Influence of Heat Collection Plate Structure on Thermoelectric Generation Unit Performance for Radiant Waste Heat Recovery in Continuous Casting Process

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In recent years, environmental issues such as global warming and the energy resource depletion have become serious matters. Waste heat recovery can be one of the key technologies to solve these issues. Thermoelectric generator (TEG) is one of the promising technologies expected to play an important role for steel plant’s waste heat recovery, particularly radiant heat from steel products which had not been used yet efficiently. Despite the improved performances of thermoelectric materials, more effort on a TEG unit is needed to maximize TEG system performance. In optimizing the TEG unit performance, the influence of the surface shape of the TEG units has been investigated. Two types of the heat collection plate have tested. The first one was with a fin structure and the second one was with plain plate structure. Based on the results of the simulation and the experiments, it can be concluded that a better performance will be achieved by the TEG unit which has plain type heat collection plate because of larger total heat flux input to TEG modules of the TEG unit with plain type heat collection plate structure compared to the fin type heat collection structure.

KEY WORDS: exhaust heat; heat recovery; continuous casting; thermoelectric generator; heat collection plate; energy.

1. Introduction

In recent years there has been an increase in social awareness of issues related to the Earth’s environment, such as global warming, and there is a demand for efficient energy use, especially the efficient use of previously unused energy. The integrated steel works 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 as mentioned above. One of the key technologies to achieve the requirement is the waste heat recovery.

Thermoelectric power generation is technology designed to generate electric power from heat by taking advantage of the Seebeck effect which converts temperature differences of metals or semiconductors to electric voltage, and is one of innovative technologies for waste heat recovery. The thermoelectric generator (TEG) has a lot of advantages in energy conversion, for example, direct conversion of low-grade thermal energy such as waste-heat energy into high-grade electrical energy, no mechanical moving parts, wide range of operating temperature, scalability, compact, little noise, little vibration, lack of CO₂ emission during operation and long lifetime. These merits make TEG attractive for energy generation applications.

Furthermore, as steel works operate around the clock, constantly generating waste heat regardless of weather conditions, this system might have the potential to be able to supply low-cost electric power stably throughout the year. Therefore TEG is one of the promising technologies expected to play an important role for steel plant’s waste heat recovery, particularly radiant heat from steel products which had not been used yet efficiently. JFE Steel Corporation (JFE) implemented a 10-kW-class grid-connected TEG system at JFE’s continuous casting line with KELK Ltd., and started verification tests to generate electric power using radiant heat from continuous casting slab at the end of fiscal year 2012.¹ ²

A number of studies have addressed the TEG systems as a thermal energy recovery method in automobiles.³ ⁶ According to previous research achievements, it can be concluded that a high-efficiency heat exchanger is necessary to increase the amount of heat energy extracted from the exhaust gas. Continuous efforts have been made to maximize their efficiency, with methods mainly concentrating on changing the
structure of the heat exchanger and introducing different heat transfer enhancement measures. Although a lot of types of heat exchanger for exhaust gas have been proposed,7–16) little has been reported on waste heat recovery, such as radiant heat from steel products.

The purpose of the present study is to clarify better surface shape of a TEG unit for radiant waste heat. The TEG unit installed at JFE’s continuous casting line is consists of a heat collection plate, TEG modules and a water cooling plate. TEG modules were sandwiched between the heat collection plate and the water cooling plate by a spring structure. The heat collection plate of the TEG unit was heated by radiation heat from continuous casting slab, and the low temperature side of the TEG unit was cooled by water. A computational fluid dynamics (CFD) model of the heat exchanger was constructed to evaluate the influence of the heat collection plate structure on TEG unit for radiant waste heat recovery. Two types of the heat collection plate have tested. The first one was with fin structure, for example, which was applied at Komatsu Ltd., Awazu plant used heat of a flame burner,17) and the second one was with the plain plate structure. Based on the results of the simulation and the experiments, the influence of the surface shape of the TEG unit’s performance has been investigated.

2. Models and Conditions

2.1. Geometry Model

The geometry model of the TEG system is based on the verification test at JFE’s continuous casting line, which can cast a 1.7 m wide slab continuously. The upper side of the TEG unit was equipped at the position of 1 993 mm above the hot slab. Each model is shown in Figs. 1 and 2 for the heat collection plate with fin structure and with plain plate structure. In those models, the size of TEG unit is 88 mm × 88 mm, and the quarter models using symmetry planes are taken as shown in Figs. 1 and 2. TEG module is sandwiched between the heat collection plate and water cooling plate. The properties of the TEG module were used as the average values, where the TEG module is assumed as the uniform plate structure in this model. Tables 1–5 show the dimensions and material properties used in experiments and simulations. In the heat collection plate with fin structure.

2.2. CFD Model

All CFD simulations were carried out using FLUENT 14.0. The computational meshes shown in Figs. 3 and 4 were composed of a structured grid with multiblock arrangement. More than 700 thousands grid points were created by GAMBIT 2.4. In this model, to provide an accurate estimation near the TEG unit, the number of the grid points around the TEG unit were larger than the other area. The renormalization group (RNG) k–epsilon model, where k is the turbulent kinetic energy and epsilon is the dissipation rate of turbulent kinetic energy, was used to simulate the turbulent airflow field. The surface to surface (S2S) model was used for radiation heat transfer. Boundary conditions were applied in the CFD simulation as shown in Table 1.

To simplify the modeling, a few hypothetical conditions were applied as follows: Firstly, thermal and flow effects are in the steady state, and no phase changes occur in the cooler. Secondly the coolant is regarded as an incompressible Newtonian fluid. Numerical modeling of thermoelectric systems was added by UDF (user defined functions).
Table 1. Dimensions and material properties used in simulations.

| Slab | Cross section: 1.7 m × 0.25 m | Distance from heat collection Cu plate: 1.95 m (fin structure), 1.96 m (plain plate structure) | Temperature: 1 323 K, 1 373 K and 1 429 K, Emissivity: 0.87 |
|------|-----------------------------|---------------------------------|-----------------------------------------------------|
| Heat collection Cu plate | Type A: Fin structure size: 0.088 m × 0.088 m × 0.025 m, Fin size: 0.004 m × 0.004 m × 0.010 m, Pitch between fins: 0.008 m, The number of fin: 11 × 11. | Thermal conductivity: 400 W/m/K, emissivity: 0.95 |
| | Type B: Plain plate structure size: 0.088 m × 0.088 m × 0.015 m | Thermal conductivity: 400 W/m/K, Emissivity: 0.95 |
| TEG module | Size: 0.044 m × 0.044 m × 0.0042 m × 4 elements (symmetry plane) | Power output: $1/4 \cdot (\Delta T) / \rho \cdot c_p \cdot M_w / T$ |
| | $\lambda$: 1.5 W/m/K, $\epsilon$: 4.2 × 10⁻³ m, $\alpha$: 2.5 × 10⁻¹ m² |
| | $T_h$: Hot side temperature of the thermoelectric element, $T_c$: Cold side temperature of the thermoelectric element, $Z$: Figure of merit K⁻¹ |
| | $Z = (a(T_h + T_c)/2)^2 + b(T_h + T_c)/2 + c)/d$ |
| | $a$: $2.14 \times 10^{-3}$, $b$: $1.8 \times 10^{-5}$, $c$: $4.0 \times 10^{-4}$, $d$: $2.4$ |
| Water cooling Cu plate | Size: 0.088 m × 0.088 m × 0.014 m | Thermal conductivity: 400 W/m/K, emissivity: 0.1 |
| | Heat transfer coefficient: 2 900 W/m²/K, Water temperature: 303 K |
| Thermal resistance between Cu plate and TEG module | $0.05 \times 10^{-3}$ m, 0.8 W/m/K |
| Ambient temperature | 303 K |

Table 2. Properties of the air used in simulations.

| Air fluid | Molecular weight | 28.85 kg/kmol | Equation of state of ideal gas: $\rho = \rho_{ref}(R/M_w)T$ |
|-----|-----------------|---------------|--------------------------------------------------|
| Density | kg/m³ | 101 325 Pa, $R$: 8.314 m²·kg/s²/K/mol, $M_w$: 28.966 kg/mol |
| Specific heat | J/kg/K | FLUENT Database: $100 \text{ K} \leq T < 1000 \text{ K}$ |
| | | $C_p(T) = A_0 + A_1 T + A_2 T^2 + \ldots + A_8 T^8$ |
| | | $A_0 = 1 161.482$, $A_1 = -2.36882$, $A_2 = 0.014855$, $A_3 = -5.03 \times 10^{-3}$, $A_4 = 9.33 \times 10^{-4}$, $A_5 = -1.11 \times 10^{-10}$, $A_6 = 6.54 \times 10^{-14}$, $A_7 = -1.57 \times 10^{-17}$ |
| | | $1000 \text{ K} \leq T < 5000 \text{ K}$ |
| | | $C_p(T) = B_0 + B_1 T + B_2 T^2 + \ldots + B_8 T^8$ |
| | | $B_0 = -7 069.81$, $B_1 = -33.70605$, $B_2 = -0.05813$, $B_3 = 5.42 \times 10^{-3}$, $B_4 = -2.94 \times 10^{-5}$, $B_5 = 9.24 \times 10^{-12}$, $B_6 = -1.57 \times 10^{-15}$, $B_7 = 1.11 \times 10^{-19}$ |
| Viscosity coefficient | Pa·s | FLUENT Database: $\mu = 2.67 \times 10^{-5}(M_w T)^{1/2}/\sigma^2$ |
| | | $\Omega_2(T) = \Omega_2(T_0) T = T(\sigma/k_0)$, $\sigma$: 3.711 × 10⁻¹⁰ m, $\epsilon/k_0$: 78.6 K |
| Thermal conductivity | W/m/K | FLUENT Database: $k = 15/4 R/M \mu [4/15 C_p M_w/R + 1/3]$ |
The power generation output $P_g$ is given by Eq. (3).

$$P_g = Q_a - Q_d = (\alpha_j \Delta T_j - r_e I) I = R_e I^2$$

where $R_e$ is the external electric resistance.
Also, when \( r_c = R_z \), the maximum generation output \( P_{\text{gmax}} \) is given by Eq. (4).

\[
P_{\text{gmax}} = \frac{1}{4} \left( \frac{a_e \Delta T^j}{r_c} \right)^2 = \frac{1}{4} \cdot ZK_e \cdot \frac{\Delta T^2}{r_c} \quad \text{............ (4)}
\]

where \( \Delta T^j \) is the junction temperature difference \( T_h^j - T_c^j \).

To obtain high power generation output, a large temperature difference \( \Delta T^j \) is required. On the other hand, \( T_h^j \) must remain the TEG’s maximum tolerated temperature of 553 K. In this system, as stated above, \( Q_a \) is the receiving heat into the surface, and it consists mainly of the radiated heat from the slab. \( Q_a \) is expressed by Eq. (5). The first term relates to the radiated heat and the second term relates to the heat transfer, and the total heat flux \( q_{\text{rad}} \) relates to the heat flux by radiation \( (q_{\text{rad}}) \) and convection heat transfer \( (q_{\text{conv}}) \).

\[
Q_a = \varepsilon \cdot F \cdot \sigma \cdot A \left( T_h^i - T_c^i \right) + h \cdot A \cdot \Delta T \quad \text{............ (5)}
\]

where \( \varepsilon \) is the emissivity, \( \sigma \) is the Stefan-Boltzmann constant, \( F \) is the view factor, \( T_h^i \) is the surface temperature of slab, \( T_c^i \) is the hot-side temperature of the TEG unit, \( A \) is the area of the heat collection plate of the TEG unit, \( \Delta T \) is the temperature difference between \( T_h^i \) and \( T_c^i \) (the ambient temperature) and \( h \) is the heat transfer coefficient. \( h \) can be derived as a function of the view factor \( F \) of the system, the current \( I \) and the thermal conductivity of the heat collection plate. Using Eqs. (1)–(5), the temperature of the TEG unit and \( P_{\text{gmax}} \) were numerically investigated for several experimental conditions. When the continuous casting line is in operation, the TEG units are warmed by radiant heat, a temperature difference is generated, and power is output by the TEG units. The view factor \( F \) depends on the orientation of the small areas \( dA_1 \) and \( dA_2 \) and the distance between them \( (r) \). \( F \) is given by Eq. (6).

\[
F = \int \int \cos \phi_1 \cos \phi_2 \frac{A_1 \pi r^2}{dA_1 \cdot dA_2} \quad \text{................. (6)}
\]

where \( F_1 \) and \( F_2 \) are the angles between the unit normals to the areas and \( r \) is the distance between the two areas, as shown in Fig. 5.

The view factor \( F \) in Eq. (5) is a function of the slab width and the distance from the slab to the TEG units and is inversely proportional to the distance. So, the heat input \( Q_a \) becomes larger as the slab becomes wider. Therefore the power output of the TEG units increases with the slab width.\(^2\)

3. Experiments

A verification test was carried out at JFE’s continuous casting line. Figures 6 and 7 show an illustration and photograph of the TEG system installed at JFE’s continuous casting line. Figure 8 shows a photograph and schematic illustration of the TEG units array. The TEG system has 56 TEG units. Each TEG unit is containing 16 TEG modules, and all 16 TEG modules were connected in series in each TEG unit.

The size of bismuth telluride TEG module, made of 161 pairs of n- and p-type thermoelectric elements, is 50 mm × 50 mm × 4.2 mm.\(^2\) Figure 9 shows the conversion efficiency and the power output density plotted as a function of hot-side temperature of TEG module. Its maximum power output density of a TEG module is 9.6 kW/m\(^2\) (power output: 24 W), with maximum conversion efficiency of 7.2%, when the hot-side and cold-side temperatures are 553 K and 303 K, respectively.\(^17\) Because its operating temperature range is 553 K at high-temperature side, 523 K or less is taken in nominal operation. It was 423 K at maximum at low-temperature side.

Each TEG module was sandwiched between the heat collection plate and water cooling plate by a spring structure, meaning that an almost constant pressure was applied to the modules, even when a temperature difference was generated. The pressure on the TEG unit was set at 1 MPa as a criterion, with a cooling water flow rate of 1.7 \( \times \) \( 10^{-4} \) m\(^3\)/s per TEG unit. The size of the heat collection plate was 400 mm × 280 mm. Copper was used for the heat collection plate and water cooling plate. The heat collection plate was blackened using surface treatment by electroless nickel plating to yield an emissivity of about 0.95.\(^17\)
Figure 10 shows the schematic illustration of the laboratory test bench setup for power output evaluation of TEG unit using an infrared heater. Thermocouple is inserted into hole on the side face of heat collection plate, which is controlled in the range between 518 K and 523 K. Also, the temperature of inlet cooling water is 298–303 K and flow rate is $1.5 \times 10^{-4} \text{ m}^3/\text{s} - 1.7 \times 10^{-4} \text{ m}^3/\text{s}$. The power output of TEG unit was measured for 5 times under the condition of $I = 2.5 \text{ A}$, that is optimum current condition. The measured voltages were 103.5 V, 103.3 V, 107.2 V, 104.2 V...
and 100.9 V, and the power outputs were 259 W, 258 W, 268 W, 261 W and 252 W. Taking the thermal resistance of the both heat collection and water cooling plate and thermal contact resistance between the thermoelectric module to heat collection plate and to water cooling plate into account, the temperature difference of thermoelectric module in TEG unit is estimated to be approximately 200 K. This measurement condition is close to be 503 K at hot-side temperature in Fig. 9 and the power output density TEG module is 6.4 kW/m² (power output: 16 W). Therefore, we estimated the power output per TEG unit is over 250 W, and the measured results are well consistent with the estimation.1)

The size of the TEG system is 3.56 m × 2.21 m, with a distance between the slab and the TEG units of about 1.95 m, as listed in Table 1. The heat collection plates of the TEG units were heated by radiant heat from continuous casting slab. As shown in Fig. 8, the heat collection plates of TEG units were arranged in symmetrical attitudes. The influence of the surface shape of the TEG units has been investigated under various operating conditions at the continuous casting line. The surface temperature of slab is about 1 073‒1 273 K. Other specifications of the #3 continuous casting machine (The Keihin District of JFE Steel East Japan Works) are shown in Table 5.

4. Results and Discussion

To investigate the influence of the surface shape of the TEG units, heat balances and the power output density of TEG units were calculated based on the above-mentioned

![Simulation results for heat flux distribution of heat collection plate: (a) upper surface, (b) side, (c) lower surface and (d) side surface of fins. (Online version in color.)](image-url)
models and conditions. The heat flux distribution examples for the heat collection plate with fin structure and the heat collection plate with plane plate structure are shown in Figs. 11, 12, and 13. In the analysis area, the temperature near the heat source, heated slab, is high, but the ambient temperature around the TEG unit except a heat collection plate is approximately 303 K. In other words, ambient temperature around the TEG system is lower than heat collection plate temperature. Therefore, the heat collection plate is cooled by a natural convection.

Figure 14 shows the simulated results of the heat flux to the heat collection plate by radiation \( q_{rad} \) and convection heat transfer \( q_{ht} \), and the total heat flux \( q_a \) was evaluated by this difference under the same slab temperature condition. The results suggest that the \( q_{rad} \) showed positive values, while the \( q_{ht} \) showed the negative values. Therefore, the heat collection plate was heated by radiation \( q_{rad} \) and cooled by convection heat transfer \( q_{ht} \). Heat input to the heat collection plate by radiation using fin structure is larger than that of plain plate structure, but heat output from the heat collection plate by convection heat transfer using fin structure is larger than that of plain plate structure. In total, the heat input to the TEG module using fin structure is smaller than that of plain plate structure.

Figure 15 shows the simulated results of the TEG module’s total heat flux \( q_a \), the heat flux flowing out at the cold surface \( q_d \) and the power output density \( p \). It was shown that the higher total heat flux \( q_a \), the higher the hot-side junction temperature \( T_{hj} \), and the power output increased accordingly. The power output of TEG module using fin structure is smaller than that of plain plate structure. However the effect of fin structure might not be clear, so the effect of fin structure and plain plate structure was showed the following figure.

Figure 16 shows the example of TEG unit’s power output distributions obtained by verification test, which shows the slab width from 1.3 m to 1.7 m. The frequency means the number of measurement of TEG unit’s power output. The average power outputs of TEG unit with plain plate structure and fin structure are 1.37 kW/m² and 1.12 W/m², respectively. It is found that the power out of the heat collection plate with the plain plate structure is larger than that with the fin structure.

Figure 17 shows the experimentally measured and simulated TEG unit’s power output relationship between the heat collection plate with the fin structure and with the plain plate structure. These plots were pointed in the average value of the experimental data simultaneously obtained in each surface structure of the TEG unit. As shown in Fig. 16, the power output of TEG unit of the heat collection plate
with the plain plate structure is larger than that with the fin structure, and the experimentally measured results tend to be similar to the simulated values.

The heat flux to the heat collection plate surface by radiation had positive values. Even if the tip of the heat collection plate surface is heated by radiant heat, the heat needs to pass through the heat collection plate before it is taken into the TEG module. On the other hand, the heat flux to the heat collection plate surface by convection heat transfer had negative value, because the ambient temperature around TEG system is lower than heat collection plate surface temperature. Therefore, the heat collection plate is cooled by a natural convection. Even if the heat input to
the heat collection plate by radiation using fin structure is larger than that of plain plate structure, the heat output from the heat collection plate by convection heat transfer using fin structure is larger than that of plain plate structure. In total, the heat input to the TEG module using heat collection plate becomes larger than that with fin structure. Furthermore, the TEG unit’s total heat flux becomes larger when using plain plate structure heat collection plate. For greater heat input, the heat collection plate temperature rises and the temperature difference $\Delta T$ increases. Therefore, the power output of the TEG units with plain plate structure heat collection plate increases.

From the above simulated and experimentally measured results and discussion, it can be concluded that a better performance will be achieved by the TEG unit which has plain type heat collection plate.

5. Conclusions

The TEG test system was installed in the #3 continuous casting machine (The Keihin District of JFE Steel East Japan Works) for recovering waste heat from the continuous casting slab. In this work, two different configurations on the surface shape of the TEG unit’s heat collection plate were proposed and analyzed. The first type was heat collection plate with the fin structure and the second one was heat collection plate with the plain plate structure. Regarding radiant heat from the continuous casting slab, the results of the simulation and the experiments, the experimentally measured results tend to be similar to the simulated values, and it can be concluded that a better performance will be achieved by the TEG unit which has plain type heat collection plate.

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Fig. 16. Experimental results of the TEG unit power output distributions of the heat collection plate with plain plate structure and fin structure.

Fig. 17. Relationship between power output of TEG unit of the heat collection plate with fin structure and with plain plate structure. (Online version in color.)