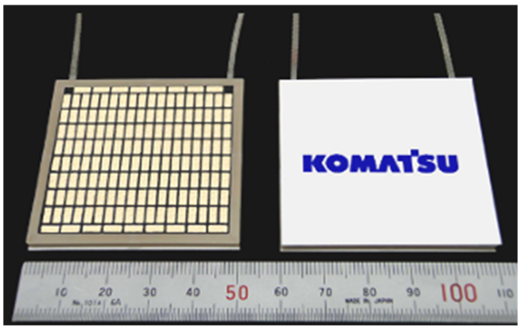


Fig. 4 Appearance of "High-output thermoelectric generation module"

3. Development of thermoelectric generation unit

3.1 Details of development and overview of the products

Since thermoelectric generation has high output density which allows to be small in size, it can be installed near a local heat source where energy recovery was difficult before. KELK has proceeded with the development of thermoelectric generation units to efficiently utilize the waste heat generated abundantly at the continuous casting equipment or casting / casting equipment and heat treatment furnace in iron and steel mills. In 2023, we launched thermoelectric generation units "KELGEN G-Unit KSGU250" rated at 250W. Furthermore, to improve the cost-effectiveness by increasing the power generation output, we developed "KSGU400" in the same size rated at 400 W (see **Fig. 5**).

Item	KSGU250	KSGU400
Normal power generation output (rated)	250 W	400 W
Possible operation temperature	Heat receiving plate temperature: 280°C or below	
External dimensions	291 × 291 × 66 mm	
Weight	Approx. 18 kg	
Coolant temperature	10 to 35°C	
Coolant flow rate	5 to 20 LPM	

Fig. 5 Appearance and main specifications of thermoelectric generation unit "KELGEN G-Unit"

The output density of thermoelectric generation is higher than that of solar power system by 10 times or more, and the capacity factor of the equipment installed with a thermoelectric generation unit is higher by 4 times or more because the temperature of the heat source must be maintained from the viewpoints of the stability in economic efficiency and manufacturing conditions (**Table 1**).

These allow the thermoelectric generation system to generate more electric power in a very compact area compared to the solar power system.

Table 1 Thermoelectric generation unit and solar power generation

	Thermoelectric generation unit		Solar power system (general value)
	KSGU250	KSGU400	
Output density (W/cm²)	0.30	0.47	0.016 to 0.02
Capacity factor	75%		14.5% *1
Required area (m²) for 100,000kWh/Year	5.2	3.2	394 to 492

*1: Ministry of Economy, calculation committee for procurement price, etc. Feb. 2022

In the process of demonstration and development to date, the commercialization of the thermoelectric generation technology has been hindered by the water vapor and dew condensation water generated from the equipment flooding into the thermoelectric generation module causing the deterioration of thermoelectric elements upon migration and earth fault in the thermoelectric generation units. KELK has established a complete waterproof structure that withstands environments with high temperature/humidity by reviewing the structures of thermoelectric modules and thermoelectric generation units from the start. For the thermoelectric generation modules, the stress on the thermoelectric elements was mitigated by optimizing the shape and thickness of the structure and heat exchanger. A structure that can withstand temperature changes of 200°C or more was also realized for a large-area thermoelectric generation module. To evaluate their durability, a temperature cycle test was performed with the temperature alternating between 50°C and 280°C on the high-temperature side of the thermoelectric generation unit in parallel with a 1-hour/day submersion test assuming the verification of the waterproof structure and the deterioration of the thermoelectric elements due to temperature cycles. The target value of the temperature cycle test was set to be 10% or less of the power generation output deterioration assuming the continuous casting equipment at iron and steel mills with the high possibility of applying the thermoelectric generation; the durability evaluation shall be based on the results of 10,000 temperature cycles, which is equivalent to the number of cycles from high temperature to room temperature performed 3 times/day in average for 10 years. As the result of the verification, the goal was achieved because the power generation output deterioration became 1% after 10,000 cycles were completed. Disassembly investigation on the thermoelectric generation unit was performed after testing. According to the result, no marks of flooding inside the thermoelectric module was confirmed; this also verified that the waterproof property has no problem (see **Fig. 6**).

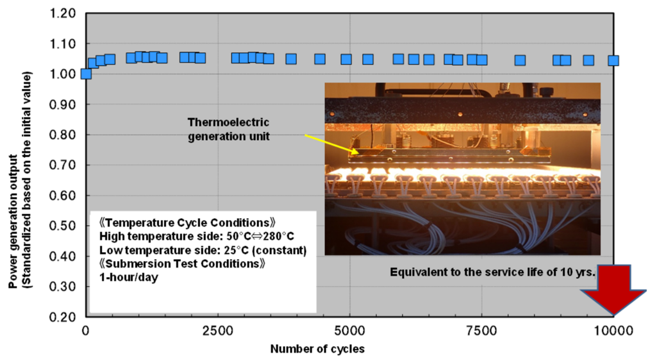


Fig. 6 Verification of durability evaluation

The goal of power generation output was set to be rated at 400 W which is 1.6 times of the one for existing models considering the target investment pay-back years of thermoelectric generation units. To improve the thermoelectric generation output, it is effective to improve the performance of thermoelectric generation materials or expand the temperature differential. The concept of the development of "KSGU400" is to improve the power generation output by increasing the quantity of heat passing the thermoelectric generation module (heat quantity of penetration) to expand the temperature differential. The passage optimization that improves the cooling efficiency of the water-cooling plate and the design of a thermoelectric generation module which achieves the maximum output conforming to the cooling capacity of the water-cooling plate were performed. First, the flow passage shape was reviewed to improve the cooling performance of the water-cooling plate. The shape of the passage was optimized by modifying it to a spiral shape, changing the structure so that the cooling water flows spirally from the center and drains from the periphery side (see **Fig. 7**). These modifications contributed to the improvement of the cooling performance significantly; the thermal resistance dropped by half compared to that of the cooling-water plate for the conventional "KSGU250".

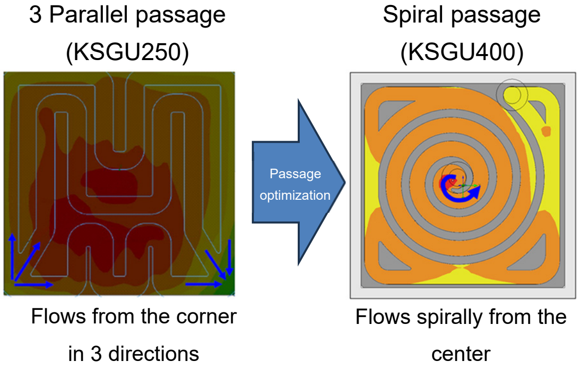


Fig. 7 Comparison of the thermal fluid simulation of a water-cooling plate

Next, the optimum shape of the thermoelectric generation module was examined. Along with the improvement of the cooling performance of the water-cooling plate, more heat quantity of penetration was enabled to flow, and power generation output was improved by reviewing the shape and logarithm of the elements. Under the conditions restricted by the temperature of a heat receiving plate and the heat resistance of the water-cooling plate, the shape and logarithm of the elements were optimized to achieve the maximum power generation output of the thermoelectric generation module (see **Fig. 8**).

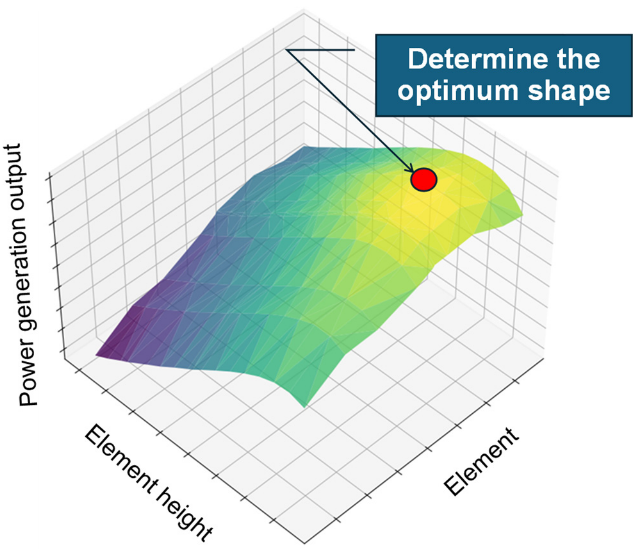


Fig. 8 Optimization calculation for the shape of thermoelectric elements

As a result, "KSGU400" with the power generation output rating of 400 W, which is 1.6 times of that for "KSGU250," was developed (see **Fig. 9**).

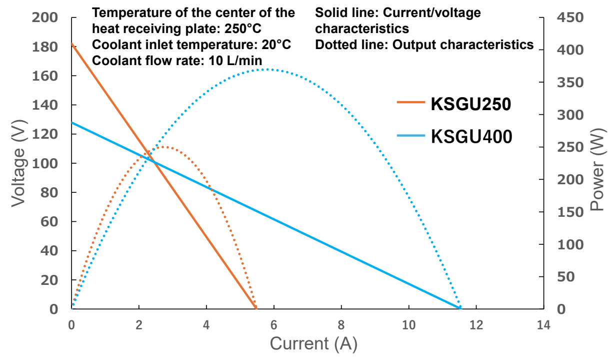


Fig. 9 Characteristics of "KELGEN G-Unit"

3.2 Application of thermoelectric generation

Thermoelectric generation units "KSGU250" and "KSGU400" are applicable to the large-scale waste-heat recovery at the continuous casting equipment in iron and steel mills, etc. However, units targeting the heat sources with comparatively less waste heat quantity used in rolling process, casting, casting process, or the like are also planned to be commercialized. We proceed with the development of the units suitable for various waste-heat types (see **Fig. 10**). It became clear, for example, that increasing the heat receiving surface area improves the received heat quantity in proportion to the heat receiving area especially for small/mid-scale heat sources. We are also conducting the development to increase the received heat quantity per unit at the same time.

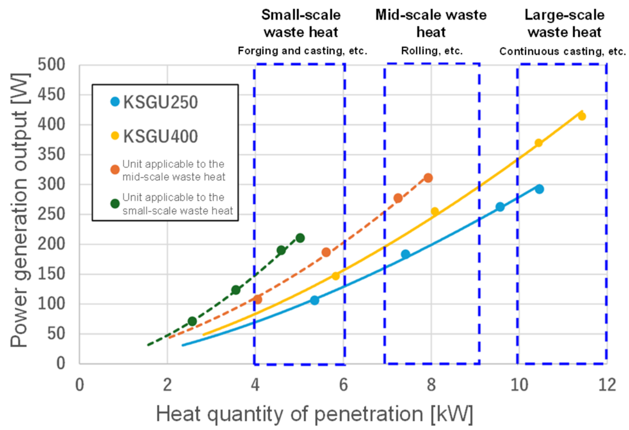


Fig. 10 Relation between the power generation output and heat quantity of penetration

At the same time, we developed an overheating protective device that cools down the thermoelectric generation unit as a protective function against the sudden overheating on a thermoelectric generation unit by forming a short circuit to the thermoelectric generation module when overheating occurs to generate the Peltier effect (see **Fig. 11**). Safer operation shall be available by installing this device.

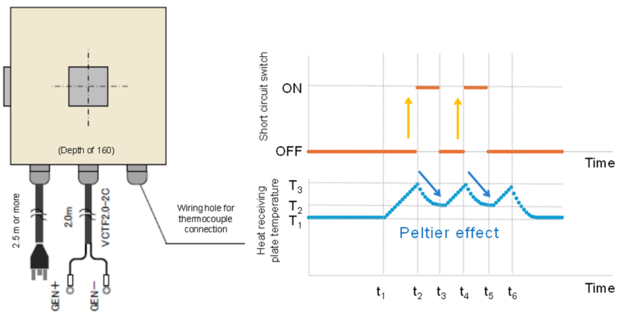


Fig. 11 Overview of the overheating protective device

3.3 Thermoelectric generation system

System construction is indispensable to commercialize thermoelectric generation, and electric power at kW or more is generated by lining up multiple units. This power is expected to be used as electricity for plants, etc., through power system interconnection through a power conditioner, similar to solar power systems (see **Fig. 12**).

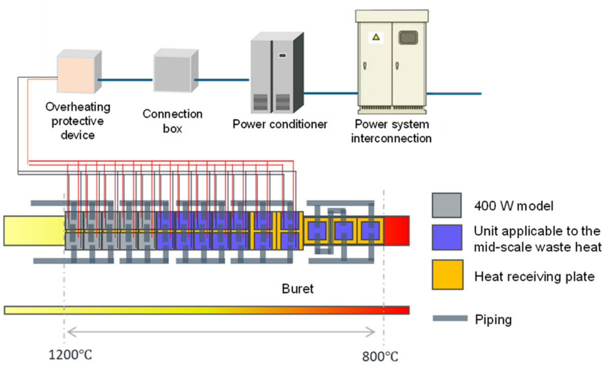


Fig. 12 Example of the thermoelectric generation system (stands, piping, etc.)

Specifically, the radiation waste heat of the workpieces conveyed on the cooling line in the continuous casting equipment (see **Fig.13**) or casting/casting process in iron and steel mills is recovered and converted to electricity. The radiation waste heat transfers in accordance with theory if the temperature, size and distance of the heat source are known. By the temperature and size of the heat source, the optimum distance of rated operation can be calculated and the thermoelectric generation unit can be placed above or below the workpiece.

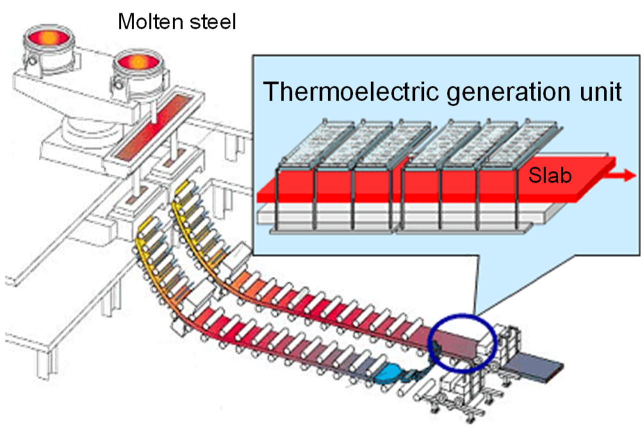


Fig. 13 Continuous casting equipment at iron and steel *1

3.4 Recovery of investment and application of subsidies

Thermoelectric generation unit “KSGU250” launched into market in January 2023 was adopted by Supplementary Budget for FY2023, Subsidy for supporting projects of Promotion of energy conservation investment / Transformation of the demand structure “(1) Plants/Workplace type” Advanced facilities/systems. This subsidy is provided to contribute to the achievement of “Outlook for energy supply and demand in FY2030” by supporting the introduction of devices/equipment related to the advanced energy conservation technology. This is a project to support the introduction of advanced equipment that can realize significant energy conservation at plants and workplaces. “KSGU250” was adopted for the first time as an industrial waste heat recovery equipment using thermoelectric conversion system. For “KSGU400,” we are also preparing to apply for the subsidy the same as “KSGU250.” If the subsidy is applied, the investment pay-back years is expected to be ten years or less. We are also proceeding with the application process of the subsidy for the units applicable to small/mid-scale waste heat in order. At present, we are promoting the introduction of thermoelectric generation using the subsidy. Toward its full-scale dissemination, however, we are accelerating the cost reduction development aiming to decrease the investment pay-back years to 7 years or less without the subsidy by 2030, the same as the solar power system.

4. Thermoelectric EH wireless device

4.1 Thermoelectric EH vibration monitoring device “KSGD-SV10”

About the half of the equipment troubles are caused by rotating equipment such as motors. Sudden equipment troubles become the cause of lowering productivity, opportunity loss, and energy loss due to the occurrence of urgent maintenance. In the 2010s, IoT took the world by storm, and the condition based maintenance (CBM) was expected to spread in the field of equipment maintenance. However, its spread was limited due to the power supply problems for IoT and data analysis issues.

KELK measured the equipment conditions with thermoelectric generation obtained from the temperature differential of 3℃, and developed the thermoelectric EH vibration monitoring device “KSGD-SV10” that transmits data for the distance of 500 m (see **Fig. 14**) In comparison to the conventional models, the range of the communication distance became greater by approx. 10 times; and the continuous measurement of data on the equipment/devices in wider areas such as iron and steel mills and plants became possible.

Fig. 14 Appearance of thermoelectric EH vibration monitoring device “KSGD-SV10”

New product “KSGD-SV10” adopted LoRa that uses the frequency in the 920 MHz band as the radio standard. LoRa uses the chirp spread spectrum for radio modulation that enables long-distance communication even with weak signals. In the 920 MHz band, transmission over long distances possible, however, the required transmission energy is more than 10 times greater than that of the 2.4 GHz band (see **Table 2**). To fulfil this electric power with the weak electric power obtained by thermoelectric generation, KELK designed an optimum thermoelectric generation module that efficiently recovers the waste heat from weak heat sources, developed a structure that removes the heat transfer loss in the temperature differential of the upper and lower surfaces of the power generation unit, made a power saving operation circuit, and achieved the practical level operation (see **Table 3**)

Table 2 Communication standards and transmission energy ratios

Communication standard	Communication output	Communication speed	Transmission energy ratio
2.4 GHz	1 mW	250 kbps	1
920 MHz LoRa	10 mW	5.5 kbps	13

Table 3 Major specifications for thermoelectric EH vibration monitoring device

Model			KSGD-SV10	KSGD-SV8
Communication standard			**920 MHz band**	**2.4 GHz band**
Communication distance *2 (Figure in parentheses is line-of-sight distance)			**500 m (1 km)**	50 m (250 m)
Vibration	Travel speed *3	RMS	✓	✓
	Acceleration *4	PEAK, RMS, CF, OA	✓	✓
	Sampling frequency		26.7 kHz	26.7 kHz
Temperature	-20°C to 80°C		✓	✓
Measurement duration			300 msec	300 msec
Temperature difference at the time of starting operation			3°C	3°C
Temperature difference and measurement interval (/times)		3°C	40 min	40 min
		5°C	30 min	30 min
		10°C	6 min	6 min
Operating temperature range of PGU			-5°C to 80°C (surface temperature of the installed side)	
IP code			IP67	

*2: Indicates reference value. It depends on the surrounding environment.
*3: Frequency range (±3 db) 10 Hz to 1.0 kHz
*4: Frequency range (±3 db) 1.0 kHz to 7.5 kHz

Assuming an environment with obstacles, the communication status was evaluated in an urban area with many buildings, comparing the 920M Hz-band products "KSGD-SV10" to that of 2.4 GHz-band products "KSGD-SV8". (Refer to **Fig. 15**)

Comparison of communication evaluation in an urban area

Fig. 15 Difference in radio communicable area

The radio communicable area of the 2.4 GHz-band product "KSGD-SV8" for a straight line distance is about 200 m, and radio waves from the back side of the workshop near the receiver was not received. On the other hand, "KSGD-SV10," a 920 MHz-band product, was able to receive radio waves from the back side of a workshop equivalent to a 6-story-high building near the receiver. It was also confirmed that radio waves were able to be received in the further areas if the height of a workshop is equivalent to a 3-story-high building.

4.2 Equipment abnormality monitoring "KELGEN swift"

KELK developed "KELGEN swift," software for monitoring equipment abnormality that operates on an on-premise computer and analyzes IoT measured values to deal with data analysis, another issue in equipment maintenance using the IoT (see **Fig. 16**) "KELGEN swift" operates on an on-premise PC and is equipped with a noise removal function to deal with the noise problem of vibration sensors. It is also equipped with a multivariate analysis function based on the MT method *5. This function realizes more stable judgments even for load fluctuations of rotating equipment caused by changes in workpieces or processing methods.

"KELGEN swift" can analyze large quantity of data from IoT devices at high speed on an on-premise PC and significantly reduce communication expenses and cloud-based analysis costs. It is also effective for use in plants where security is strict.

*5: Mahalanobis Taguchi method. A method of multivariate analysis that judges the degree of abnormality according to MD value (an index standardized in a multivariate manner considering the correlation of the applicable multivariate data)

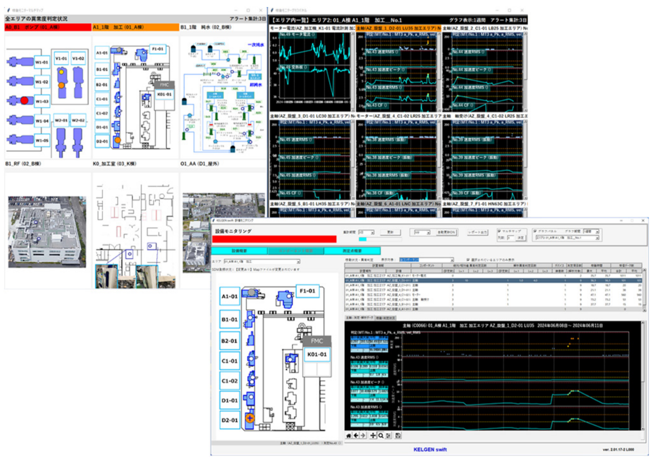


Fig. 16 Monitoring screen of "KELGEN swift"

4.3 KELGEN SD system

"KSGD-SV10," which adopts the 920 MHz band, significantly expanded the radio communication area and continues to measure data collection by IoT for equipment on large sites such as iron and steel mills without battery replacement. "KELGEN swift," which monitors the degree of equipment abnormality on-premise, can easily confirm the status of equipment abnormality by utilizing the IoT data.

The KELGEN SD system is equipped with a gateway which enables it to output the data to PLC or to plural devices by branching the output destinations via a hub. It can also be linked to the customer's existing system (see **Fig. 17**).

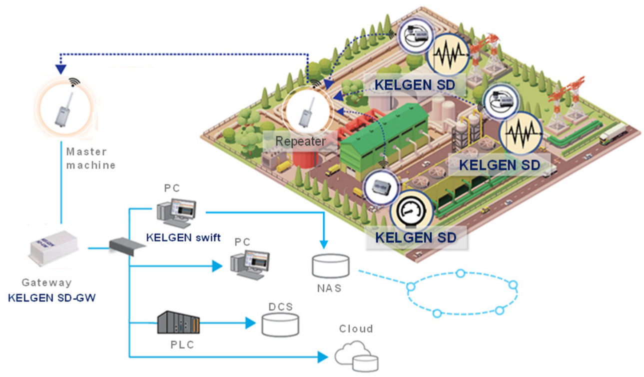


Fig. 17 Overview of the KELGEN SD system

5. Conclusion

Thermoelectric generation units that recover industrial waste heat can be operated flexibly according to the scale of the applicable waste heat. Additionally, this technology meets social goals such as decarbonization and SDGs, as it can be used to generate electricity in conjunction with plant operations that require electricity and is expected to be a stable source of electricity. We hope that the spread of thermoelectric generation units applicable to various waste heat scales will promote the industrial waste heat recovery.

The KELGEN SD system has been utilized widely, including the Komatsu plants. Electric power from the waste heat of the motors is regenerated, and introduction of CBM in the manufacturing industry is promoted by significantly reducing the installation and operational costs of equipment abnormality monitoring systems through the analysis of large quantity of data from thermoelectric EH vibration monitoring devices in continuous operation and cloudless IoT devices. KELK plans to expand its product lineup including explosion-proof products and to broaden the range of applications.

References

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Since we established major products, such as the units for industrial waste heat recovery and energy harvesting, we believe that the full-scale market introduction is now in sight. As a pioneer of thermoelectric generation, we will continue to accelerate the development of high-performance and low-cost products and promote their market introduction.