Development of Heat Recovery System from Steelmaking Slag†

TOBO Hiroyuki[*1]   SHIGAKI Nobuyuki[*2]   HAGIO Yuki[*3]

Abstract:

JFE Steel has been developing a technology of sensible heat recovery from steelmaking slag as one of the themes in Incorporated Administrative Agency New Energy and Industrial Technology Development Organization (NEDO) project "Environmentally Harmonized Steelmaking Process Technology Development (COURSE50)." A unique process has been proposed. By using twin cooling rolls, molten slag is solidified into the form of plates, which then filled in a chamber. Sensible heat of the sheet-shaped slag is recovered by a heat exchange process. A pilot plant for proof-of-concept experiments was constructed and the validity of the proposed process has been verified by showing that the heat recovery ratio is over 30%.

1. Introduction

Since the fiscal year (FY) 2008, Japan's integrated steelmakers have been engaged in a research and development project called "COURSE50 (CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50)". This project is commissioned by Incorporated Administrative Agency New Energy and Industrial Technology Development Organization (NEDO) with the aim of achieving a substantial reduction in CO_2 generated from steel works[1)]. In the chemical absorption method, which is under development as a technology for CO_2 separation, thermal energy is necessary in order to separate CO_2 from the absorbent liquid[2)]. Recovering and supplying unused sensible heat and waste heat in the steel works is one of the targets of COURSE50. High temperature molten steelmaking slag is one form of unused sensible heat/waste heat. Its temperature usually reaches more than 1 200°C. In the COURSE50 Project, JFE Steel is in charge of developing a technology for recovering the sensible heat of this steelmaking slag in the process of producing slag products from steelmaking slag.

The main challenge of this development is to recover sensible heat from the slag efficiently in spite of its low thermal conductivity. For this purpose, we proposed a process in which sheet-shaped slag is produced continuously by a twin roll method and in which heat exchange with air occurs in a packed bed. The aims of the process are to obtain a heat recovery ratio of 30% or more and to be able to recover high temperature gas at a temperature of 140°C or higher. A pilot test plant of near-actual scale was constructed, and an experiment on sensible heat recovery from steelmaking slag was performed. The following reports the results of the development for heat recovery from steelmaking slag during the first step of COURSE50.

2. Development of Continuous Solidification Process for Steelmaking Slag

2.1 Outline of Twin Roll Type Continuous Slag Solidification Pilot Plant

The twin roll type continuous slag solidification pilot plant is illustrated in **Photo 1**. A schematic diagram of the plant and the equipment specification are shown in **Fig. 1** and **Table 1** respectively. The plant comprises two rolls which continuously solidify the slag, a slag

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[*1] Senior Researcher Deputy General Manager,
Slag & Refractries Res. Dept.,
Steel Res. Lab.,
JFE Steel


[*2] Senior Researcher Deputy Manager,
Environmental Process Res. Dept.,
Steel Res. Lab.,
JFE Steel


[*3] Staff Assistant Manager,
Plant Engineering Dept.,
East Japan Works (Chiba),
JFE Steel

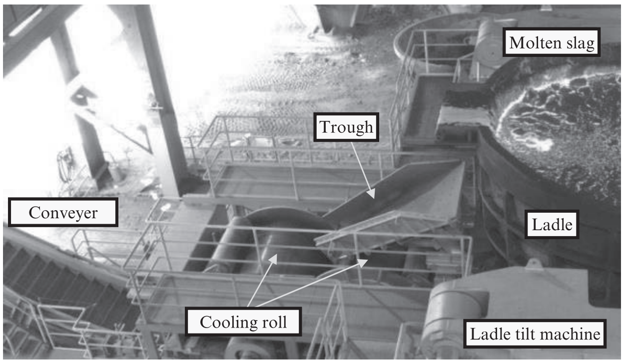


Photo 1 View of twin roll type continuous slag solidification pilot plant

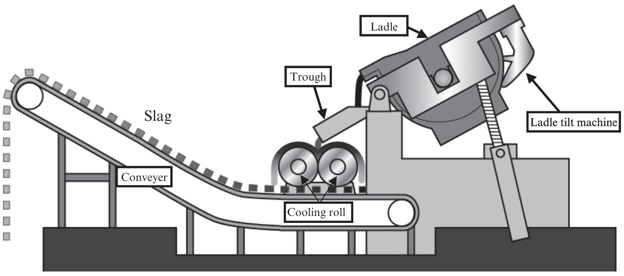


Fig. 1 Schematic diagram of twin roll type continuous slag solidification pilot plant

Table 1 Specification of twin roll type continuous slag solidification pilot plant

Equipment	Specifications	
Cooling roll	Dimensions	Φ1.6 m×W1.5 m
	Number of roll	2
	Material	Cu
	Rotation speed	Max. 20 rpm
	Cooling water flow rate	125–130 m^3/h·roll
Ladle tilt machine	Tilt speed	Max. 65°/min
	Load	Max. 140 t
Conveyer	Dimensions	W1.3 m×L14.5 m
	Lifting height	5.5 m
	Speed	25 m/min
	Material	SUS304

ladle tilting machine for supplying molten slag to the rolls at a constant flow rate, and a conveyor for transporting the slag which has been formed by the rolls. In order to secure a longer slag solidification time, the same method as that of the equipment developed and commercialized by JFE Engineering[3)] was adopted. In this particular method, the two rolls are placed in contact and are each rotated in an outward direction. Therefore, the slag is drawn upward with the rolls. In order to enhance cooling of the slag, the cooling rolls are made of copper material and are equipped with internal water cooling. Assuming a supply rate of 1 t/min for the molten slag and a thickness of about 5 mm for the slag when solidified, we designed large-scale rolls with an outer diameter of 1.6 m and roll width of 1.5 m. The ladle tilting device can accommodate the slag ladles which are used to transport molten slag in the steelmaking shop, and can tilt a ladle at constant speed by means of a hydraulic cylinder. The conveyor transporting the high temperature solidified slag after roll-forming is made of stainless steel, and its back side is equipped with spray nozzles for cooling. The slag used in this experiment is the slag obtained by the chromium ore smelting reduction furnace.

2.2 Design of Cooling Rolls

In order to study the optimum cooling roll structure, the temperature and stress distributions of the copper rolls of three water-channel shapes (slit, lotus, spiral) were compared by a finite element method (FEM) analysis. Assuming contact between slag at 1 500°C and a semicircular part of the roll, a cooling water flow rate was set at 125 t/h and the cooling water inlet temperature and ambient air temperature were both set at 30°C.

Figure 2 shows the results of the FEM analysis. The cooling capacity of all three flow channels was satisfactory, as the surface temperature of the copper plate did not exceed 300°C and strength can be maintained at this temperature. The maximum thermal stress of the spiral type was the smallest in three type. The spiral type also has the simplest structure, and its workability is excellent. Based on this evaluation, the spiral type was selected as the flow channel shape for the cooling rolls in this development.

However, when compared to the other types, the spiral type had a greater thermal expansion. If thermal expansion causes a gap to open between the copper roll and the stainless steel core, the flow rate in the center of the channel will become extremely small, and the roll cooling capacity will decrease, resulting in a problem of temperature rise in the copper roll. In order to maintain the specified cooling water flow rate, the cases of one cooling water system (1 Channel) and two cooling water systems (2 Channels) were analyzed using the general-

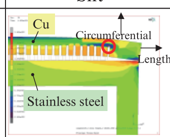
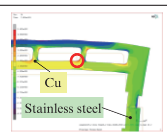
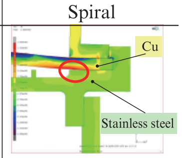
	Slit	Lotus	Spiral
FEM			
Max. Cu Temp.	169.2℃	210.7℃	219℃
Max. Stress	1 060 MPa	548 MPa	217 MPa
Workability	Fair	Fair	Good
Thermal expansional	0.72 mm	1.08 mm	2.5 mm
	1.18 mm	0.97 mm	2.5 mm

Fig. 2 Comparison of channel shape in roll

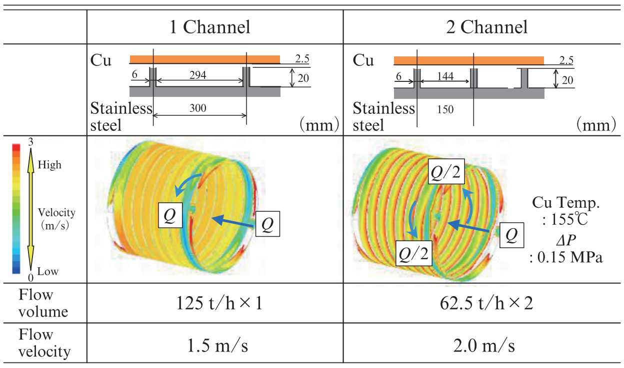


Fig. 3 Effect of water velocity by channel

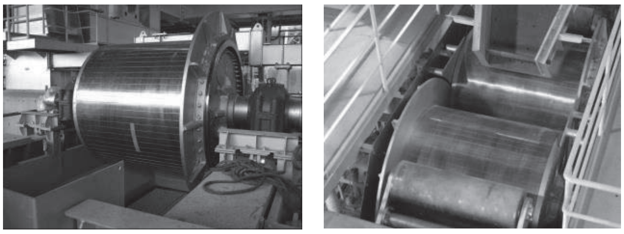


Photo 2 View of cooling roll

purpose thermal fluid analysis program FLUENT 6.3. The study assumed a constant cooling water flow volume of 125 t/h in the entire roll and a clearance of 2.5 mm between the outer cylinder and the core.

The analysis results are shown in **Fig. 3**. The flow velocity in the center of a flow channel with a clearance of 2.5 mm was 2.0 m/s with a 2 channel system and 1.5 m/s with a 1 channel system. Therefore, the 2 channel system secures a higher cooling capacity, as it has a higher flow velocity. Based on this result, a double spiral-type 2 channel system was adopted. Views of the manufactured cooling rolls are shown in **Photo 2**.

2.3 Results of Continuous Slag Solidification Experiment

An experiment was performed with the twin roll type steelmaking slag solidification pilot plant by the following procedure. The tilting device was pushed up at a constant speed by the hydraulic cylinder, and molten slag was fed from the slag ladle to the gap between the two rolls via a chute. The two rolls were rotated in an outward direction, and the slag which cooled and solidified on the roll surface adhered to the rolls and was drawn upward as the rolls rotated. After rotating approximately 180°, the slag dropped onto the conveyor. The solidified slag was transported by the conveyor and dropped from the end of the conveyor into a pit. In the pit, the slag was either cooled by water-sprinkling or allowed to cool by natural radiation, and was removed with a shovel. The temperature of the molten slag discharged from the ladle was measured with a radiation

Photo 3 View of pilot experiment

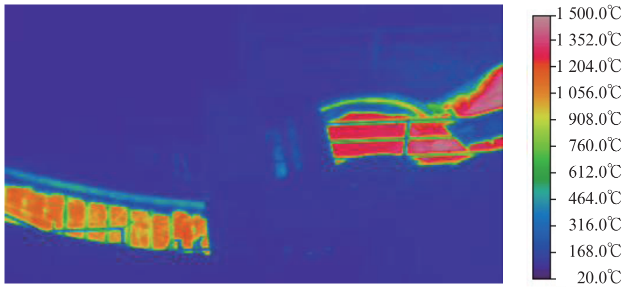


Fig. 4 Slag temperature on roll and conveyer by infrared thermography

(a) Solidified slag after experiment

(b) Sheet-shaped slag

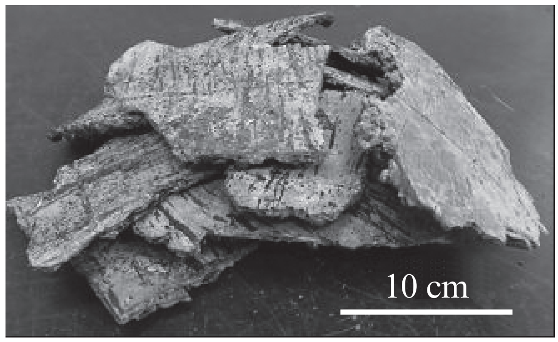


Photo 4 Appearance of solidified slag

thermometer. The temperature of the slag on the rolls and on the conveyor was measured by infrared thermography. In both cases, emissivity was assumed to be 0.92.

Photo 3 shows the typical solidification experiment

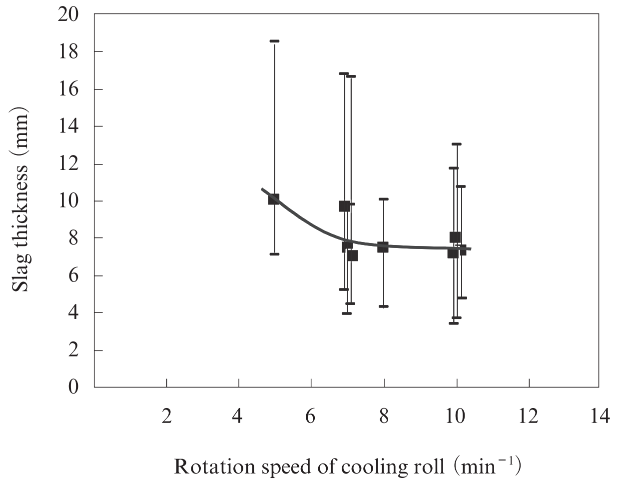


Fig. 5 Effect of cooling roll rotation speed on slag thickness

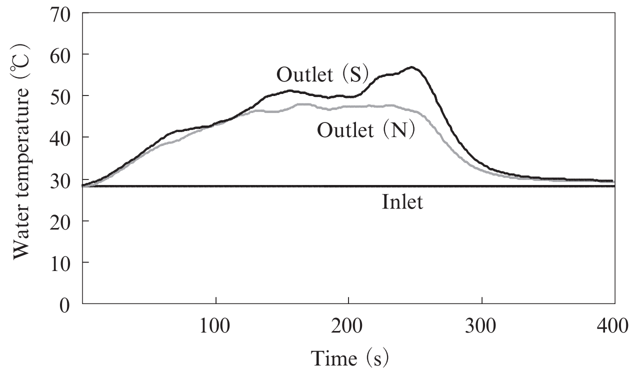


Fig. 6 Temperature of cooling water for slag roll forming

condition. In case that the molten slag have enough fluidity, molten slag spread across the full width of the rolls and was continuously solidified with the rolls.

Figure 4 shows an example of the slag surface temperature measurement results with an infrared thermography. The surface temperature of the slag decreases by 200–250°C when the slag solidifies on the roll. Temperature drop on the conveyor is slight, and the slag reaches the end of the conveyor at a temperature of around 1 100°C. This experiment confirmed that it is possible to secure the aimed slag temperature before sensible heat recovery, that is, 1 000°C or higher.

The solidified slag after cooling is shown in **Photo 4**. The slag breaks down to smaller pieces as it drops from the end of the conveyor and into the pit where it is crushed. After some observation, it was noted that the surface of the slag that had been in contact with the roll was flat and hard and that its free surface was porous and rough.

The effect of the cooling roll rotation speed on the slag thickness is shown in **Fig. 5**. Experiments were performed with cooling roll rotation speeds of 5–10 min^{-1}. At the roll rotation speed of 10 min^{-1}, the average slag thickness was 7–8 mm. **Figure 6** shows the water temperature at the inlet and outlet ends of the cooling roll. The temperature of water passing through the roll while slag is being formed rises by approximately 30°C. Since this is within the design range of 70°C or less, the designed cooling capacity can be obtained.

3. Development of Slag Heat Recovery Process

3.1 Design of Slag Heat Recovery Pilot Plant

The slag heat recovery pilot plant which was built in this development is a counterflow packed bed-type heat exchanger like the one used in coke dry quenching (CDQ). However, when compared in the same conditions (same volume and charging temperature), the amount of heat recovered by the slag heat recovery plant is only about 1/2 of that recovered in the CDQ. The amount of recovered heat is greater in CDQ because it also recovers the latent heat of the combustible gas that evolves from the coke. CDQ is therefore better in terms of economy. Moreover, in CDQ, the shape of the coke packing is lumpy, and can thus be approximated as spherical. This means that the heat transfer coefficient in the packed bed can be estimated by the Ranz-Marshall correlation, which is also used in blast furnace models, etc.[4]. However, the shape of the plate-shaped slag formed by solidification in the roll-forming pilot plant being different from that of the coke in CDQ, the heat transfer coefficient of the slag cannot be estimated by the existing model. In addition to this problem, fluidization of the packed slag is a concern if the flow volume of the heat recovery gas becomes excessive.

Therefore, before designing this slag heat recovery pilot plant, a precise evaluation of the heat transfer coefficient in the packed bed was made by a laboratory scale slag heat recovery experiment. In this experiment, the plate-shaped slag with the thickness of 7 mm, which were prepared for the experiment, were reheated and packed into the φ300 mm heat recovery experimental device, and we performed a heat recovery experiment with gas flow rates ranging from 60–200 l/min. As a result, it was deduced that the heat transfer coefficient in the packed bed of plate-shaped slag can be calculated more accurately by Eq. (1) than by the above-mentioned Ranz-Marshall coefficient. The Eq. (1), the Johnson-Rubesin equation[5], which is an equation for heat transfer in a forced convection on a flat plate, is multiplied by a correction factor β = 0.25. The value of the correction factor compensates for the ease of gas flow and localization of the gas flow in a packed bed as a change in the heat transfer coefficient. In this research, β = 0.25 was obtained as the value that best represented the heat transfer behavior in a packed bed of plate-shaped slag.

$$h_s = \beta \frac{k_g}{L_m}\left(0.037\,\mathrm{Pr}^{\frac{1}{3}}\,\mathrm{Re}^{\frac{4}{5}}\right) \quad \text{.................................} (1)$$

Pr: Prandtl number
Re: Reynolds number
k_g: Thermal conductivity
L_m: Average particle side length
β: Correction factor (= 0.25)

Figure 7 shows the relationship between the particle size and incipient fluidization velocity. Fluidization of the packed particles occurs more easily as the shape factor (1.0: Spherical, 0.5–0.3: Plate-shaped) is smaller. It is estimated that the solidified slag supplied from the roll-forming device are plate-shaped particles with an outer diameter of at least 15 mm or more due to the impact of the fall when it drops and due to the crushing treatment. Therefore, as shown in Fig. 7, the gas superficial velocity should be no more than 10 m/s in order to prevent fluidization.

Next, the slag cooling rate and heat recovery gas temperature during heat recovery were calculated for each plant scale. A preliminary calculation was made to determine the necessary plant scale for achieving a slag heat recovery ratio of ≧30% while having a slag treatment capacity of 60 t/h. This basically summarizes the aims of COURSE50. As a result, the plant with the following specifications should be able to fulfill the required treatment capacity and heat recovery ratio: a gas flow volume of 40 000 m^3/h, an inner diameter of the packed bed of ≧2.5 m (Cross-sectional area ≧4.9 m^2, Gas superficial velocity ≦8.5 m/s) and a height of ≧1.5 m for the slag packed bed. In the specifications of the pilot plant constructed in this development, the gas flow volume was reduced to 1/4 of that mentioned above and the treatment capacity was limited to 10 t/h due to limited installation space, etc. Considering some factors such as the instability of the slag shape and its crushed size, localized increases in flow velocity due to segregation of the gas flow in the heat recovery furnace, etc., the cross-sectional area was designed on the wider side (3 m^2) relative to the above-mentioned gas flow volume, therefore maintaining the gas superficial velocity to approximately 3 m/s.

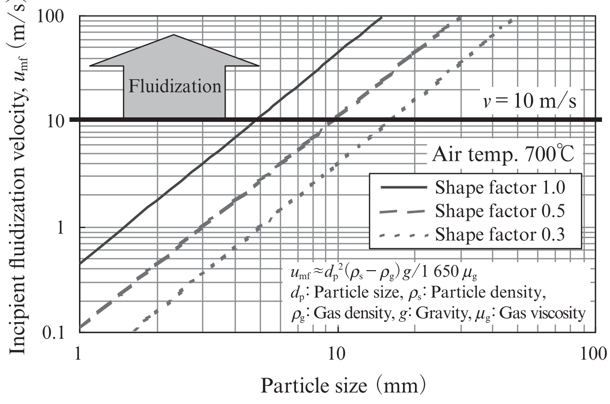


Fig. 7 Relationship between the particle size and incipient fluidization velocity

3.2 Outline of Slag Heat Recovery Pilot Plant

The production process and equipment specification of the steelmaking slag heat recovery pilot plant built in this project are shown in **Fig. 8** and **Table 2**, respectively. Slag which has been solidified and formed into a plate-shape by the roll-forming pilot plant is transported by an apron conveyor. Then, part of the solidified slag discharged from the delivery side of the conveyor is sampled for use in heat recovery experiments by means of slide type chute, and the size of the remaining slag is broken down to the proper size by a simple crusher. The crushed slag is then supplied continuously to the heat recovery plant by a bucket elevator. Heat is exchanged by blowing air into the packed slag in the slag heat recovery chamber from two blowers. Heat recovery is then evaluated by measuring the temperature history of the recovered gas and the pressure drop in the packed bed. Since the bench-scale plant constructed here is not equipped with heat utilization equipment, such as a

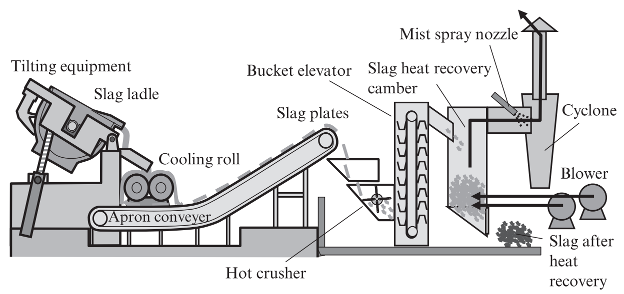


Fig. 8 Process drawing of the COURSE50 slag heat recovery plant

Table 2 Specification of the slag heat recovery pilot plant

Operating condition	Slag charging rate: 1 t/min
	Slag cooling capacity: 10 t/h (at the discharge temperature of 250°C)
Equipment specifications	Clusher Roller chain type, Capacity: 60 t/h
	Bucket elevator Transport Capacity: 60 t/h
	Heat recovery chamber Maximum size of the slag packed bed: L1.5×W2.0×H2.5 Maximum amount of slag: 6 t (at the bulk specific gravity of 1 t/m^3)
	Blower Gas flow rate: 6 000 Nm^3/h×2 Motor: 75 kW×2
	Cyclone Size ϕ 2.2×H7.5 m

Photo 5 Exterior of the COURSE50 slag heat recovery plant

boiler, etc., the heat recovery gas was cooled down by a water spray after evaluation of its properties. The gas is then released after de-dusting by a cyclone. As the pressure drop in the packed bed predicted from the Ergun equation is small at approximately to a maximum level of 10 kPa, the heat recovery chamber is designed as a square-like structure to simplify the slag charging and discharging mechanisms. An external view of the bench-scale slag heat recovery plant is shown in **Photo 5**.

3.3 Results of Slag Heat Recovery Experiment

Photo 6 shows the slag during the slag heat recovery experiment. The photo on the top was taken from above the crusher. As the slag flows from the right side of the image to the left, it is successively crushed and flows into the charging hole of the bucket elevator. The photo on the bottom shows the interior of the heat recovery chamber during slag charging, as seen by the monitoring camera. Because transportation time by the bucket elevator is short, at approximately 20 s, the decrease in the slag temperature due to heat loss during transportation is slight at no more than 50°C.

Figure 9 shows a graph of the actual temperature history of the heat recovery gas when heat recovery was performed with a blower flow volume rate of 6 000 m^3/h with 1.7 t of slag charged into the heat recovery chamber. Even though the amount of packed slag was small compared to the rated capacity of 6 t, which corresponds to a height of 0.57 m for the slag bed (approximately 0.4 m from the tip of the blower discharge hole), it was possible to obtain a high temperature of 450°C for the heat recovery gas. The hatched area in Fig. 9 is the region where the recovery gas temperature is 140°C or more, which meets the objectives of COURSE50. Continuous recovery of heat recovery gas at 140°C or higher was possible for 63 min. Since the molten slag temperature measured by the radiation thermometer immediately before the start of the test was at 1 442°C, the heat

Hot crusher

Slag chamber

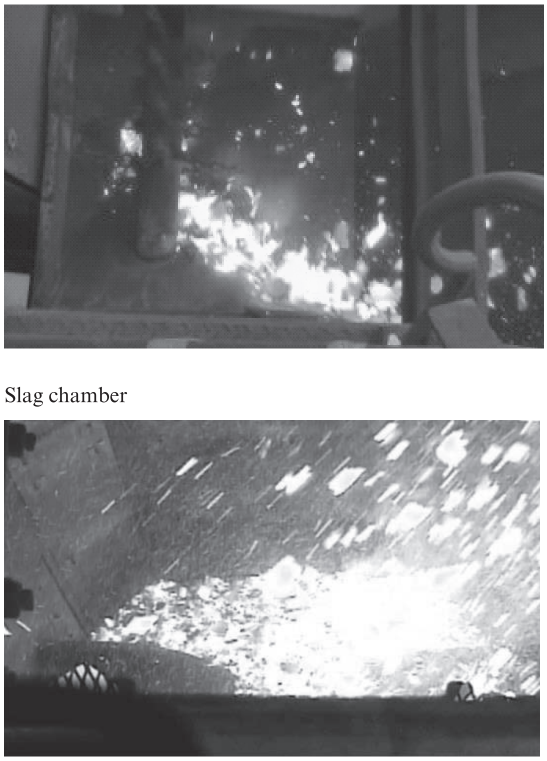


Photo 6 Hot slag plates charged for heat recovery

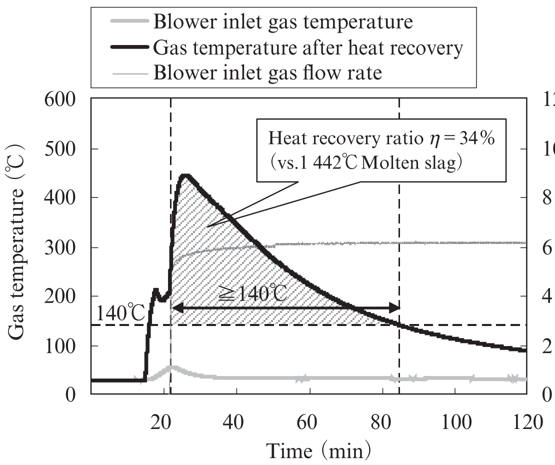


Fig. 9 Heat recovery ratio from the molten slag

recovery ratio of heat recovery gas sensible heat with a temperature of 140°C or higher relative to the heating value of the molten slag (latent heat+sensible heat) obtained from the said temperature was 34%.

4. Conclusion

As part of the COURSE50 Project for CO_2 reduction by the Japanese steel industry, a heat recovery experiment was performed with a directly-linked twin roll type steelmaking slag continuous solidification pilot plant and a slag heat recovery pilot plant. The experiment was carried out with slag from an actual steelmaking plant. A maximum of 1.7 t of sheet-shaped slag with a thickness of 7 mm, which was solidified continuously by the roll-forming pilot plant, was charged to the slag heat recovery pilot while still in a high temperature condition over 1 000°C. As a result, heat recovery ratio from molten slag was obtained 34%

These results were obtained as part of the “Course50 (CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50),” which is a project commissioned by Japan’s Incorporated Administrative Agency New Energy and Industrial Technology Development Organization (NEDO).

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