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Development of Environmentally Friendly High-Efficiency Radiant Tube Burner for Annealing Furnace

OKADA Kuniaki

Abstract:

It is widely known that the adoption of regenerative burners to reduce CO_2 emissions in industrial furnaces using gas fuel, but it is difficult to introduce expensive regenerative burners in many burners in annealing furnaces of cold-rolling line in a steel works. Therefore, JFE Steel developed a top-class ultra-low NOx radiant tube (RT) burner in Japan and improved the waste heat recovery efficiency by utilizing it in the annealing furnace, and achieved a further CO_2 reduction (energy saving) operation. In this paper, we will introduce the ultra-low NOx technology of the newly developed radiant tube burner.

1. Introduction

At present, increasingly advanced quality requirements are being imposed on steel products. Representative examples include automotive steel sheets and steel sheets for household electrical appliances. In particular, achieving high strength in automotive steel sheets, which makes a large contribution to improved fuel economy through automobile weight reduction, may be mentioned as the most important challenge of recent years. Accompanying more advanced customer requirements and increased production efficiency of high grade products, building quality into the product in the annealing process has become a key process that controls the competitiveness of cold-rolled steel sheets and coated steel sheets. Because the heat pattern, i.e., heating and cooling temperature history, of the steel strip during continuous annealing is extremely important for building quality into products, appropriate performance is also demanded in the burners used in heating. The article explains the details of technical development for energy saving in radiant tubes (RT) for use in the continuous annealing furnace.

2. Outline of RT Burner and Necessity of Energy Saving and Low NOx

Figure 1 shows an outline of the continuous annealing line (CAL). In the cold-rolled steel strip manufacturing process, the strips are coiled in coil form for handling. Because the coils are hardened after cold rolling by working (plastic deformation), annealing is performed to soften the material. Annealing is extremely critical process for building in quality. In the continuous annealing process for cold-rolled steel sheets, strips in coil form are unwound, welded successively to enable continuous processing, and then passed through the continuous annealing furnace, which consists of heating, soaking, and cooling zones, and are finally rewound after annealing.

When steel strips are heated and cooled in an annealing furnace, treatment must be performed in a nonoxidizing atmosphere (H_2, N_2 atmosphere) to prevent oxidation of the strip surface. For this reason, burners using the radiant tube heating method are generally employed so as to avoid direct contact between the strip and the exhaust gas generated by combustion of byproduct gas generated in steel works, which is used as the fuel for heating (**Fig. 2a**).

Because the CAL is an energy-consuming facility which consumes as much as 200 GJ/year of heat, the following two points should be mentioned as environmental problems of the exhaust gas: The first is com-

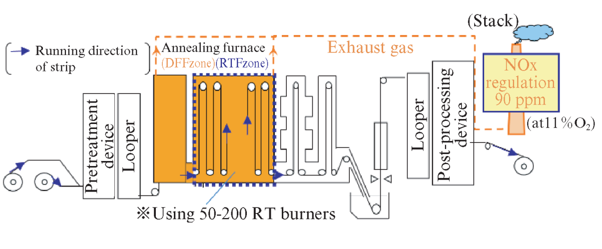

Fig. 1 Outline of continuous annealing line

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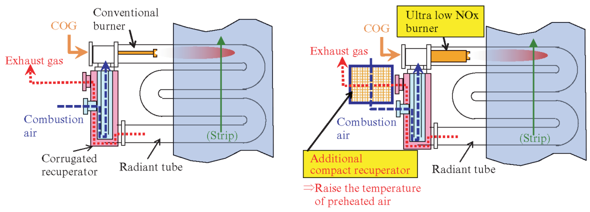
Staff Deputy General Manager, Energy Technology Sec., Energy Dept., West Japan Works (Fukuyama), JFE Steel



a. Conventional RT burner　　b. New developed RT burner

Fig. 2　Schema of conventional and new developed RT burner

pliance with regulations applied to the concentration of nitrogen oxide emissions (NOx concentration), as these compounds cause environmental pollution such as photochemical smog. The second is reduction of CO_2, which is the main cause of the greenhouse gases (GHG) that have been viewed as a global problem in recent years.

In energy saving (CO_2 reduction), a method of recovering and utilizing the sensible heat of the exhaust gas again for combustion air preheating is generally adopted. In this process, as shown in **Fig. 3**, the flame temperature generated by the combustion reaction increases when the preheating temperature of air is increased, but because thermal Nox also increases, the preheating temperature of air was limited by exhaust gas Nox regulations. Therefore, it was essential to develop a low Nox combustion technology in order to achieve energy saving (CO_2 reduction) while complying with environmental regulations, and to put a burner system to practical use(Fig. 2b) that can maintain the current Nox value even when the air preheating temperature is increased further for energy saving.

3. Transition of Low Nox Technology in RT Burners

Radiant tubes are cylindrically-shaped tubes with an inner diameter of ϕ150 mm to ϕ180 mm and a W-shaped form in the longitudinal direction. Since the flame temperature easily increases because combustion occurs in this constricted space, it was difficult to achieve low Nox for structural reasons.

The following explains the positioning of the environmentally friendly high-efficiency radiant tube burner developed in this work, based on the change in low Nox performance of RT burners.

Conventionally, the Nox value of RT burners using COG (coke oven gas, a byproduct gas generated in the steel works) as a fuel had transitioned at about 160 ppm (11% O_2 conversion value). Moreover, the limit values was approximately 120 ppm, even when using various low Nox combustion technologies, such as addition of exhaust gas recirculation to two stage combustion (**Fig. 4**).

In this development, extremely low Nox combustion was achieved in a continuous combustion-type RT burner by using a newly-developed self-exhaust gas recirculation (self EGR) combustion technology.

In order to achieve energy saving in a burner, it is essential to strengthen waste heat recovery and utilize the recovered waste heat to preheat the combustion air. The NOx value also generally increases if the combustion air preheating temperature is increased. However, if the developed burner is used, combustion is possible without increasing the exhaust gas NOx value, even if the preheated air temperature is increased greatly from the present level of 320°C to 590°C. The developed burner demonstrates the highest performance in Japan, and conforms to Japanese regulations on NOx and other emissions, which are as strict as those in the EU and United States, even in combustion with 590°C preheated air.

4. Development Targets and Mechanism of Low NOx

As the target value of energy saving for the newly-developed radiant tube burner, the waste heat recovery rate was set at 48%, which was equivalent to two times the current 24%. In achieving this, it was neces-

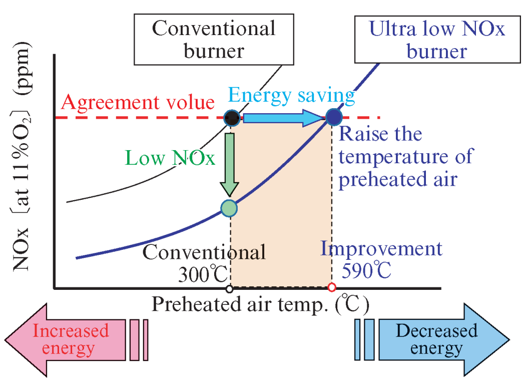


Fig. 3　Concept of energy saving by reducing NOx

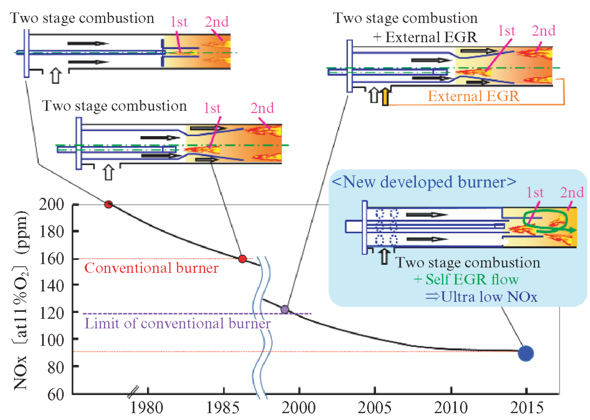


Fig. 4　Advances in NOx reduction technology for annealing furnace RT burners

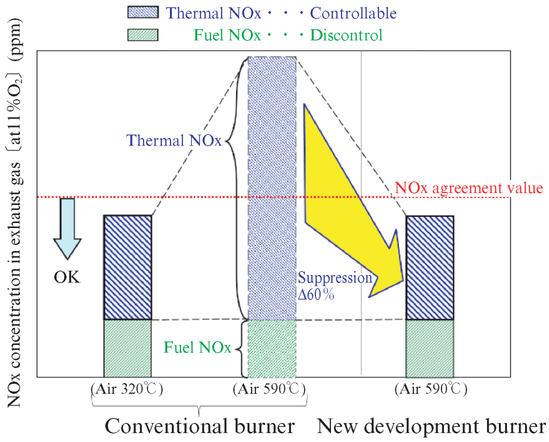


Fig. 5 Development target of RT burner (Thermal NOx suppression)

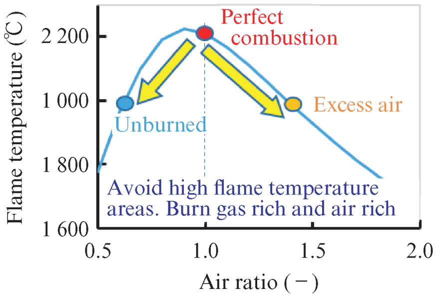


Fig. 6 Explanation of NOx reduction by rich-lean flame combustion

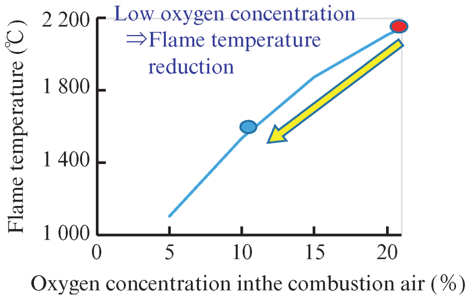


Fig. 7 Explanation of NOx reduction by low oxygen concentration combustion

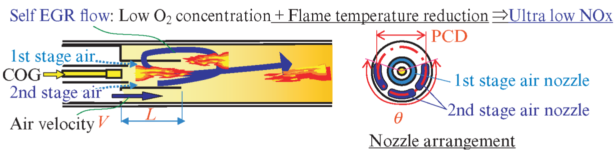


Fig. 8 Parameters in self EGR burner geometry

sary to substantially reduce the rise in thermal NOx, which generally accompanies an increased preheated air temperature and higher flame temperature, to the equivalent of the current NOx value.

The specific policy for achieving low NOx was as follows. Generally speaking, the NOx generated when byproduct gases generated in steel works are burned consists of two types: Fuel NOx originating from the N containing in the ammonia and other compounds that exist in trace amounts in the fuel, and thermal NOx, which increases along a quadratic curve at higher flame temperatures during combustion. Because fuel NOx originates from the fuel, it cannot be reduced by changing the combustion method[1,2]. Therefore, it was necessary to optimize the burner layout and consider a method that can hold the exhaust gas NOx value to the same level as the conventional technology by reducing thermal NOx (**Fig. 5**).

As a low NOx measure, conventional RT burners employed either two stage combustion, or a combination of two stage combustion and forced exhaust gas recirculation. As the mechanism of low NOx in two stage combustion, the flame temperature is reduced by performing combustion in the incomplete combustion region and excess air region (rich-lean combustion), while avoiding the peak flame temperature region around an excess air ratio of 1.0, and as a result, NOx generation is reduced[1,2] (**Fig. 6**). Forced exhaust gas recirculation is a technique in which NOx is reduced by reducing the flame temperature during combustion by mixing part of the exhaust gas generated by combustion in the combustion air, thereby reducing its oxygen concentration[1,2] (**Fig. 7**).

In this development, it was thought that the flame temperature could be reduced, in the same manner as in forced exhaust gas recirculation, by using two stage combustion in the radiant tube while partially forming a circulating flow of combustion exhaust gas in the space inside the tube. In other words, it should be possible to achieve the same effect by appropriately controlling the flow in the radiant tube to form a "self-exhaust gas recirculation (self-EGR) flow," in which the exhaust gas from combustion returns once again to the upstream side of the flow. For this, it was found that the most suitable burner layout for forming this "self-EGR flow" is one in which, in addition to the conventional two stage combustion, the 2nd stage air nozzles are arranged eccentrically with respect to the axial center of the burner, and the installation angle θ of the 2nd stage air nozzle shape, the arrangement of the nozzle pitch circle diameter PCD, the 2nd stage combustion air nozzle velocity V, the combustion tube length L and the 1st stage combustion ratio, *etc*. are optimized.

The developed environmentally friendly high-efficiency radiant tube burner (**Fig. 8**) forms a special exhaust gas flow, which is not formed in conventional burners, as a result of the eccentric arrangement of the 2nd stage combustion air nozzles. In this burner, top-level low NOx performance was achieved by forming a return circulation flow of the 1st stage combustion exhaust gas with a swirling motion around the periphery of the combustion tube in the longitudinal direction, and reducing the flame temperature by low oxygen concentration combustion that surpasses the conventional level as a result of this self-EGR action.

5. Behavior during Burner Combustion (Numerical Analysis Results)

The behavior of the developed RT burner during combustion was clarified by a numerical analysis.

As shown in **Fig. 9**, in a conventional two-stage combustion burner, a generally straight flow in the direction of the central axis (toward the right in the figure) of the RT can be observed. Furthermore, the distribution of the flame temperature accompanying that flow shows that the flame reaches a high temperature at the cross section approximately 0.9 m from the 2nd stage air injection hole, as the red-colored area indicating temperatures of 2 000°C and higher occupies approximately 70% of the diameter.

In contrast to this, in the developed burner, the red-colored area indicating temperatures of 2 000°C and higher has decreased to about 10% of the diameter at the cross section 0.9 m from the 2nd stage air injection hole because, according to the analysis, approximately 30 vol% of the flow forms a swirling self-EGR flow in the opposite direction to the main flow (toward the left in the figure).

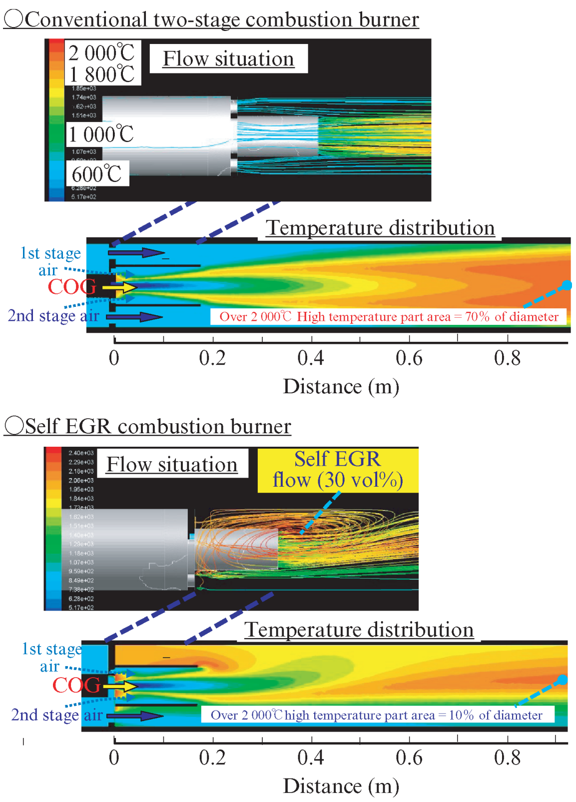


Fig. 9 Numerical analysis result of combustion in radiant tube burner

Based on the analysis results described above, in the conventional burner, a larger amount of thermal NOx, which is caused by temperature and increases quadratically, is generated due to the high temperature flame. However, in the developed burner, it was found that generation of thermal NOx is substantially reduced by the effect of the self-EGR flow in suppressing flame temperature rise.

6. Compact Recuperator

In introducing the developed burner to the actual facility, the recuperators which are installed to double the waste heat recovery rate to 48% should have dimensions that make it possible to arrange recuperators between adjacent radiant tubes, so the distance between flange faces was designed to a short 375 mm. In combination with this, the shape and specification of the recuperators was decided as shown in **Table 1** and **Fig. 10**, considering the heat transfer surface area of the elements, so that the waste heat recovery rate could be doubled. In comparison with the conventional device, the ratio of the heat transfer surface area occupied per unit of volume was increased from the conventional 35.5 m^2/m^3 to 207 m^2/m^3 in order to improve performance while also achieving a compact design. To ensure a uniform circulation of air to all the elements in the recuperator, an innovative design was adopted, in which efficiency was improved by tapering the tubes on the air piping side, where the diameter is particularly small. It may also be noted that the durability of the elements in the compact recuperator was secured by adopting a high temperature-resistant, acid-resistant

Table 1 Recuperator spec

	[Newly adopted]	[Conventional]
Recuperator type	Compact	Corrugated
Heat transfer area S	2.46 m^2	1.29 m^2
Volume V	0.0118 m^3	0.036 m^3
S/V	207	35.5
Exhaust heat recovery rate (Single use)	40%	25%

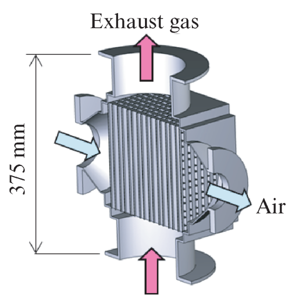


Fig. 10 Compact recuperator (3D cut view)

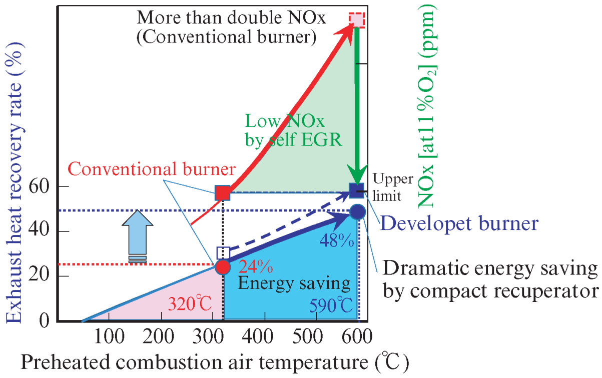


Fig. 11 Achievement of energy-saving and NOx by applying the developed RT burner

metal, considering corrosion by the trace amount of sulfur in coke oven gas (COG).

7. Condition of Introduction

A total of 162 units of the developed environmentally friendly high-efficiency burners were introduced at two lines with annealing furnaces at JFE Steel's West Japan Works (Fukuyama) in November 2016. Both lines achieved a combustion capacity of 110 000 to 120 000 kcal/h, a preheated combustion air temperature of 590°C and the targeted waste heat recovery rate of 48% when using COG, a byproduct gas generated in steel works, as the fuel gas in the basic specification (**Fig. 11**). As a result, a fuel gas reduction rate of ▲12% was achieved, contributing to a CO_2 reduction of 18.6 kt-CO_2/y. Environmental performance is also being maintained, as the exhaust gas NOx value at the chimney outlet is currently trending at 90 ppm or less.

8. Conclusion

As described above, the environmentally friendly high-efficiency RT burner introduced in this paper is continuing to operate smoothly at present, and is maintaining environmental performance as aimed. In the future, the author plans to study deployment of this technology to other annealing furnaces, as necessary.

References

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