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Thermoelectric Generation Using Waste Heat in Steel Works

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The steelmaking industry in Japan has significantly reduced its energy use for the past several decades and has kept the highest energy efficiency in the world. However, the steelmaking industry is strongly required to develop new technologies for further energy conservation in view of energy security, high and volatile energy prices, and climate change. One of the key technologies to achieve the requirement is waste heat recovery. This paper describes the thermoelectric generation (TEG) system using the waste heat in the steelmaking process. In this system, the TEG unit, which consists of 16 thermoelectric modules made of Bi-Te thermoelectric materials, generates the electrical power directly by converting the radiant heat released from hot steel products. Each thermoelectric module, whose size is 50 mm × 50 mm × 4.2 mm, generates 18 W when the hot-side temperature is 523 K and the cold-side is 303 K. Therefore, the output of the TEG unit is over 250 W. The performance and the durability of the system have been investigated under various operating conditions in steel works. The results of the verification tests in the JFE steel Corporation's continuous casting line will be discussed.

Key words: Thermoelectric generation, waste heat, heat recovery, thermoelectric generation system

INTRODUCTION

In the steel industry, the steel manufacturing process requires enormous quantities of resources, including iron ore and coal, and requires large amount of energy in the form of electric power and fuels. To reduce the environmental loads, JFE Steel Corporation (JFE) has carried out a variety of ranges of technology development and implemented environmental countermeasures for the past several decades. On the other hand, recent society is faced with new problems, such as global warming, which demand maximum use of innovative technologies. In these circumstances, JFE supplies environmental friendly iron and steel products which make a large contribution to reducing the environmental loads in industrial society, and is continuing technical development and the introduction of equipment with the aim of achieving further energy savings and preventing global warming and reducing environmental loads in each of its steel manufacturing processes. Table I shows the main technologies applied as the energy saving measures such as waste heat recovery equipment and power generating equipment in each steel manufacturing process, for example coke dry quenching (CDQ), blast furnace top gas pressure recovery (TRT), regenerative burner, and so on.[1]

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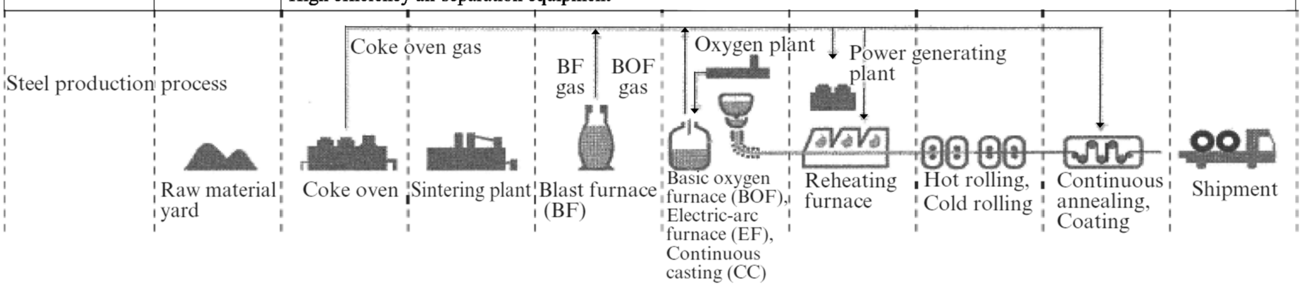
Table I. Overview of energy and environmental conservation technologies

Counter-measures-Facility		Coke dry quenching (CDQ), Coal moisture control (CMC), Combustion control	Sintering cooler waste heat recovery, Ignition furnace line burner, Super-SINTER®	Waste plastics feeding, Pulverized coal injection, Top pressure recovery turbine, Hot stove waste heat recovery, Fuel gas preheating, Shaft furnace, City gas injection	Gas recovery, Gas sensible heat recovery, Nitrogen jet heater, Ladle heating	Regenerative burner, Direct charging, Low-temperature extraction, Fuel switch from oil to gas	Endless rolling, Process coupling	Waste heat boiler, Rotary regenerative heat exchanger	Selection of transportation mode, Shortening of transportation distance, Improvement of load efficiency, Modal shift, Application of information technology (IT)
		Gas turbine combined cycle power plant, Power plant fuel preheating device, High efficiency air separation equipment							



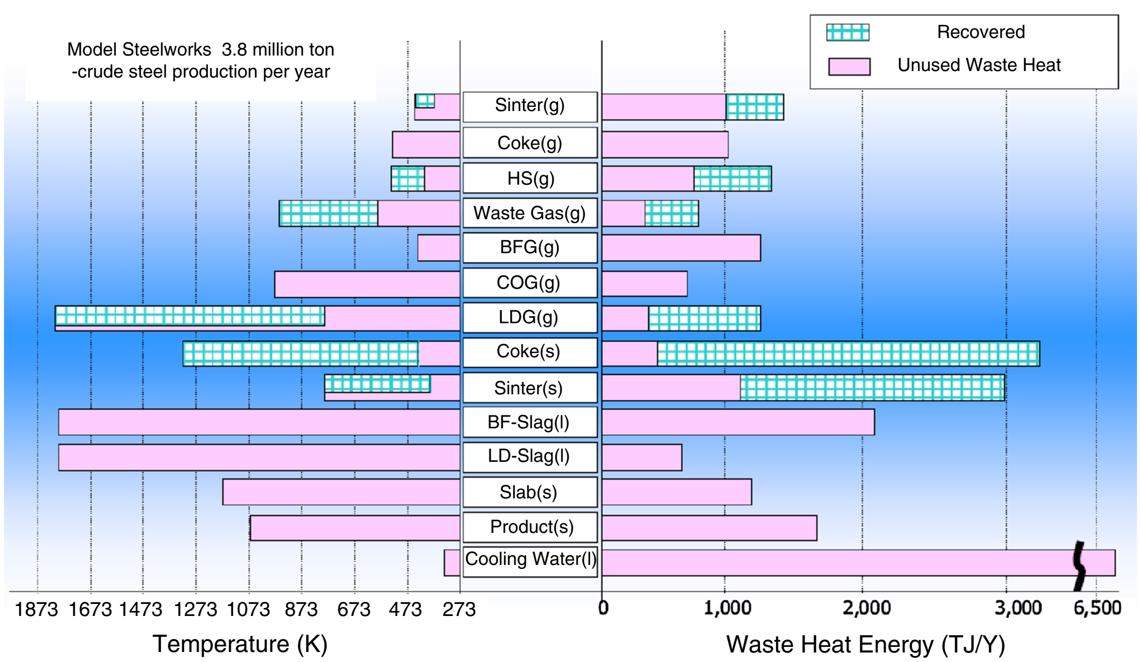


Fig. 1. Waste heat for various processes of steelworks.[2]

technologies to achieve the requirement is waste heat recovery. Figure 1 shows the waste heat for the various processes of steelworks.[2] There are still large amounts of waste heat which are not utilized effectively. For example, we create a great deal of energy (19 TJ/year) under these conditions:

- The amount of waste heat = 10 GJ/ton crude steel
- The crude steel production = 380 million ton/year
- Total energy recovery ratio = 0.05%

Thermoelectric generation is a technology which directly convert heats into electricity using the Seebeck effect. This environmentally friendly technology has an important role in energy conservation, waste heat recovery, and CO_2 reduction. Thermoelectric generation has many advantages such as no mechanical moving parts, compactness, no CO_2 emissions on working, and a long lifetime. This paper describes the thermoelectric generation system using waste heat in the steelmaking process.

THERMOELECTRIC GENERATION SYSTEM AT STEELWORKS

Thermoelectric Generation Module

Figure 2 shows the appearance of the Bismuth-Telluride thermoelectric generation module (TEG module), which is made up of a number of n-type and p-type thermoelectric elements.[3] It has the world's highest conversion efficiency and the highest powered commercial thermoelectric generator. The TEG module size is 50 mm × 50 mm × 4.2 mm excluding lead wires, and its weight is 47 g. Figure 3 shows the conversion efficiency and the output power plotted as a function of the hot-side temperature of TEG module. Its maximum output power is 24 W, with maximum conversion efficiency of 7.2% when the hot-side temperature is 553 K and the cold-side temperature is 303 K, respectively. Its operating temperature rage is 553 K at the high-temperature side, in normal operation is 523 K or less and is 423 K maximum at the low-temperature side. The evaluation of maximum output and conversion efficiency is measured by the cold-side temperature T_c = 303 K. The voltage V value at current I = 0 is open-circuit voltage V_o and is 12 and 14 V when T_h = 523 and 553 K, respectively. V linearly decreases with I and the inclination becomes the internal resistance R_i of the TEG module. R_i increases as the T_h rises. In the case of T_i = 553 K, R_i is about 2 Ω. Output P can be obtained from the external load r connected to the TEG module and calculated by $P = V \times I$. P brings the maximum output P_{max} in impedance matching when $R_i = r$. The maximum outputs are 18 and 24 W when T_h = 523 and 553 K, respectively. The conversion efficiency η increases and reaches η = 7.2% when T_h = 553 K.[4]

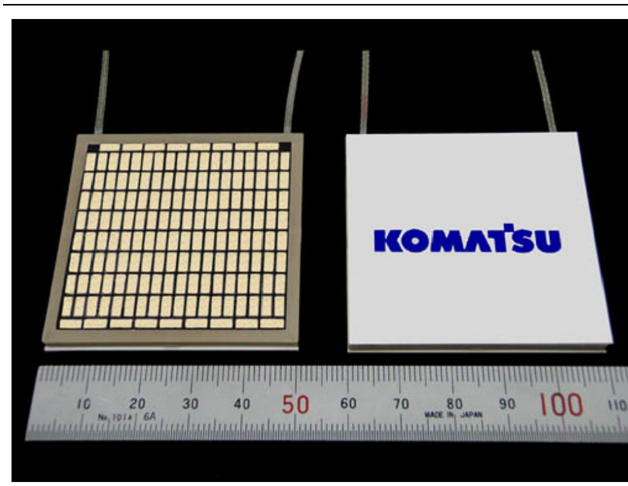


Fig. 2. Bi-Te thermoelectric generation module.[3]

Thermoelectric Generation Unit

Figure 4 shows a illustration of a partial cross-section of the thermoelectric generation unit (TEG unit). A total of 16 TEG modules connected in series (shown in Fig. 1) are placed on the opposite side of the heat collection plate. Each TEG module is sandwiched between the heat collection plate and the water-cooled plate by a spring structure, meaning almost constant pressure is applied to the modules, even if a temperature difference is generated. The pressure is set at 1 MPa as a criterion, with a cooling water flow rate of 1.7 × 10^{-4} m^3/s and the cold-side temperature maintained at 313 K

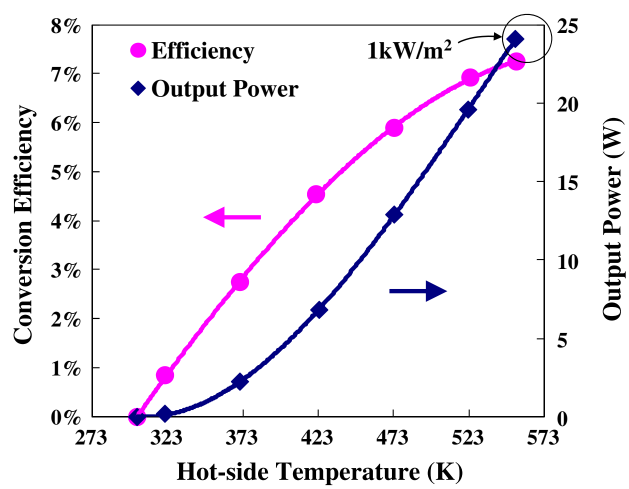


Fig. 3. Conversion efficiency and output power for the TEG module as a function of the hot-side temperature of TEG module with constant cold-side temperature at 303 K.

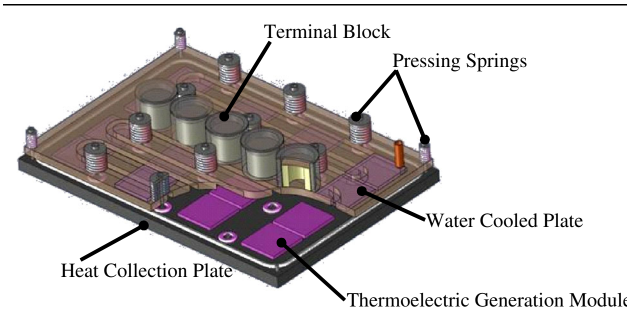


Fig. 4. Thermoelectric generation unit.[4]

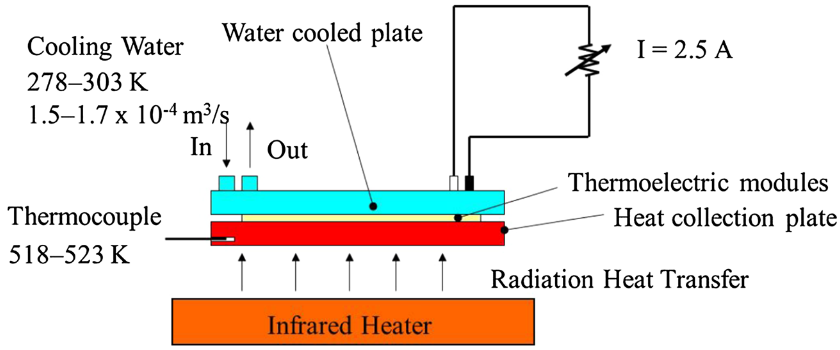


Fig. 5. Schematic of the power output evaluation of the TEG unit.

or less. The size of the heat collection plate is 400 mm × 280 mm. Copper is used for the heat collection plate and the water-cooled plate. The surface treatment of the blackened heat collection plate is nickel plating.[4] Figure 5 illustrates the test bench set up for output power evaluation of TEG unit using an infrared heater. The thermocouple is inserted into a hole on the side face of the heat collection plate, which is controlled in the range between 518 and 523 K. Also, the temperature of the inlet cooling water is 298–303 K and the flow rate is 1.5–1.7 × 10^{-4} m^3/s. The power output of the TEG unit is measured under the condition of I = 2.5 A, which is the optimum current condition. The measurement results are listed in Table II. Taking the thermal resistance of both the heat collection and the water-cooled water-cooled plate and the thermal contact resistance between the thermoelectric module to heat the collection plate and the water-cooled plate into account, the temperature difference of the thermoelectric module in the TEG unit is estimated to be approximately 200 K. This measurement condition is close to the hot-side temperature of 503 K in Fig. 3, and the output power of the module is 16 W. Therefore, we estimated the output power of the TEG unit is over 250 W, which is consistent with the estimate.

Table II. Measurement results of output power

Unit No.	*P* (W)
1	259
2	258
3	268
4	261
5	252

Thermoelectric Generation System

Figures 6 and 7 show the thermoelectric generation system installed in the JFE's continuous casting line. Figure 7 shows a schematic illustration of the TEG system. The TEG system has 56 TEG units, thus the TEG system has 896 TEG modules. The size of the TEG system is about 4 m × 2 m, and the distance between the slab and the TEG units is about 2 m. The heat collection plates of the TEG units are heated by radiation heat from continuous casting slab.

Verification Tests

JFE have implemented a 10-kW class thermoelectric power generation system for its continuous casting line with KELK Ltd., and started verification tests to generate electric power by using radiant heat from the continuous casting slabs at the end of 2012. The performance of the grid-connected TEG system has been investigated under various operating conditions in the steelworks.

Equations 1 and 2 are the basic equations of thermoelectric generation

$$Q_a = \alpha_e T_{hj} I - \frac{1}{2} r_e I^2 + K_e \Delta T_j \tag{1}$$

$$Q_d = \alpha_e T_{cj} I + \frac{1}{2} r_e I^2 + K_e \Delta T_j \tag{2}$$

Here, heat Q_a is supplied by the thermal source at the hot surface, Q_d is the heat flowing out at cold surface, α_e is the Seebeck coefficient, r is the internal electrical resistance, K_e is the thermal conductance, and I represents the electric current.[5] These equations are derived from the heat equation subject to the Seebeck effect and Joule heating with boundary conditions of the hot side temperature (T_{hj}) and the cold side temperature (T_{cj}).

The power generation output P_g is given by Eq. 3

$$P_g = Q_a - Q_d = (\alpha_e \Delta T_j - r_e I) I = R_L I^2 \tag{3}$$

Here, R_L is the external electric resistance.

Also, the maximum generation output P_{gmax} is given by Eq. 4

$$P_{gmax} = \frac{1}{4} \cdot \frac{(\alpha_e \Delta T_j)^2}{r_e} \tag{4}$$

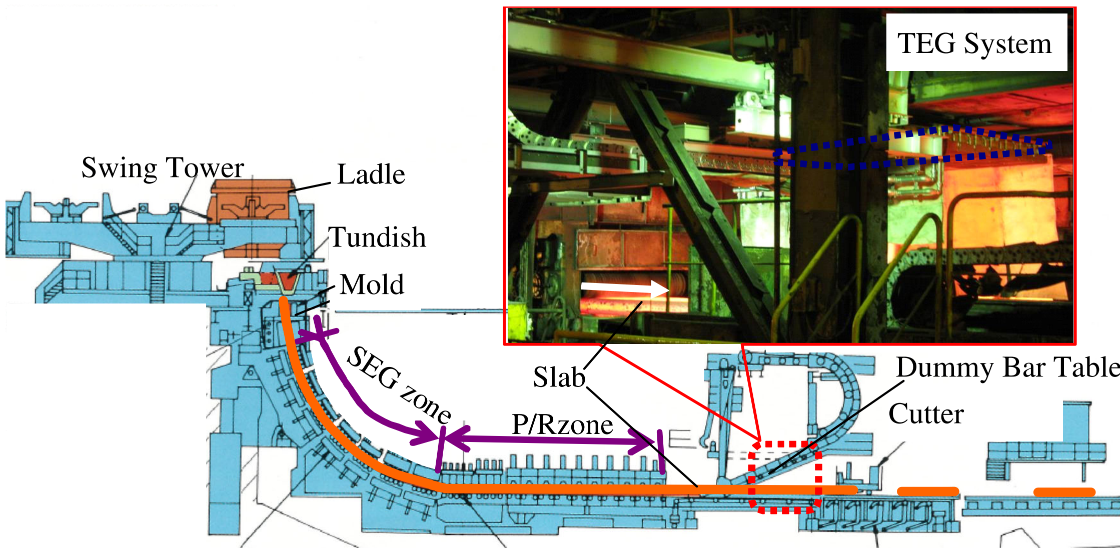


Fig. 6. Thermoelectric generation system installed in the JFE's continuous casting line.

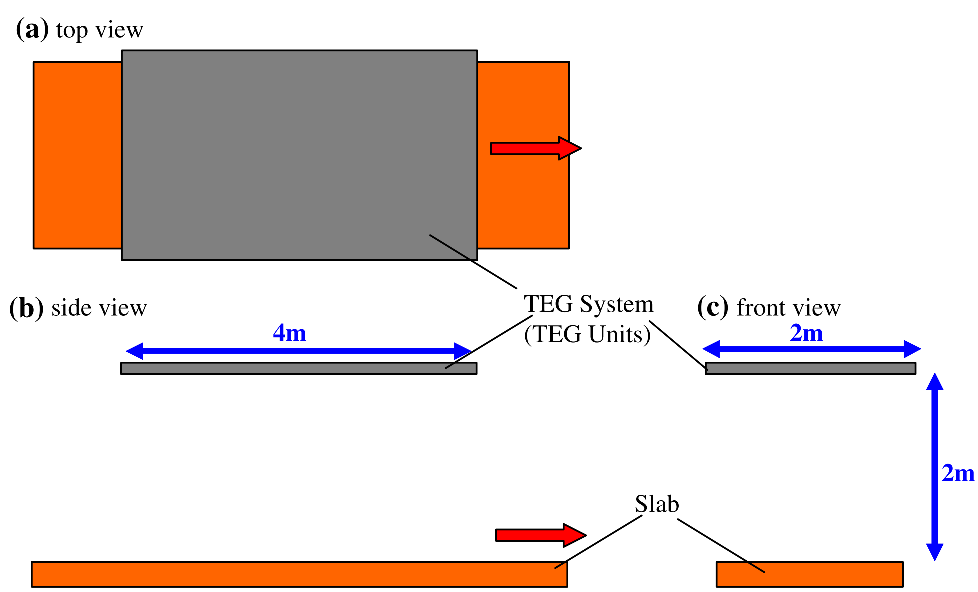


Fig. 7. Schematic illustration of TEG system (a) top view, (b) side view and (c) front view.

Here, ΔT_j is the temperature difference $T_{hj} - T_{cj}$.

In order to obtain high power generation output, a large temperature difference, ΔT_j, is required. On the other hand, T_{hj} must be under the tolerance maximum temperature. Therefore, it is very important to simulate T_{hj} for various conditions. In this system, Q_a is the radiation heat from the slab. The radiation heat Q_a is expressed by Eq. 5.

$$Q_a = \varepsilon \cdot F \cdot \sigma \cdot A\left(T_s^4 - T_h^4\right) + h \cdot A \cdot \Delta T \quad (5)$$

Here, ε is the emissivity, σ is the Stefan–Boltzmann constant, F is the view factor, T_s is the slab temperature, T_h is the hot-side temperature of the thermoelectric generation unit, A is the area of the heat collection plate of the TEG unit, ΔT is the temperature difference between T_h and T_a (the atmosphere temperature), and h is the heat transfer coefficient.

Using Eqs. 1–5, the temperature of the TEG unit and P_{gmax} have been numerically investigated for several experimental conditions. When the continuous casting line is under operation, the TEG units are warmed by radiant heat and a temperature difference is generated, and the power outputs are generated by the TEG units. Figure 8 shows the measurements of the output of TEG units in different slab widths as a function of slab temperature. The view factor F in Eq. 5 is a function of the slab width and the distance from the slab to the TEG

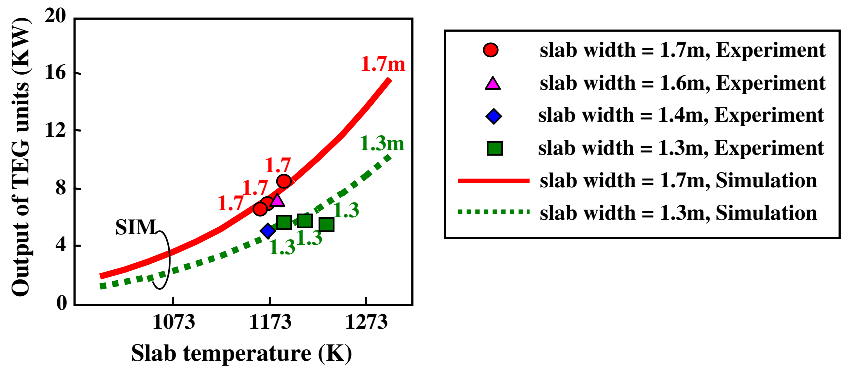


Fig. 8. Measurements of the output of the TEG units in different slab widths as a function of slab temperature.

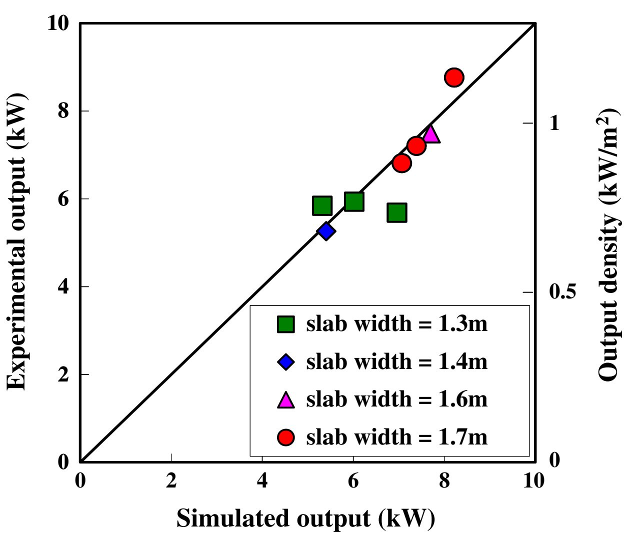


Fig. 9. Simulated and experimental power output of the TEG units.

units, and is inversely proportional to the distance. So the heat input Q_a becomes larger as the slab width increases. Furthermore, the heat input Q_a becomes larger when the slab temperature T_s rises. The larger the heat input, the more the heat collection plate temperature rises and the temperature difference, ΔT_j, increases. Therefore, the power output of the TEG units increases with the increases of the slab temperature and slab width. The thermoelectric generation system outputs about 9 kW when the slab temperature is about 1,188 K. Figure 9 shows the simulation and some experimental results of the power output of the TEG units. The measurements of the power output of the TEG units seems to be similar to the simulated output. A power output density of the TEG system about ten times that of solar power systems can be obtained.

The calculated maximum temperatures at the hot side of the TEG module in the TEG system are 484, 528. and 543 K when the slab temperatures are 1,198, 1,273, and 1,298 K, respectively. These hot-side temperatures of the TEG module are lower than 553 K, which is the maximum operating temperature of TEG module.

CONCLUSION

A thermoelectric generation system was installed in the continuous casting line at the East Japan Works in the Keihin District of JFE to recover waste heat. The thermoelectric generation system outputs about 9 kW when the slab temperature is about 1,188 K and the slab width is 1.7 m. The result of the output is a good fit between the simulation and the experimental data.

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