

Technical Paper

**Recovery of Plant Waste Heat
by a Thermoelectric Generating System**

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From October 2009, KELK started verification tests of a thermoelectric generating system using a carburizing furnace at the Awazu Plant of Komatsu. [1] This furnace introduces a carburizing gas, which comprises carbon monoxide, hydrogen and nitrogen, into the furnace and surplus gas having traversed a carburizing process unit is fed to an afterburner for combustion and decontamination, to be released outside the furnace. The lower combustion heat of flames in the afterburner is estimated to be 20 to 30 kW and this waste heat is converted into electricity by the thermoelectric generating system. The thermoelectric generator consists of sixteen thermoelectric generating modules made of a Bi-Te thermoelectric material. Each thermoelectric generating module is 50mm wide and deep and 4.2mm high. Each module is specified to generate an output of 24 W when the hot-side temperature is 280 and the cold-side temperature is 30°C. The sixteen modules are categorized into four groups, each of four modules. The electrical connections of the modules are roughly divided into parallel and serial connections. When robustness and reliability are paramount, a parallel connection is used and when the wiring is simple and the impedance is high, a serial connection. At present (as of October 2011), four modules are connected serially in a four-line configuration.

The durability and reliability of the thermoelectric generating modules were verified by a heat cycle, continuous generation tests and various high-temperature exposure tests on a device level. Improvements in durability and reliability are repeated. For example, in heat cycle tests, output degradation is controlled to several percent or lower after 10,000 cycles under constant cycle conditions of 30°C on the low temperature side and between 250 and 50°C on the high-temperature side.

A maximum power point tracking (MPPT) system uses a simple control circuit embedded with an 8-bit one-chip microcomputer to generate power under optimum conditions, despite the flame conditions varying from time to time. The output of sixteen thermoelectric generating modules is used to charge four lead storage batteries and supply power to light up LED lamps in the Awazu Plant of Komatsu through an inverter. The modules output 240 W when the temperature of the heat collection plate is 240°C and the cooling water temperature is 20°C.

Key Words: Thermoelectric Generation, Bi-Te, Awazu plant, Carburizing furnace, MPPT

1. Introduction

Based on the achievements gained in “Development of High-efficiency Thermoelectric Conversion System 2002 - 2006” of NEDO (New Energy and Industrial Technology Development Organization) project in September 2009, KELK Ltd., a subsidiary wholly owned by Komatsu, started the volume production and sale of thermoelectric generating modules (hereinafter referred to as “thermo-modules”) using a Bi-Te alloy. [1] Under the NEDO project, Komatsu developed a cascade-type module stacked with Bi-Te and silicide modules and targeting 15% conversion efficiency at hot- and cold-side temperatures of 550 and 30°C, respectively. [2], [3] Based on these results, a thermoelectric generating system was installed at a carburizing furnace in the Awazu Plant of Komatsu to study the feasibility of the thermoelectric generating system in recovering plant waste heat, as part of reliability and durability tests and promote social recognition of the system. This paper reports the system features and performance.

2. Power Generation Characteristics of the Thermo-Module

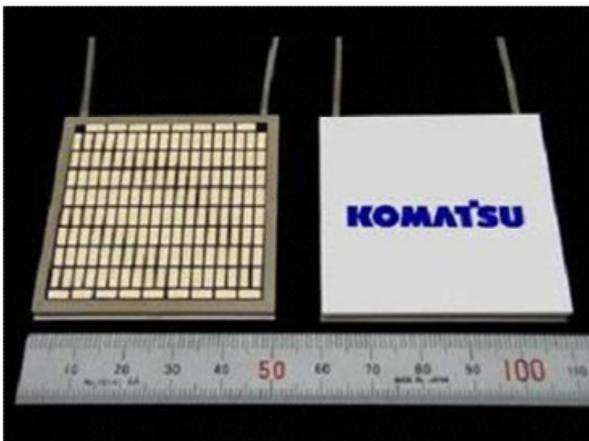


Fig. 1 Developed Bi-Te thermo-module

Fig. 1 is a photo showing an appearance of the Bi-Te thermo-module, the features and specification of which are supplied in the following. [1]

[Features]

- World’s highest conversion efficiency. Large output obtainable, even with a small temperature difference (Operating conditions: High-temperature side 280°C, low temperature side 30°C)
- High output density of about 1 W/cm², compact equipment and system
- Low current and high voltage of 3A and 8V at maximum output, featuring easy handling of electric circuits

[Product Specification]

- Dimensions in mm: 50 x 50 x 4.2 excluding lead wires
- Weight: 47g
- Output: 24 W maximum (at hot- and cold-side temperatures of 280 and 30°C respectively)

- Operable temperature range: High-temperature side 280°C maximum, normal operation 250°C or less, low temperature side 150°C maximum
- Conversion efficiency: 7.2% maximum
- Material: Bi-Te alloy

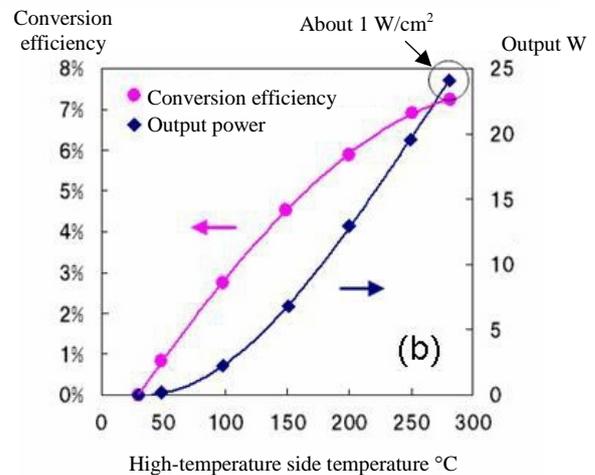
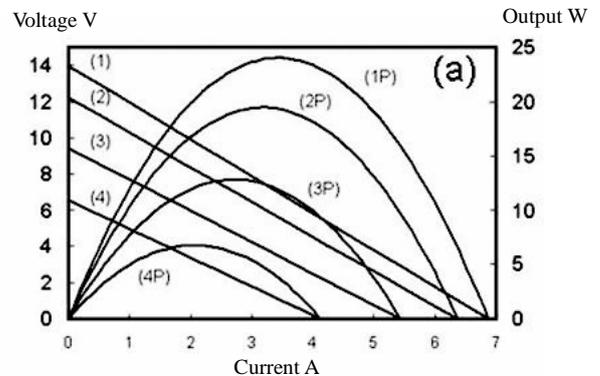


Fig. 2 Power generation characteristic (a), maximum output and conversion efficiency (b) of the thermo-module. In (a), corresponds to (1) (1P): $T_h = 280^\circ\text{C}$, (2) (2P): $T_h = 250^\circ\text{C}$, (3) (3P): $T_h = 200^\circ\text{C}$, (4) (4P): $T_h = 150^\circ\text{C}$. $T_c = 30^\circ\text{C}$.

Fig. 2 plots the power generation characteristics, maximum outputs and conversion efficiency of the thermo-module. Voltage V and output P corresponding to various hot-side temperatures T_h are plotted as functions of current I flowing into the thermo-module. This evaluation of maximum output and conversion efficiency is measured by limiting the cold-side temperature T_c to 30°C. The V value at $I = 0$ is open-circuit voltage V_o and 12 and 14V when $T_h = 250$ and 280°C, respectively. Differing significantly from the I - V characteristic of solar cells, V linearly decreases alongside I and the inclination of the straight line at this time becomes the internal resistance R_i of the thermo-module. R_i has no prominent temperature dependence on T_h and is generally constant at about 2Ω. Output P can be obtained from the external load r connected to the thermo-module and calculated by $P = V \times I$. P fetches the maximum output P_{\max} in impedance matching when $R_i = r$. As shown by $P_{\max} - T_h$ plotting in **Fig. 2** (b), the

maximum outputs are 20 and 24W when $T_h = 250$ and 280°C , respectively. Fig. 2 (b) also plots the conversion efficiency $\eta - T_h$ of the thermo-module. η increases linearly alongside T_h and reaches $\eta = 7.2\%$ when $T_h = 280^\circ\text{C}$.

3. Thermoelectric Generating System [4], [5]

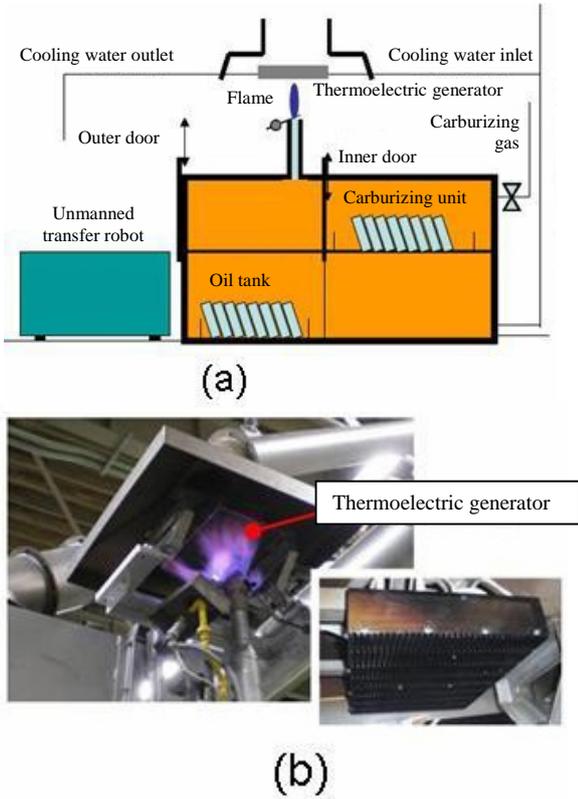


Fig. 3 Thermoelectric generating system (a) and example of a thermoelectric generator (b) installed at the Awazu Plant of Komatsu

Fig. 3 (a) shows a sketch of the thermoelectric generating system installed at the Awazu Plant of Komatsu. The flame is generated by igniting a pilot burner to decontaminate H_2 and CO in the carburizing gas (RX gas) and is burnt to heat the heat collection plate of the thermoelectric generator. When the flow rate of RX gas is $10 \text{ m}^3/\text{h}$, the combustion heat is estimated at about 20 kW. Fig. 3 (b) shows an example of the thermoelectric generator. The heat collection plate measures $400 \times 280 \text{ mm}$ and has a fin structure to increase the heat collection area and efficiency. The surfaces of the heat collection plate are blackened. A total of sixteen thermo-modules (in 4 groups, each having four modules) shown in Fig. 1 are placed on the opposite side of the heat collection plate. The method used to connect the thermo-module should be flexible depending on where the system is installed. The advantages of connecting all modules in series are to ensure high impedance can be produced and high voltage obtained, enabling a power conditioner for solar cells to be used without a DC/DC converter, simple wiring and

other factors. However, one of the sixteen modules connected was damaged and the entire generator output was shut down, showing a lack of robustness. This robustness can be improved by installing a bypass diode, but this does not allow utilization of the largest advantage, namely, simple wiring. Conversely, parallel connections have shortcomings, namely, the wiring becoming complex and an inability to handle large currents due to low impedance. However, the maximum power of each module can be tracked (MPPT - Maximum Power Point Tracking). Even if temperature distribution becomes uneven by MPPT, each module can be made independent to implement MPPT to each of the modules and high robustness can be achieved as advantages. In reality, serial and parallel connections will be suitably combined depending on the locations. However, a fail-safe circuit by the bypass diode must be embedded as mentioned above.

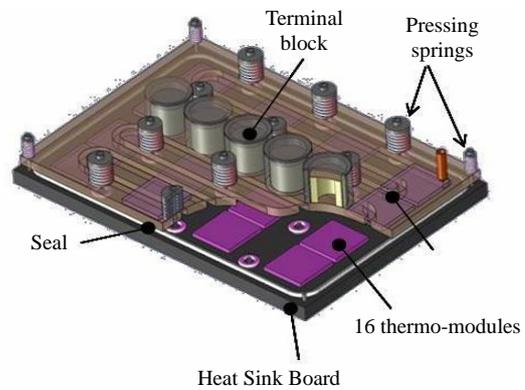


Fig. 4 Partial cross section of the thermoelectric generator shown in Fig. 3 (b)

Two typical examples of heat collection plates tested to date are as follows. The first is a simple flat plate and the second has a simple fin structure. (Fig. 3 (b)). Fig. 4 illustrates a partial cross section of the thermoelectric generator shown in Fig. 3 (b). Each thermo-module is sandwiched between the heat collection and water cooled plates by a spring structure, meaning almost constant pressure is applied to the module, even if a temperature difference is generated. The pressure is set to 1 MPa as a criterion, with a cooling water flow rate of 10 to 12 liters/minute and the cold-side temperature maintained at an estimated 40°C or less. The heat collection plate temperature T_h that is read from the temperature sensor in Fig. 4 varies within the range 120 to 250°C depending on the carburizing process. The heat collection efficiency is about 20% and a heat quantity of only about 4 kW is introduced from flame combustion heat of 20 kW. A comprehensive study is urgently needed to optimize the fin structure and study the material of the heat collection plate, the layout position of the thermoelectric generator and other matters.

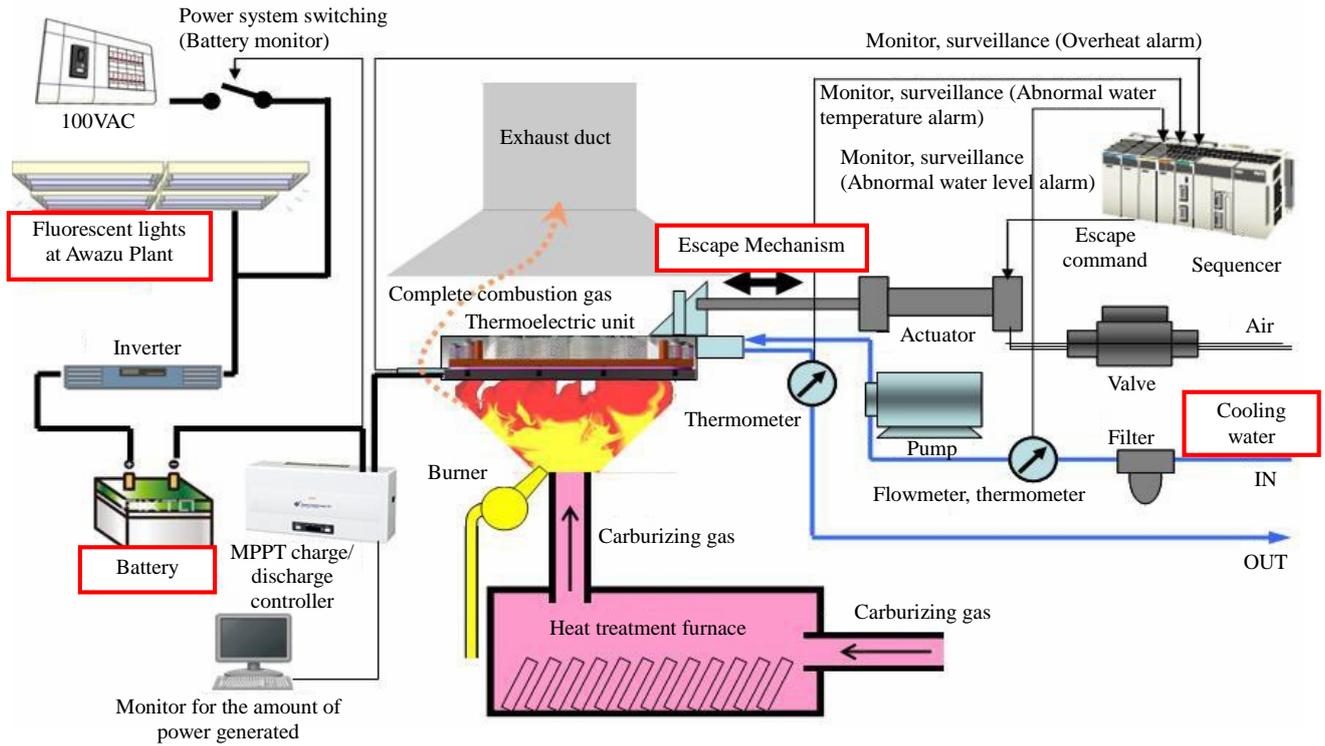


Fig. 5 Power system of a thermoelectric generating system installed with carburizing equipment of the Awazu Plant of Komatsu

Fig. 5 illustrates the power system of the thermoelectric generating system installed with the carburizing equipment of the Awazu Plant of Komatsu. The power generation output is stored in the lead storage battery through the MPPT charge/discharge controller. The power from the battery is converted into 100VAC by a general-purpose inverter to supply power to light up the LED lights inside the plant. The MPPT efficiency is about 85%. The cooling water flow rate, cooling water temperature and heat collection plate temperature are always monitored. The escape mechanism extinguishes the flames of the thermoelectric generating unit after receiving an alarm signal from the meters and thermometers, which ensures safety.

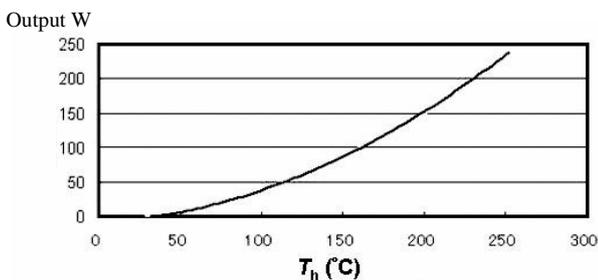


Fig. 6 Plotting of the heat collection plate temperature T_h and thermoelectric generator output P

The thermoelectric generator output P is plotted in Fig. 6 as a function of the heat collection plate temperature T_h . When $T_h = 250^\circ\text{C}$, a 240 W output is obtained, showing that each module outputs 15 W on average. According to the power generation output characteristic of each module shown in Fig. 2, an output of 20 W is estimated to be obtainable when $T_h = 250$ and $T_c = 30^\circ\text{C}$. This difference can be explained by a reduction in the real temperature difference provided to the hot and cold-sides of the thermo-modules due to the heat collection plate, ceramic substrate and inclusions such as grease, by non-uniform heating of the sixteen thermo-modules and losses caused by the resistance of the lead wires that fetch the output.

Conclusion

A thermoelectric generating system was installed with a carburizing furnace at the Awazu Plant of Komatsu to recover waste heat. The thermoelectric generator has sixteen thermo-modules developed jointly by KELK and the Corporate Research Division and outputs 240 W when the heat collection plate temperature is 250°C . However, of the total waste heat of 20 kW, the quantity traversing the thermoelectric generator is 4 to 5 kW and the heat collection efficiency remains low, at about 20%. A heat collection efficiency of 40% or higher is considered feasible by refining the generator layout and fin structure of the heat collection plate. This means that penetrating heat of 2 kW per furnace can be fetched. A trial

calculation shows that 500 W output can be fetched per generator. There are more than ten carburizing furnaces of equivalent size at the Awazu Plant. When all the carburizing furnaces are installed with a thermoelectric generator, power generation output of about 10 kW is obtainable. An operating ratio of about 80% is feasible and total power output about six times that of solar power systems operating at 12% can be obtained. [6]

The thermoelectric generating system has been in operation for more than 10,000 hours in aggregate from October 2009 to date (November 2011). No decline in output was found during continuous operation of more than 2,000 hours. In fiscal 2012 ending March 2013, the system will be expanded to a power generation capacity of the 10 kW class, to demonstrate power generation capability, start a new market and expand applications.

Acknowledgments

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Introduction of the writers



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[A few words from the writers]

We believe that the project is fulfilling a pioneering mission as an example of the industrial application of the thermoelectric generating system. Aside from thermoelectric power generation itself, efforts will be made to develop the market by making further progress in the areas of power recovery technology, durability and cost competitiveness through the cooperation of related personnel.