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Thermoelectric Generation Technology Using Waste Heat from Integrated Steelworks

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Abstract:

The steel 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 steel industry is strongly required to develop new technologies for further energy conservation in view of energy security, high and volatile energy prices and CO_2 reduction. Waste heat recovery can be one of the key technologies to solve these issues. Thermoelectric generation 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 efficiently yet. This paper describes the thermoelectric generation system using waste heat in steelmaking process.

1. Introduction

In the iron and steel industry in Japan, the popularization of energy saving technology and equipment was greatly advanced by the introduction of large-scale energy saving equipment such as the continuous casting machine and CDQ (Coke Dry Quenching) through the two Oil Crises of 1970's, and introduction of technologies and equipment that are on the level of practical application has now reached substantially 100%. As a result, the Japanese steel industry leads the world in energy efficiency (energy intensity required to produce 1 ton of steel)[1].

However, from the viewpoints of energy security and the high and volatile energy prices of recent years, extremely large expectations are placed on technologies which contributes to further energy saving. Among them, heat recovery technology is one of the key technologies for effectively utilizing unused waste heat in steel mills to contribute to higher efficiency of energy utilization.

1.1 Thermoelectric Power Generation Technology Using Waste Heat in Steel Works

Waste heat generated in steel works is an important energy source, and many types are already recovered and utilized. However, about 30% of waste heat is still left unused and is not effectively utilized[2]. From the viewpoint of economic rationality, it is difficult to recover this waste heat with existing technology due to the small scale and dispersion, large fluctuations, and low generation temperature of the remaining sources of waste heat; that is, waste heat recovery is extremely difficult in terms of facilities and technology. In the steel manufacturing process, there are many cases in which hot steel plates and other steel materials are conveyed while heat dissipates into the atmosphere. After an actual-machine test with a small-scale thermoelectric generator of several 100 W class utilizing radiant heat dissipated by hot tubes at a forged pipe plant[3], JFE Steel focused on the radiant waste heat dissipated by hot slabs (thick semi-finished steel for rolling) during continuous casting of steel, and developed a large-scale thermoelectric power generation technology of 10 kW class as a technology for effectively utilizing unused waste heat[4].

1.2 Overview of Thermoelectric Conversion

In general, all solid metals and semiconductors have the property of thermoelectric conversion as long as they are materials that conduct electricity. However, this property is remarkable in only a few materials, and such materials in particular are called thermoelectric conversion materials. Thermoelectric conversion is an energy conversion method in which heat and electricity

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are converted by using the characteristics of materials, and can be classified into the two utilization methods of power generation and heat transfer (cooling or heating). Temperature difference power generation is caused by the phenomenon called Seebeck effect, in which thermoelectric power is generated by a temperature difference between two metal or semiconductor materials which are in contact, which means that heat energy can be converted to electric energy. On the other hand, in cooling or heating, electric energy can be converted to thermal energy by the phenomenon of heat transfer by passing a current, which is called the Peltier effect.

1.3 Thermoelectric Power Generation Technology

As mentioned above, thermoelectric power generation technology is one of the innovative technologies that can effectively utilize heat by using the Seebeck effect. The features of thermoelectric power generation which can convert heat to electricity include (1) direct conversion of heat energy to electric energy, (2) a simple and compact structure without moving parts, (3) no noise, vibration or CO_2 emission in power generation and (4) power generation corresponding to various heat sources and temperatures by appropriate selection of the materials. Considered from the viewpoint of waste heat utilization, this method can be applied effectively even to small-scale and dispersed waste heat sources, and the power generation system can be expanded gradually by partially utilizing waste heat. Thermoelectric power generation has been actively researched as the simplest system of direct energy conversion in various countries around the world, and has already been used practically as a power source for space development and in remote areas. There are also examples of commercialization of wristwatches powered by the temperature difference between the user's body temperature and the ambient air, and thermoelectric power generation pots using fire, such as burning firewood, etc. during disasters, as a heat source. However, large-scale trials for industrial use have not been reported.

Since steel works operate 24-hours-a-day and waste heat always exists during operation, it is possible to obtain stable electric power throughout the year, regardless of the time of day and weather. If this technology is applied to various types of factory waste heat, it is expected to be effective for energy saving and reduction of CO_2 emissions.

2. Demonstration Test of Thermoelectric Power Generation Technology in Steelmaking Process

In JFE Steel, the first phase of 10 kW class thermoelectric generation (TEG) experiments was carried out from 2011 to 2013 as a technology for effectively utilizing the radiant heat dissipated by hot slabs in the continuous casting of steel. Afterwards, after various technology developments, actual-machine verification experiments were carried out from 2017 to 2019 as the second phase (**Figure 1**, **Table 1**)[5].

2.1 Thermoelectric Power Generation Module

In the thermoelectric power generation (TEG) module, p-type and n-type thermoelectric elements are alternately joined via electrodes. These elements are thermally connected in parallel and electrically connected in series, and are sandwiched by an insulating substrate. By creating a temperature difference between the upper and lower substrates of this module, it is possible to generate power corresponding to the temperature difference by the Seebeck effect. The TEG modules are combined in series and parallel to construct a TEG

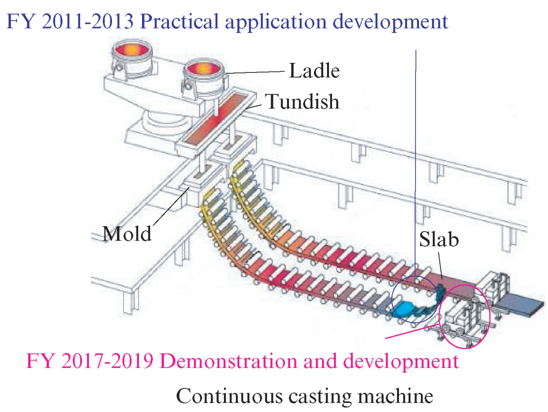
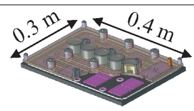
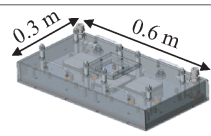


Fig. 1 Schematic illustration of thermoelectric generation (TEG) system installed in the JFE's continuous casting line (East Japan Works (Keihin))

Table 1 Specification of 10 kW thermoelectric power generation system

	FY 2011-2013 Practical application development	FY 2017-2019 Demonstration and development
Total TEG unit area	7.9 (m^2)	3.0 (m^2)
Power generation density	0.2 (W/cm^2)	0.45 (W/cm^2)
TEG unit		

system. Since the maximum working temperature of TEG module[6] used here is 280°C in the high temperature side electrode part, and the normal working temperature is 250°C, this system can be used in the temperature range of unused industrial waste heat. The maximum power generated is proportional to the square of the temperature difference (ΔT^2) between the hot side and the cold side, which means it is important to ensure a large temperature difference in order to obtain a large output. However, it is very important to predict the high temperature side temperature under various conditions because the high temperature side temperature of the thermoelectric element must be below the heat resistance temperature.

2.2 Thermoelectric Power Generation Unit

The modules described above were integrated in a single unit and used in a demonstration test of thermoelectric power generation in the steel manufacturing process. One thermoelectric power generation unit[3] is composed of a heat receiving plate, TEG modules, a water cooling plate and other components.

The configuration of the TEG units used in the first phase was as follows: 16 TEG modules (about 50 mm×50 mm×4.2 mm) connected in series were arranged between the heat receiving plate and the cooling plate, and were sandwiched with a pressure of about 1 MPa by pressing springs so as to maintain a good state of contact. The surface of the heat receiving plate was blackened to improve heat collection efficiency. The cooling water quantity was about 10 L/min, and the low temperature side was cooled efficiently so as to maintain the temperature difference.

In the second phase, an actual-machine demonstration test was conducted using lower cost, higher generated output TEG modules. The modules were improved for weight reduction, soaking technology, etc. In addition, the conventional method of connecting the TEG modules by wiring was changed, and the wasted space due to the use of wiring to connect the modules was reduced by integrally molding large modules. As a result, the density of the TEG elements in the thermoelectric power generation equipment increased, and the power generation power density was improved from the conventional 0.2 W/cm^2 to 0.45 W/cm^2.

2.3 Thermoelectric Power Generator

Although the core of the thermoelectric power generation system utilizing waste heat is the TEG module, a heat management technology which efficiently collects the heat from the high temperature heat source (waste heat source) by a heat exchanger, supplies that heat to the TEG modules, creates electric power, and discharges the remaining heat quantity to the low temperature heat source is very important for practical recovery of the waste heat as electricity. Moreover, since the electric power obtained by thermoelectric power generation is DC, an electric power management technology that can efficiently utilize that power for the user's required application is also needed. Concretely, since factory waste heat is generated in various places, a system shape corresponding to each waste heat location is necessary. Therefore, it is necessary to predict the heat flow to the system and the power generation, based on how the system is to be installed at the waste heat source, and what kind of heat flow will exist when it is installed.

In the thermoelectric power generation system utilizing the radiant heat from continuous casting slabs installed in this project, the heat input from the high temperature heat source originates from the radiant heat from the slabs, etc.

The image and a feeling of the sizes of the TEG module, the TEG unit and the TEG system in the first phase are shown in **Figure 2**[7].

The temperature and power of the TEG unit were determined by an analysis under various operating conditions, and the specification of the thermoelectric equipment was determined. The exterior of the thermoelectric power generation equipment installed in the continuous casting facility at JFE Steel's East Japan Works (Keihin) is shown in **Photo 1**[7]. Here, 56 panels of TEG units (comprising 896 TEG modules) are arranged at a position about 2 m above the horizontal

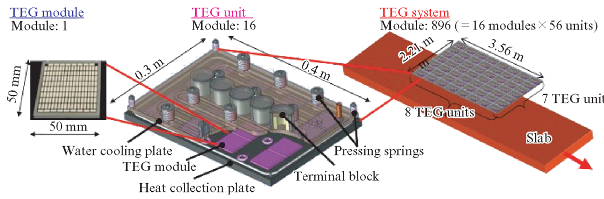


Fig. 2 Schematic illustration of TEG module, TEG unit and TEG system

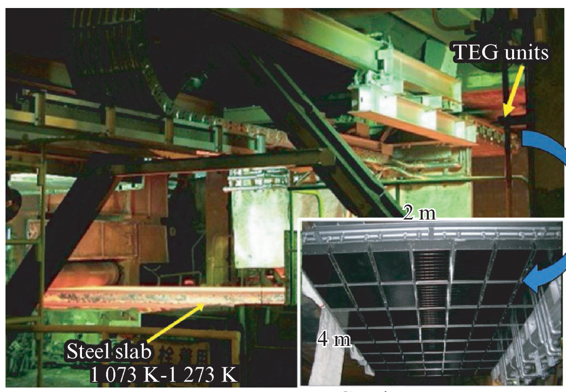


Photo 1 Appearance of a thermoelectric power generator installed in a continuous casting machine

part of the slab where casting proceeds and the slab is exposed. This TEG generator generates power from the radiant heat emitted from the slab, which has a surface temperature of about 800°C to 1 000°C and an area of about 7.9 m^2 (about 2 m in width x 4 m in length). The generated output is converted from DC to AC by a power conditioner with a MPPT (Maximum Power Point Tracking) control function, and then connected to the existing distribution line of the steel plant (system interconnection) and used as a part of the air conditioning in the steel works. The opposite side of the TEG unit from the slab is water-cooled to produce the temperature difference. Since nothing is in contact with the slab, including water, and the TEG unit is simply suspended over the slab, the cooling condition of the slab is substantially unaffected.

The basic concept in the second phase was the same as in the first phase. The equipment output specification was prepared for a 10 kW TEG system, and the temperature and output were obtained analytically under various operating conditions based on the change in the specification of the TEG unit to determine the specification of the thermoelectric equipment. Concretely, 18 TEG units (comprising 36 TEG modules each) were arranged at a position about 0.4 m above the slab, and a slab cutting machine equipped with the TEG system was used.

2.4 Thermoelectric Power Generation Test

The analysis results and results of the power generation demonstration test of the output of the first-phase TEG system are compared in **Figure 3**. Thermoelectric generation increases as the slab temperature and slab width increase, and the analytical and experimental values are in good agreement. The demonstration test of thermoelectric power generation at this scale is the first in the world.

Next, considering the slab size and the relative positions of the TEG unit and the slab, the height of the TEG unit (distance from the slab) was modified appropriately in the width direction. **Figure 4** shows the power generation output per TEG unit in the slab width direction for the conventional arrangement and the arrangement after optimization, together with the analysis results and the power generation demonstration test results (slab width: 1.5 m, slab temperature 925°C). Power generation output in the width direction was improved by reducing the distance between the TEG unit and the slab at the width edge part by 0.49 m, as the analysis showed, and an output improvement result of 1.4 times was obtained at the width edge part.

In addition, some of the units were removed replaced at the time of the remodeling (due to steel

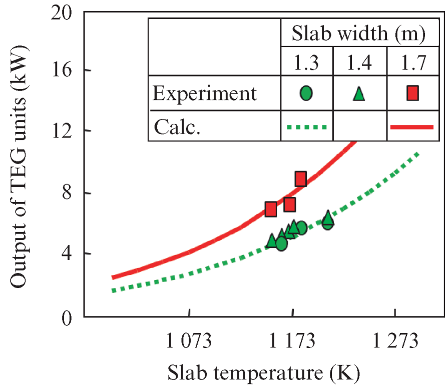


Fig. 3 Slab temperature and thermoelectric power system output (Parameters: slab width 1.3 m, 1.7 m)

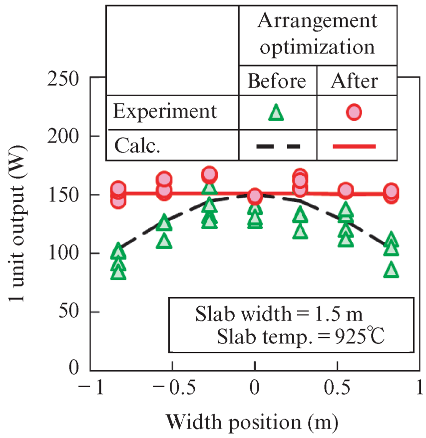


Fig. 4 Power output per thermoelectric generation unit in the width position (conventional arrangement and optimized arrangement)

works dust after approximately 4 500 hours and installation in a high humidity atmosphere environment), and and a durability evaluation was carried out, including an investigation of the interior of the units. Although there was the dirt in the TEG units, it was found that there was no remarkable damage and no foreign matter in any of the 28 units investigated. Module failure occurred in some units, but the problem was that there were some metal parts in the insulation board, which is a component of the TEG modules, and a countermeasure has already been taken. In addition, although some units showed a decrease in power output, this seems to have been caused by separation between the solder/diffusion prevention film/element due to thermal stress and a rise in module resistance, which can be solved by improving the quality of the diffusion prevention film (countermeasure by the TEG module manufacturer).

As described above, a TEG technology was developed, and a TEG experiment was carried out with an actual machine. The results confirmed that the actual values agreed with the values predicted in advance, and a durability evaluation of the existing TEG unit was also carried out. In addition, the height position of the TEG units was optimized, and good results were obtained.

Although the cost of TEG systems is high, the following countermeasures for this problem can be considered:

① Reduction of the cost of the TEG units
② Increased output per installed area and reduction of the cost per unit output by improving power generation output
③ Reduction of equipment costs by packaging the thermoelectric equipment, considering the entire process from production to installation

In the second phase, a demonstration test using a TEG unit with low cost and high power generation output was carried out. With this TEG unit, total generated output was 10 kW, power density was 0.45 W/cm^2 and good results for durability were obtained, as there was no deterioration of output after 1 500 hours. However, in a considerable number of TEG units, ground faults and short circuits occurred due to the effect of moisture intrusion into the units, and it was found that the countermeasures were a problem from the viewpoints of reliability and durability. That is, in this development, we were able to achieve certain results in terms of power generation output and durability, and on the other hand, we were able to identify problems for full-scale commercialization, such as long-term high-temperature durability and the cost aspects of TEG unit sealing parts[5]. In order to reduce the cost of thermoelectric power generation, as mentioned above, we will make earnest efforts to develop an inexpensive TEG system that can realize a large amount of power generation by high power density and a high operation rate.

3. Conclusion

As one energy saving technology development utilizing the unused waste heat of steel works in the iron and steel industry, this paper described a demonstration experiment using a newly-developed thermoelectric power generation technology. In the future, we will continue to contribute to global environmental conservation through the development of technologies that contribute to further energy conservation.

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