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Yonmo Sung [1],* , Sangyoun Lee [2], Kyungmoon Han [2], Jaduck Koo [3], Seongjae Lee [3], Doyoung Jang [4], Changyong Oh [5] and Byunghwa Jang [5]

[1] Department of Energy and Mechanical Engineering, Gyeongsang National University, Tongyeonghaean-ro 2, Tongyeong-si, Gyeongsangnam-do 53064, Korea
[2] EAF Production Technology Team, Hyundai Steel Company, Incheon 22525, Korea; steelsmith@hyundai-steel.com (S.L.); hankm@hyundai-steel.com (K.H.)
[3] D/Bar Steel Making Department, Hyundai Steel Company, Incheon 22525, Korea; kooti@hyundai-steel.com (J.K.); coolbase@hyundai-steel.com (S.L.)
[4] Mechanical Engineering Team, Hyundai Steel Company, Incheon 22525, Korea; badajdy@hyundai-steel.com
[5] Environment and Energy Engineering Team, Hyundai Steel Company, Chungcheongnam-do 31719, Korea; cyoh1017@hyundai-steel.com (C.O.); bhjang@hyundai-steel.com (B.J.)
* Correspondence: ysung@gnu.ac.kr

Abstract: The energy cost of producing steel in an electric arc furnace (EAF) has a sizable influence on the prices of natural gas and electricity. Therefore, it is important to use these energies efficiently via a tailored oxy-fuel combustion burner and oxygen lance. In this study, an important modification of the side-wall injector system in the EAF at Hyundai Steel Incheon works was implemented to reduce electrical energy consumption and improve productivity. A protruding water-cooled copper jacket, including a newly designed burner, was developed to reduce the distance between the jet nozzle and the molten steel. In addition, the jet angles for the burner and lance were separately set for each scrap melting and refining mode. The modifications led to a reduction in electrical energy consumption of 5 kWh/t and an increase in productivity of approximately 3.1 t/h. Consequently, total energy cost savings of 0.3 USD/t and a corresponding annual cost savings of approximately 224,000 USD/year were achieved.

1. Introduction

In the recycled steel processing industry, the electric arc furnace (EAF) is an energy-intensive facility. Electric energy, with a moderate addition of chemical energy, provides sufficient heat to melt recyclable scraps charged in the EAF [1]. For the production of 1 t of steel at 1600 °C from steel scrap at 25 °C, a typical EAF process, approximately 60% of the energy input comprises electric energy and chemical energy provides the remaining 40% [2]. Similar values have been reported for the energy required to melt steel scraps in EAFs [3,4]. Efforts are needed to improve the efficiency of electricity use in the EAF sector owing to the recent rise in electricity rates and the implementation of the greenhouse gas emission trading system [5]. Therefore, to improve the efficiency of heat used in the EAF, it is important to utilize a heat source other than electric power. To save energy in EAFs, it is important to optimize the utilization of chemical energy; energy can potentially be saved by reducing electrical energy use while increasing the chemical energy input [6,7]. Chemical energy, supplied by a side-wall injector system, is an auxiliary form of energy and is delivered by the oxidation of fossil

fuels; exothermic reactions of chemical elements, such as iron, carbon, manganese, and silicon; and by post-combustion of carbon monoxide [8,9]. Hence, this study focuses on modifying the side-injector system, with an oxygen lance and an oxy-fuel burner to enhance energy efficiency in EAFs.

The prices of natural gas (NG) and electricity, or their ratio, have a large impact on the production costs of steel in the EAF [10]. Table 1 lists the energy prices of industrial NG and electricity in different countries (the prices are converted to cent/kWh content to simplify the energy comparison [11,12]). The maximum and minimum prices for NG are 1.05 cent/kWh in Canada and 7.27 cent/kWh in Switzerland, respectively. For electricity prices, the values are 6.81 cent/kWh in the USA and 17.12 cent/kWh in Italy, respectively. Replacing electricity by NG in an oxy-fuel burner, is more effective at a high ratio of electricity to NG prices. The maximum and minimum values for the ratio of NG and electricity are 7.86 in Canada and 1.39 in Sweden.

Table 1. Comparison of energy prices of industrial NG and electricity with different countries in 2018 [11,12].

Country	NG (Cent/kWh)	Electricity (Cent/kWh)	Electricity/NG (-)
Canada	1.05	8.24	7.86
USA	1.36	6.81	5
Germany	3.03	14.28	4.72
United Kingdom	2.99	13.66	4.57
Italy	3.88	17.12	4.57
Belgium	3.10	13.41	4.32
Spain	2.96	12.52	4.23
Slovakia	3.38	13.87	4.10
Portugal	3.29	13.28	4.04
Turkey	1.97	6.98	3.55
Japan	4.52	15.79	3.49
Poland	2.96	9.39	3.17
Ireland	4.10	12.63	3.08
Netherlands	2.97	9.13	3.07
Hungary	3.09	9.26	3.00
Czech Republic	3.17	9.47	2.99
Austria	3.69	10.83	2.93
Greece	3.55	10.26	2.89
France	4.28	11.42	2.67
Luxembourg	3.25	8.20	2.52
Korea	4.24	9.85	2.32
Denmark	4.11	9.13	2.22
Switzerland	7.27	11.99	1.66
Finland	5.27	7.70	1.46
Sweden	4.93	6.85	1.39
Mean values	3.53	10.88	3.43
Max. values	7.22	17.12	7.86
Min. values	1.05	6.81	1.39

In South Korea, as of 2018, both energy prices are below the mean values shown in Table 1. However, the ratio of both prices is higher than the mean value. During the last 15 years, the price of NG has continuously increased in South Korea but the price of electricity has decreased since 2014, as shown in Figure 1 [11,12]. From 2006 to 2014, the average price ratio of NG and electricity was 1.67. Therefore, either oxy-fuel burner operations in EAFs have been minimized in South Korea or the system was not in use between 2006 to 2014, in particular at the Hyundai Steel Company. The price ratio of NG and electricity increased from 2014. For these reasons, the reuse or development of oxy-fuel burners in South Korea has increased in the recent years; hence, research was initiated into the system modification presented herein.
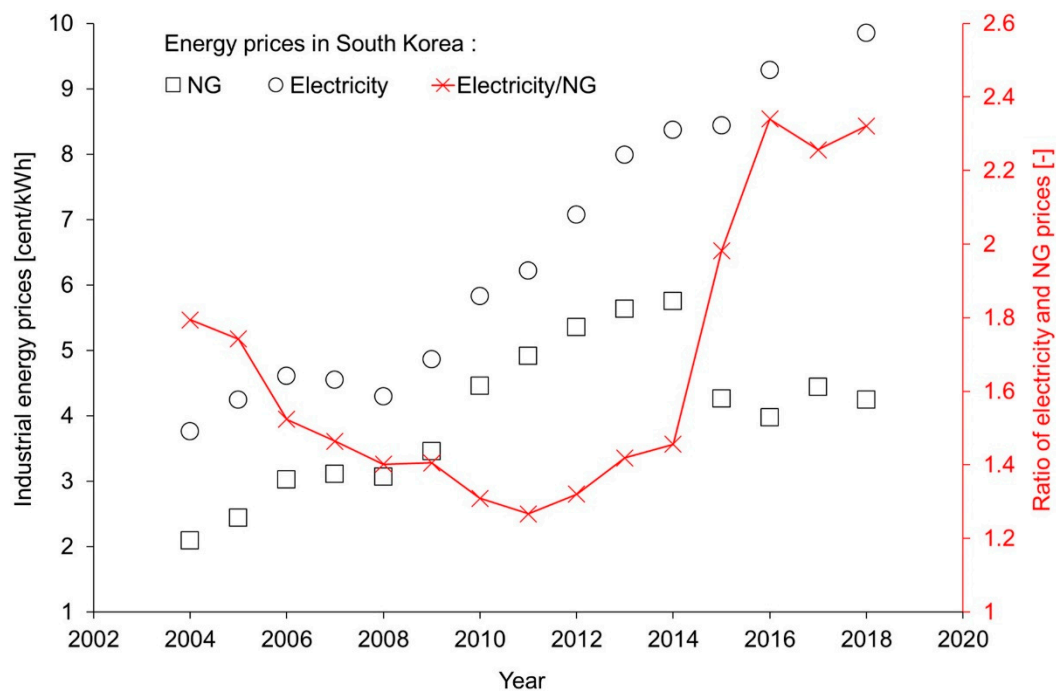
Figure 1. Variation of the prices of industrial NG and electricity and their ratios from 2004 to 2018 in South Korea [11,12].

In EAF operations, several oxy-fuel burners, including oxygen lances, have been integrated to reduce electrical energy consumption by substituting electricity with fuels. The oxygen lance and oxy-fuel burner can be used for pre-heating, cutting, and removing cold spots to ensure uniform temperature distribution inside the furnace and promote the circulation of molten steel in the refining process, thereby reducing the tap-to-tap time (TTT) by approximately 6%, improving power consumption and productivity [5]. When optimizing the oxy-fuel burner/lance, the electric power savings can be expected to be 20–40 kWh/t (t: tons of steel), by injecting NG, which is 0.3 Nm^3/kWh [13]. Typical savings, ranging from 2.5–4.4 kWh/Nm^3 oxygen injection, can be achieved, with electricity savings of 0.14 GJ/t [14,15].

Oxygen jet and oxy-fuel flame configurations modifications have been researched to reduce electrical energy consumption in EAFs [16–19]. Megahed et al. [16] conducted an upgradation by using oxygen injections with jet location, length, and flowrate at Ezz Flat Steel. The modifications led to a reduction in electrical power consumption by 64 kWh and an increase in furnace productivity of 30%. Thomson et al. [17] investigated the effect of the oxy-fuel burner ratio on energy efficiency in Co-Steel Lasco's EAF. They concluded that the decrease in specific electrical energy consumption (4%) and TTT (4.5%) could be realized by optimizing the oxygen-to-fuel ratio in the oxy-fuel combustion burner. Memoli et al. [18] achieved electrical energy savings of approximately 27% through multi-point supersonic oxygen injection within a real-scale EAF with a nominal capacity of 105 tons. Cantacuzene et al. [19] investigated the distribution of lancing oxygen among multiple locations to improve the effectiveness of oxygen usage in an EAF. Through this tailored use of oxygen, the electrical energy consumption was reduced from 427 to 400 kWh/t and the power-on time (POT) was also reduced from 41 to 37 min. Kirschen et al. [20] demonstrated that the assessment of multiple EAF energy balances did not reveal a significant influence of NG consumption on the total energy input in an EAF but did demonstrate an associated decrease in the electrical energy requirement.

The above-mentioned studies showed that the reduction in electrical energy consumption of EAFs primarily depends on the oxygen usage of the burner and lancer, in terms of the installation location, flame type, injection angle, and ratio of NG-oxygen. In particular, the injection angle of the jets requires optimization according to the time step (period), such as the heating/melting of scraps and refining of

molten steel. Therefore, the jet angles from the oxy-fuel burner and oxygen lance have to be separately maintained at their corresponding roles during each period. A jet with an impinging point too close to the refractory walls can cause excessive consumption of the refractory, while a jet that is less inclined with respect to the horizontal plane can produce splashing of hot steel [15]. If the distance from the jet nozzle to the molten steel is too large, the fuel and oxygen usage efficiency in the side-wall injectors will be reduced. This study primarily focuses on these specific aspects, which include modifications to the side-wall injector system, with different burner and lance jet angles, but also closely modifies the distance from the jet nozzle to the molten steel. A protruding water-cooled copper jacket, including a tailored oxy-fuel burner, was developed. The energy savings and productivity performance before and after modification were evaluated for a real-scale EAF.

2. Materials and Methods

2.1. Modification Concept of Side-Wall Injector System For Improving Energy Efficiency and Productivity in the EAF

Figure 2 shows the modification concept of the side-wall injector system in the present study. The conventional injector (Badische Stalhl-Engineering, Kehl, Germany), before modification, was a hybrid system, which operates the oxy-fuel combustion and oxygen lance. The new modified system was designed to operate the burner and lance separately, using the existing three lines for the supplied gases. For the conventional system installed in the EAF wall, shown in Figure 2a, a problem arises; the efficiency of heat transfer becomes low since the distance between the injector and molten steel is large during the scrap heating, meting, and refining periods. In addition, the injection angles for both the oxygen jet and oxy-fuel burner flame were fixed at 40° to the horizontal. This may cause the occurrence of non-melted scrap and the reduction in reaction efficiency between the molten steel and slag layer. Therefore, it is necessary to enhance the efficiency of heat transfer by introducing a designed injector system to close the distance between the injector nozzle and molten steel. Figure 2b shows the design of the new injector system to differentiate the injection angle by separating the lance (40°) and burner (25°) roles. Separated nozzles were installed at the protruding water-cooled jacket to enable the injection of the oxy-fuel flame and oxygen jet with different angles, as well as closer jet distances. The oxy-fuel burner has two lines for supplying oxygen and NG and the lance has a single oxygen supply line. This new jet allowed a shorter distance to the molten steel, as compared to the conventional jet, allowing an increase in the chemical energy usage and production efficiencies in EAFs.
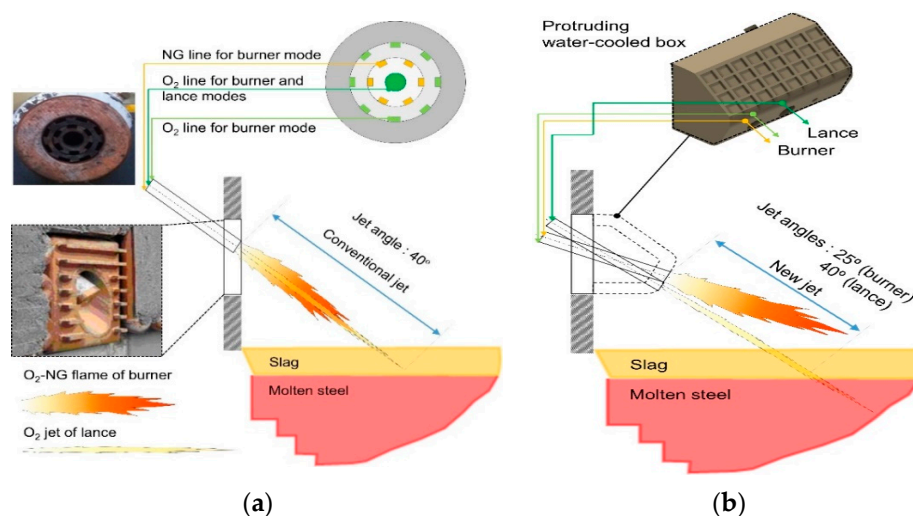

Figure 2. Modification schemes of the side-wall injector system: (**a**) conventional system; (**b**) new system.

2.2. Flame Test of the Oxy-Fuel Burner and Thermal/Mechanical Analysis of Protruding Water-Cooled Copper Jacket for the Side-Wall Injector System

To minimize the system modification costs, the existing oxygen and NG supply lines for the oxy-fuel burner and oxygen lance have been used without additional lines. The new modified oxy-fuel burner, as shown in Figure 2, has only one supply line for oxygen in the nozzle. This damages the oxy-fuel flame formation and hence degrades the performance of the oxy-fuel burner. Therefore, the design of the burner nozzle was optimized. The number of nozzle holes was modified from 6 to 12 to enhance the mixing performance of NG and oxygen. The effect of the nozzle configuration of the oxy-fuel burner on the flame performance was tested. In this flame test, the burner nozzle was selected by comparing conventional oxy-fuel burner and new modified burner flames.

EAFs operate at high thermal and mechanical loads. The protruding water-cooled jacket must have sufficient strength to withstand collisions with falling heavy scraps. The scrap is charged during the EAF process and the cooling performance of the jacket at high temperatures must be maintained efficiently. Figure 3 shows the flame photos obtained with and without damage to the cooling jacket surface. In Figure 3a, flames generated at the oxy-fuel burner nozzle and cracked surface by a damaged cooling jacket are shown and this damage is attributed to the weight of the scraps and material softening at the EAF operating temperature. Even though the amount of NG and oxygen supplied to the burner was the same in both cases, the oxy-fuel combustion flame in Figure 3a is smaller than that in Figure 3b. The heat of oxy-fuel combustion will be distributed by generating junk flames and thus there is an inefficient chemical to thermal energy conversion. The junk flames caused by system damage are not favorable for the EAF refining process as compared to the undamaged oxy-fuel flame, as shown in Figure 3b.

(**a**)   (**b**)
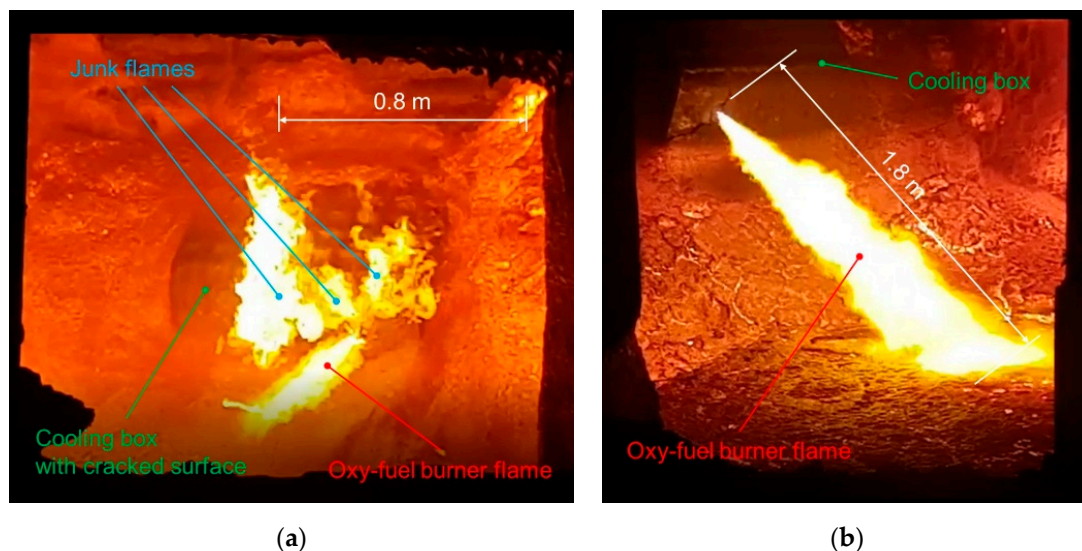
Figure 3. Oxy-fuel combustion flames of the burner installed at protruding water-cooled box: (**a**) flames generated at oxy-fuel burner nozzle and cracked surface with system damage; (**b**) observed flame without system damage.

In this context, computational fluid dynamics simulations were carried out using the commercial simulation program ANSYS to better understand the temperature and stress distribution on the jacket. The effects of the rib height and thickness of the protruding water-cooled box on the thermal and mechanical characteristics were evaluated. This can help design the protruding water-cooled jacket with high durability and without any damage due to scraps charged in the EAF.

2.3. Evaluation of EAF Performance Before and After System Modification

The melting experiments were tested in a real-scale EAF at Hyundai Steel Incheon works, with a nominal capacity of 120 t per charge and a three-phase current supply from a 95 MVA transformer. The furnace has a diameter of approximately 6 m and is equipped with three side-wall box-type systems, including an oxygen lance, oxy-fuel burner, and carbon injector. Performance parameters, such as electric power (kWh/t), oxygen consumption (Nm^3/t), NG consumption (Nm^3/t), carbon injection (kg/t), POT (min), TTT (min), product rate (t/h), and cost savings (USD/yr), have been evaluated by the conventional injector system (before) and the new injector system (after).

3. Results and Discussion

3.1. Flame Characteristics of the Developed Oxy-Fuel Burner

Figure 4 shows the oxy-fuel burner flame tests. A photograph of the experimental test rig with burner and fluid supply lines for fuel and oxygen is shown in Figure 4a. The nozzle and flame configurations of the conventional and newly designed jets are shown in Figure 4b. Case A1 represents the conventional burner with three supply lines before modification. Cases A2 and A3 represent the initial and final burner models with two supply lines, respectively. Even though the size and area of the nozzle hole changed according to the variation in cases A1–A3, the entire area remained the same for each case, in terms of the fuel and oxygen nozzles. The initial model (case A2) can be conceptualized most easily as only the auxiliary oxygen is removed from the existing burner (case A1). The purpose of the initial model is to identify the characteristics of a single oxygen nozzle and set the burner design direction. The flame in case A1 showed a strong elliptical configuration in the center and it can be seen that NG does not diffuse into the surroundings due to the presence of the auxiliary oxygen. However, it can be seen that the flame in case A2 (as shown in the dotted box) is strongly formed at the center, with a blue flame, owing to the bulk oxygen supplied. Moreover, the flame forms with a yellow band due to the combustion reaction of the surrounding air with NG. Therefore, the initial model is expected to show a low combustion efficiency as a large amount of NG does not participate in combustion and diffuses into the surroundings; thus, the mixing of NG and oxygen is an important nozzle design factor for suitable oxy-fuel combustion.

(**a**)　　　　　　　　　　　　　　　　　　　　　　(**b**)
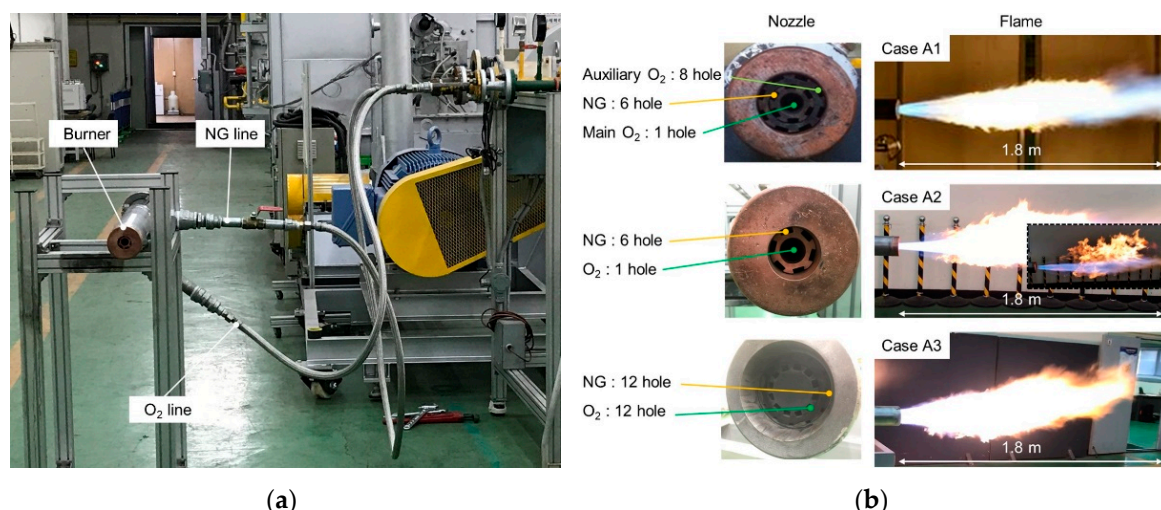
Figure 4. Oxy-fuel burner flame tests: (**a**) photo of flame test rig; (**b**) flame photos with different types of burner nozzle configuration.

To improve the mixing of NG and oxygen for oxy-fuel combustion, the final model was designed with a 12-hole nozzle for fuel and oxygen supply. In addition, the holes for supplying both NG and oxygen were located at the edge of the nozzle to increase the width of the flame. In Figure 3b, the flames

in case A3 seem to be the most stable and active combustion reaction among cases A1–A3. The flame width—in particular just behind the nozzle—increased in comparison with that in other cases due to the increasing nozzle diameter of the fuel and oxygen. Considering the scrap melting operational characteristics of the oxy-fuel burner in EAFs at high temperatures, the burner must incorporate a water-cooling jacket. In addition, it must be designed to separate the NG and oxygen nozzle parts for maintenance. Therefore, the final burner model was designed to facilitate cooling, water circulation, and repair.

3.2. Thermal and Mechanical Characteristics of the Developed Protruding Water-Cooled Copper Jacket

Figure 5 shows the analysis of the jacket with different rib heights and thicknesses. For the simulation conditions, a static load of 15 t of charging scraps and cooling water inside the water-cooling jacket, with a temperature of 30 °C, were set at an external temperature of 1000 °C, as shown in Figure 5a. Case B1 represents the initial model, with a rib height and thickness of 30 and 20 mm, respectively. Cases B2 and B3 represent at comparable model, with a 40 mm height and 20 mm thickness, and the final model, with a 30 mm height and 30 mm thickness. As shown in Figure 5b,c, a higher protruding jacket rib height, corresponds to reduced cooling performance. However, the equivalent (von Mises) stress was reduced and the temperature was relatively low when the thickness of the rib was high, i.e., lower height and thicker rib of the protruding jacket result in a better load stress and cooling capacity. The final model, case B3, exhibited the superior thermal and mechanical characteristics among the three cases. The maximum stress and temperature were approximately 383 MPa and 92 °C, respectively.

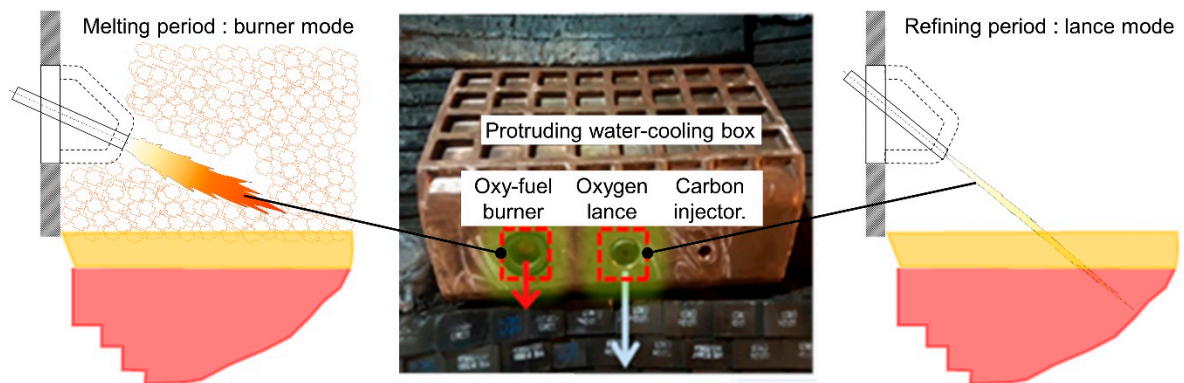### 3.3. Improvement of EAF Performance Before and After System Modification

The EAF performance was evaluated using a newly designed side-wall injector system consisting of an oxy-fuel burner, oxygen lance, and carbon injector, mounted on the developed protruding water-cooled jacket, as shown in Figure 6. The jets have two different operational modes: the oxy-fuel burner and oxygen lance mode, both of which cause chemical exothermic reactions. The oxy-fuel burner operates during periods of scrap charging and melting. The oxygen lance follows the burner mode in the order of operation during the refining periods. In the present EAF performance test, 304 charges were performed for 17 days before system modification and 155 chargers were performed for 9 days after system modification.

The operating results before and after the installation of the new system are summarized in Table 2. To evaluate the economic advantages, Figure 7 shows the differences between pre- and post-modification in terms of key values, such as production rate, TTT, POT, and consumption of electric energy, oxygen, NG, and carbon. The benefits are a 0.8 min reduction in POT and 5 kWh/t in power savings. The oxygen jet efficiency increases because of the relatively short distance between the jet nozzle and molten steel by the protruding side-wall injection and its ability to use the optimal injection angle of the oxy-fuel burner flame to efficiently melt scraps after modifying the system. However, the consumption of oxygen and NG increased by 2.5 Nm^3/t and 0.2 Nm^3/t, respectively. Half of the oxygen consumption was used to prevent clogging of the nozzle due to scattering from the molten steel when injecting the burner and oxygen while approaching the molten steel. Consequently, the total conversion cost was reduced by 0.298 USD/t and productivity increased by 3.1 t/h.
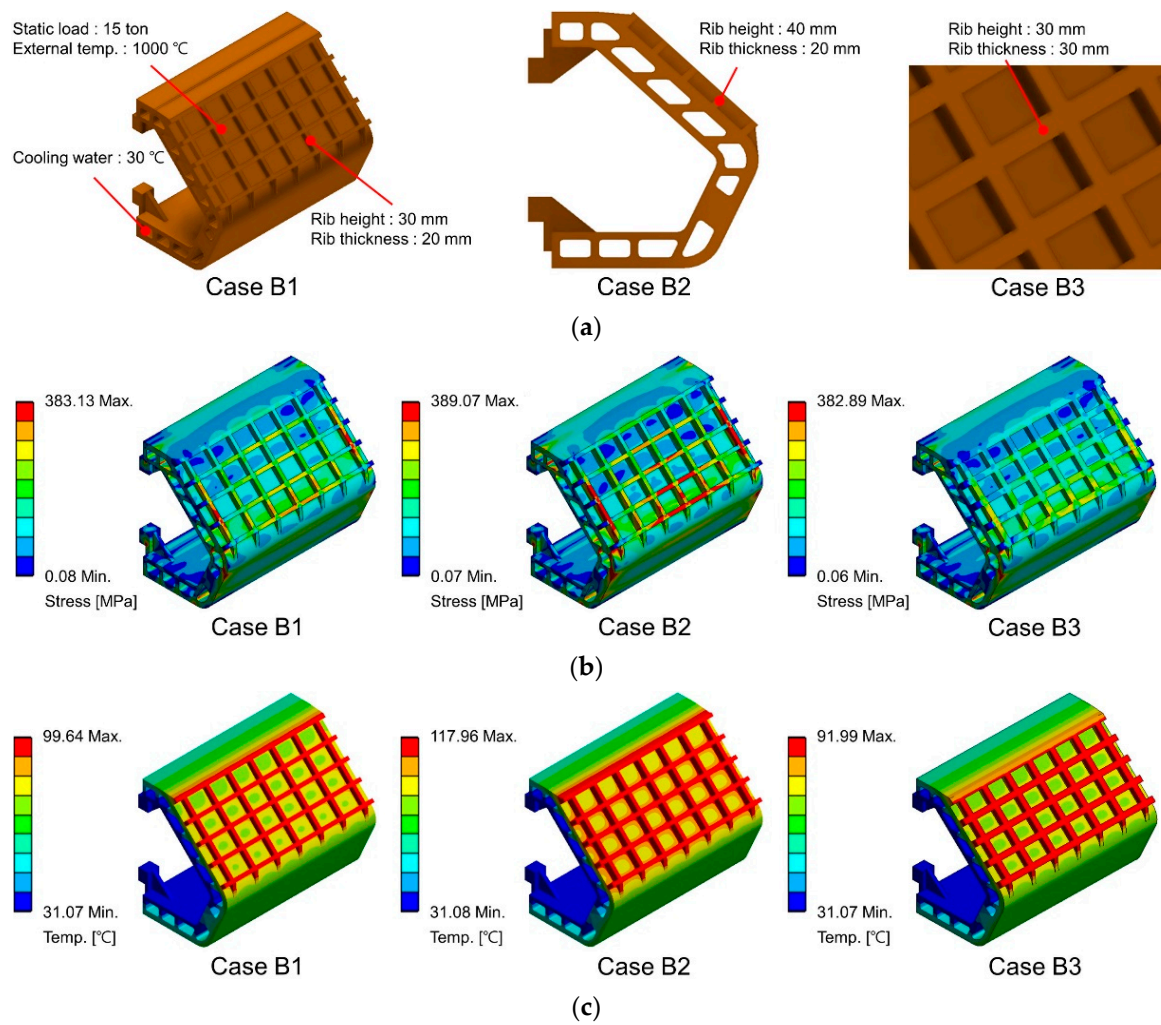
Figure 5. Analysis of protruding water-cooled box for the side-wall injector system with different rib height and thickness: (**a**) analysis condition and case; (**b**) distribution of equivalent (von Mises) stress; (**c**) temperature distribution.

Figure 6. Developed protruding water-cooled jacket installed at the EAF wall with different operating modes.

Table 2. Overview of EAF performance before and after system modifications.

Item	Before	After	Difference	Cost [USD/t]
Production [t]	37,945	19,437		
Charge number during the test (time, day)	304 (17)	155 (9)		
Electrical consumption [kWh/t]	396.2	391.2	-5	-0.41
Oxygen consumption [Nm^3/t]	18.8	21.3	+2.5	+0.2
Natural gas consumption [Nm^3/t]	0.2	0.4	+0.2	+0.072
Carbon consumption [kg/t]	11.4	10.3	-1.1	-0.16
Power-on time [min]	49.2	48.4	-0.8	
Tap-to-tap time [min]	62.4	61.1	-1.3	
Productivity [t/h]	120	123.1	+3.1	
Total energy cost savings [USD/t]			0.298	
Annual production [t/yr]			774,908	
Annual cost savings [USD/yr]			224,329	
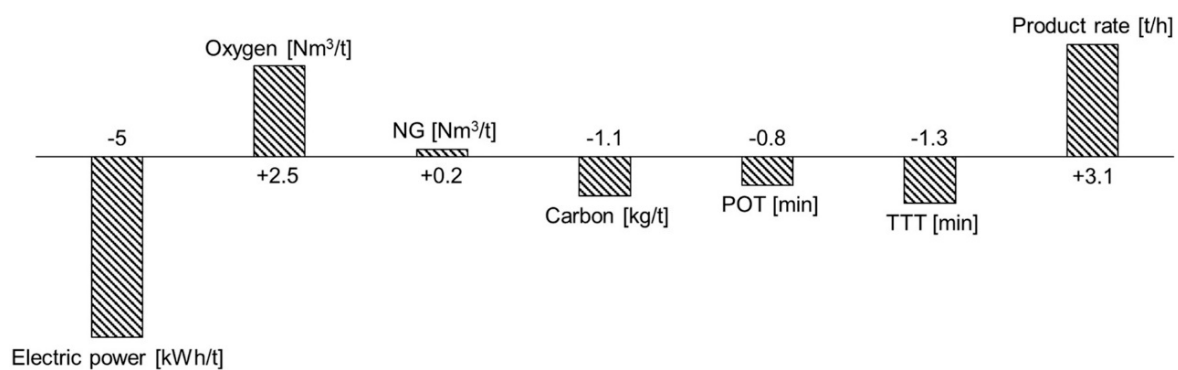
Figure 7. Differences in electricity, oxygen, natural gas, carbon, power-on-time, tap-to-tap time, and productivity before and after system modification.

4. Conclusions

In order to save electrical power in EAF operations, a side-wall injector system featuring an oxy-fuel burner and oxygen lance has been developed. The protruding water-cooled copper jacket was designed, based on thermal and mechanical analysis, to close the distance between the jet nozzle and molten steel, but also to separate the burner and lance separately with different jet angles. Any damage such as surface cracks by charging scraps was not observed in the developed cooling jacket. The oxy-fuel burner nozzle was designed through various flame tests for different nozzle geometries. The developed burner was operated properly without degrading the flame performance in comparison with the conventional one.

For the overall performance of energy efficiency and productivity before and after system modification, the electrical energy consumption was reduced by 5 kWh/t and the productivity was increased by 3.1 t/h. Thus, the total energy cost savings calculated by the consumption of electricity, oxygen, NG, and carbon achieved by 0.298 USD/t. The annual cost savings of the EAF in this study were approximately 224,329 USD/yr.

Author Contributions: Conceptualization, J.K.; methodology, C.O.; validation, D.J.; investigation, B.J.; data curation, S.L. (Seongjae Lee); writing—original draft preparation, Y.S.; writing—review and editing, Y.S.; supervision, K.H.; project administration, S.L. (Sangyoun Lee). All authors have read and agreed to the published version of the manuscript.

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