Chapter 17
Waste Heat Recovery in Steelworks Using a Thermoelectric Generator

T. Kuroki, K. Kabeya, K. Makino, H. Kaibe, H. Hachiuma, and A. Fujibayashi

Abstract In Japan the integrated steel industry has largely lowered its energy use for the past several decades by investing in energy efficient processes and facilities, and has kept the highest energy efficiency in the world. However, in view of energy security, the steelmaking industry is strongly required to develop new technologies to save more energy. Waste heat recovery can be one of the key technologies to meet this requirement.

Thermoelectric generation is one of the most effective technologies to recover waste heat, such as the radiant heat from steel products which has not been efficiently used, because it can convert heat directly into electric power.

A thermoelectric generation system was installed in the butt welded pipe mill at East Japan Works (Keihin District) of JFE Steel Corporation in May 2011. In this system, a thermoelectric generation unit consists of 16 Bismuth-Telluride thermoelectric genera-

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tion modules. Each module can generate 24 W when the hot-side temperature is 553 K and the cold-side temperature is 303 K. These 16 thermoelectric generation modules are separated into four groups of four modules connected in series, and each group is connected in parallel. A commercial battery charger for off-grid photovoltaic systems was used as a maximum power point tracking (MPPT) control unit, and the output of 16 thermoelectric generation modules was used to charge storage batteries and supply power to LED lamps through the MPPT controller.

This paper describes the performance and durability of the thermoelectric generation system which has been investigated under operating conditions in butt welded pipe mill.

Keywords Thermoelectric generation • Waste heat • Heat recovery • Radiant heat • Thermoelectric generation system • Butt welded pipe

Introduction

The integrated steel industry in Japan has significantly reduced its energy use for the past several decades by investing in energy efficient processes and facilities, 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. Figure 17.1 shows the waste heat for various processes of steelworks [1]. We have been investing in many energy efficient processes and facilities. However, a large amount of heat still remains wasted. For waste heat such as radiant heat from steel products which has not been efficiently used, thermoelectric generation is one of the most effective technologies to recover it, because thermoelectric generation can convert heat directly into electric power using the Seebeck effect. This environmentally friendly technology is expected to have an important role for energy conservation, waste heat recovery and CO_2 reduction. Thermoelectric generation has many advantages such as no mechanical moving parts, compact, no CO_2 emissions and long lifetime. This paper describes the thermoelectric generation system which was installed at East Japan Works of JFE Steel Corporation, using waste radiant heat from the butt welded pipe.

Thermoelectric Generation System at Steelworks

Thermoelectric Generation Module

Figure 17.2 shows a Bismuth-Telluride thermoelectric generation module (TEG module), which is made from a number of n-type and p-type thermoelectric elements [2]. It has high conversion efficiency and is a high-powered commercial thermoelectric

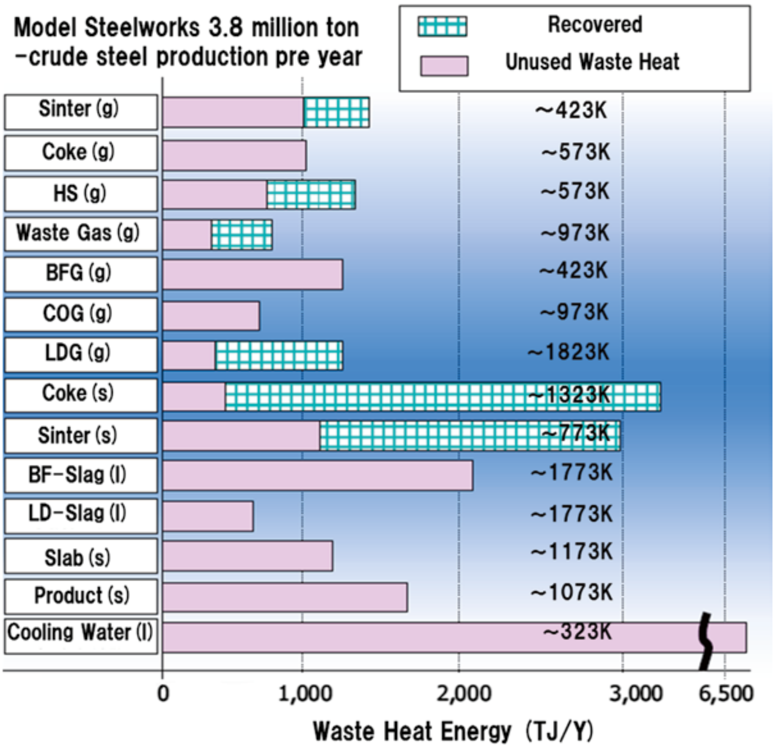

Fig. 17.1 Waste heat energy in the various processes in steelworks [1]

generator. The size of TEG module is 50 mm × 50 mm × 4.2 mm. Its maximum output power is 24 W, with a maximum conversion efficiency of 7.2 %, when the hot-side temperature is 553 K and the cold-side temperature is 303 K respectively [3]. The output P can be obtained from the external load r connected to the TEG module. P brings the maximum output P_{gmax} in impedance matching when $R_i = r$.

Thermoelectric Generation Unit

Figure 17.3 shows an illustration of a partial cross section of the thermoelectric generation unit (TEG unit). The TEG unit consists of 16 TEG modules. These thermoelectric generation modules are separated into four groups of four thermoelectric generation modules connected in series, and each group is connected in parallel. The TEG modules were connected to the MPPT control unit to achieve maximum power at any temperature conditions. The output of 16 thermoelectric generation modules is used to charge storage batteries and supply power to LED lamps through the MPPT controller. Each TEG module is sandwiched between the heat collection plate and the water cooled plate by a spring structure, meaning that almost constant

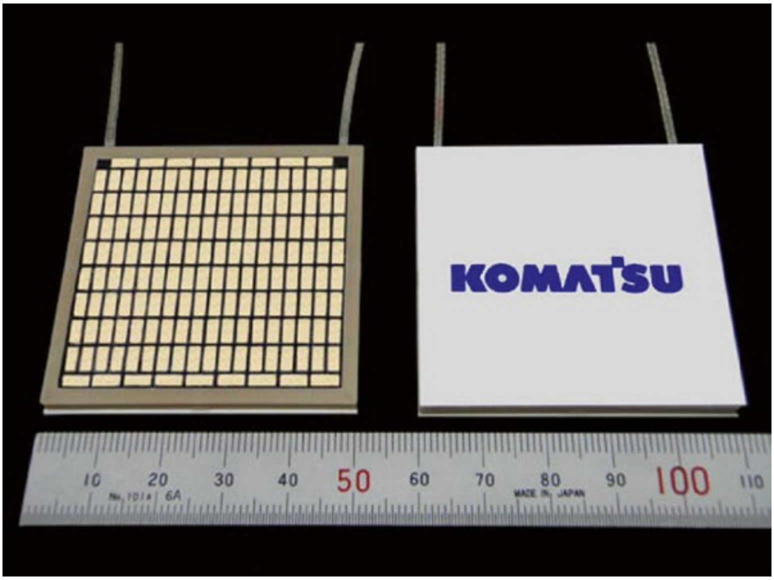

Fig. 17.2 Bi-Te thermoelectric generation module [2]

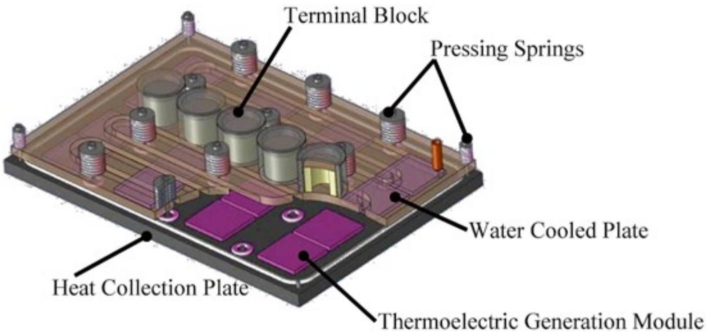

Fig. 17.3 Thermoelectric generation unit [3]

pressure is applied to the modules, even if a temperature difference is generated. The pressure is set at 1 MPa, with a cooling water flow rate of 10 l/min. The size of the heat collection plate is about 400 mm × 280 mm. Copper is used for the heat collection plate. The surface treatment of the heat collection plate is an electroless nickel plating (black) [3]. The temperature of heat collection plate T_h and water cooled plate T_c were measured by thermocouples. Figure 17.4 shows the thermoelectric generation unit installed in the JFE's butt welded pipe mill. The heat collection plate of the TEG units was heated by radiant heat from the butt welded pipe.

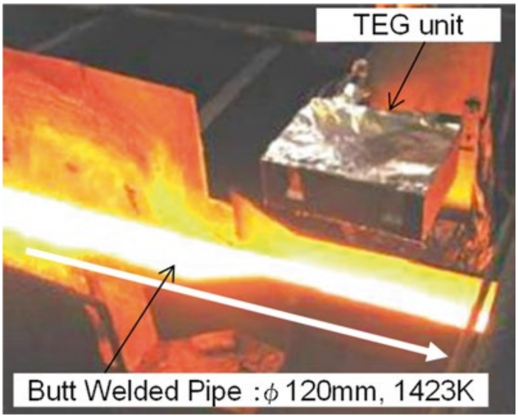

Fig. 17.4 Thermoelectric generation unit installed to the JFE's butt welded pipe mill

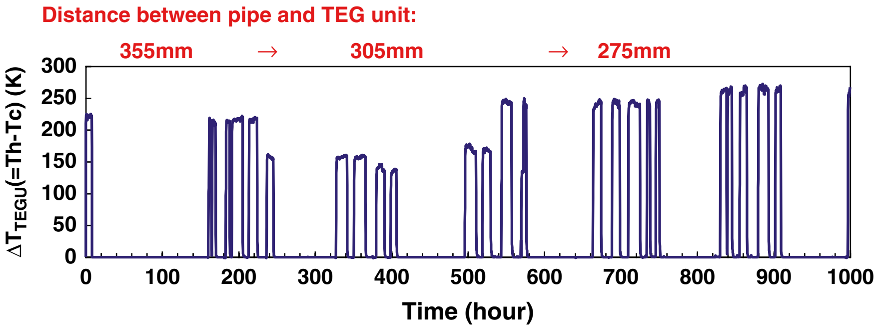

Fig. 17.5 One of the examples of the verification test data

Verification Tests

JFE started verification tests to generate electric power by using radiant heat from butt welded pipes in 2011. The performance of the TEG unit had been investigated under various operating conditions in steelworks. Figure 17.5 shows the results of the measured temperature difference $\Delta T_{\mathrm{TEGU}}(=T_{\mathrm{h}}-T_{\mathrm{c}})$. Here, ΔT_{TEGU} is the temperature difference of the heat collection plate (T_{h}) and the water cooled plate (T_{c}) of the thermoelectric generation unit.

When the welded pipe mill is under operation, the TEG unit is warmed up by radiant heat inducing a temperature difference, and the power output is generated by TEG unit.

The Eqs. (17.1) and (17.2) are the basic equation of thermoelectric generation:

$$Q_{\mathrm{a}} = \alpha_{\mathrm{e}} T_{\mathrm{hj}} I - \frac{1}{2} r_{\mathrm{e}} I^2 + K_{\mathrm{e}} \Delta T_{\mathrm{j}} \tag{17.1}$$

$$Q_{\mathrm{d}} = \alpha_{\mathrm{e}} T_{\mathrm{cj}} I + \frac{1}{2} r_{\mathrm{e}} I^2 + K_{\mathrm{e}} \Delta T_{\mathrm{j}} \tag{17.2}$$

where the 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_e is the internal electrical resistance, K_e is the thermal conductance, I represents the electric current [4], $\Delta T_j(=T_{hj}-T_{cj})$ is the temperature difference of thermoelectric element, T_{hj} is the hot side temperature, and T_{cj} is the cold side temperature. These equations are derived from the heat equation subject to the Peltier effect and Joule heating with boundary conditions of the hot side temperature and the cold side temperature.

The power generation output P_g is given by Eq. (17.3):

$$P_{\mathrm{g}} = Q_{\mathrm{a}} - Q_{\mathrm{d}} = \left(\alpha_{\mathrm{e}} \Delta T_{\mathrm{j}} - r_{\mathrm{e}} I\right) I = R_{\mathrm{L}} I^2 \tag{17.3}$$

where R_L is the external electric resistance.

Also, the maximum generation output P_{gmax} is given by Eq. (17.4).

$$P_{\mathrm{g\,max}} = \frac{1}{4} \frac{\left(\alpha_{\mathrm{e}} \Delta T_{\mathrm{j}}\right)^2}{r_{\mathrm{e}}} \tag{17.4}$$

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 maximum tolerance temperature. Therefore, it is very important to simulate T_{hj} for various conditions. In this system, the heat input Q_a is mainly the radiant heat from the pipe. The heat input Q_a is expressed by Eq. (17.5):

$$Q_{\mathrm{a}} = \varepsilon \cdot F \cdot \sigma \cdot A\left(T_{\mathrm{s}}^4 - T_{\mathrm{h}}^4\right) + h \cdot A \cdot \Delta T \tag{17.5}$$

where ε is the emissivity, σ is Stefan-Boltzmann constant, F is the view factor, T_s is pipe temperature, T_h is the hot side temperature of the thermoelectric generation unit, and h is heat transfer coefficient.

The view factor F is a function of the distance from the pipe to the TEG unit and it is inversely proportional to the distance. Therefore, the heat input Q_a becomes larger as the TEG unit approaches the pipe. With a larger heat input, the heat collection plate temperature rises and the temperature difference ΔT_{TEGU} increases.

Using the thermal resistance of TEG unit and Eqs. (17.1)–(17.5), the relationship between ΔT_{TEGU} and the distance from the pipe to the TEG unit is numerically investigated. The result is shown in Fig. 17.6. The experimental results are compatible with the simulation results.

Figure 17.7 shows the power output of TEGS units as a function of ΔT_{TEGU}. The measurements of the power output of the TEG units seem to confirm the simulated output. The TEG output increases with ΔT_{TEGU} and the thermoelectric generation system output is about 250 W when the ΔT_{TEGU} is 250 K.

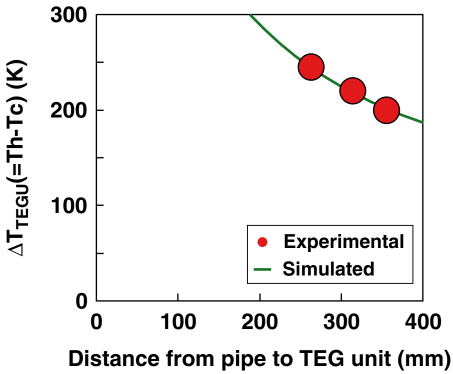

Fig. 17.6 Relationship between the distance from the pipe to TEG unit and the temperature difference ΔT_{TEGU}

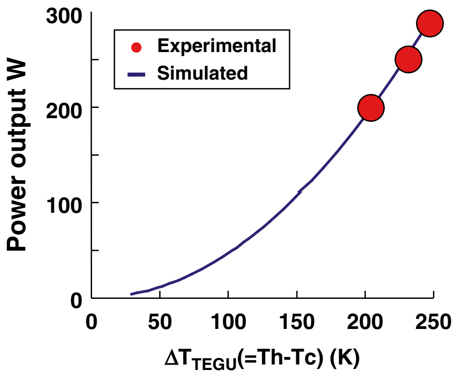

Fig. 17.7 Electric power output of TEG units as a function of ΔT_{TEGU}

Conclusion

A thermoelectric generation unit was tested in the butt welded pipe mill at the East Japan Works in the Keihin District of JFE Steel Corporation to recover waste heat. The thermoelectric generation unit which has 16 thermoelectric generation modules provides about 250 W when the temperature difference between the heat collection plate T_h and water cooled plate T_c at the thermoelectric generation unit is 250 K. The resulting electric output is a good fit between the simulation and the experimental data.

References

1. Kabeya K (2012) Symposium on technology of the waste heat energy (AIST), No. 2, p 67
2. KELK Ltd. (2009) http://www.kelk.co.jp/english/news/120419.html. Accessed 12 Sept 2013
3. Kaibe H, Kajihara T, Fujimoto S, Makino K, Hachiuma H (2011) Recovery of plant waste heat by a thermoelectric generation system. Komatsu Tech Rep 57(164):26–30
4. Uemura K, Nishida I (1988) Netsudenhandoutai to Sono Ouyou (a thermoelectric semiconductor and the application). Nikkan Kogyo Shinbunsya, Tokyo, pp 26–33