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EXPERIMENTAL STUDY ON THE RADIANT TUBE BURNER WITH SELF-BIASED FUEL NOZZLE

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Abstract—Full scale combustion tests for a conventional fuel nozzle and a self-biased one were carried out using a two-stage radiant tube burner as the basis. Compared with the conventional nozzle, more than 40% reduction in NO_x emission was achieved with the self-biased nozzle. Under the same furnace temperature, the peak temperature was lowered and the temperature uniformity on the radiant tube was enhanced with the self-biased nozzle. The optimal design criteria for the self-biased nozzle were derived.

INTRODUCTION

An indirect heating method using radiant tube (R/T) which uses the radiation of the R/T to heat materials without oxidation is widely used at heat treating facilities such as continuous annealing lines and continuous galvanizing lines in steel industry [1, 2]. For the compactness of the furnace size in these heating facilities, radiation flux for each R/T should be relatively high. Enhancement of radiation is enabled by the installation of the R/T burner of high intensity combustion. Some important requirements for the R/T burner with high intensity combustion are, (1) no hot spot on the R/T and uniform temperature distributions for longitudinal and circumferential directions, (2) low level emission of NO_x, (3) complete combustion and no soot [3]. Among the above, item (1) is concerned with the uniform heating of materials and the life of R/T. If a hot spot occurs, temperature on that spot easily exceeds the durable limit of the R/T and the life of R/T is shortened. Meanwhile, a special counterplan for NO_x emission is necessary for R/T burner since the combustion load in the R/T is much higher than that of an ordinary furnace, wherein combustion takes place in a large space. Low NO_x emission becomes a prerequisite for all burners presently.

To meet the above requirements, a fuel nozzle enabling self-biased combustion was designed. Full scale combustion tests for a conventional nozzle and a self-biased one were carried out using a two-stage R/T burner as the basis.

Compared with the conventional nozzle, over 40% reduction in NO_x emission was achieved with the self-biased nozzle. Under the same furnace temperature, the peak temperature was lowered and the temperature uniformity on the R/T was enhanced with the self-biased nozzle. The optimal design criteria for the self-biased nozzle were derived through optimization tests.

EXPERIMENTAL

1. Experimental equipment

The experimental equipment used in this experiment is shown in Fig. 1. This equipment consists of test furnace, air and fuel supply systems, cooling air supply system, nitrogen supply system and combustion gas exhaust system. All parts of the equipment were designed to operate up to the air ratio of 1.5 for the combustion capacity of 1.6×10^5 kcal/hr. The test furnace is hexahedral and its dimension is 1.5m (H)×0.6m(W)×2.3m(L). A W-shaped, heat resistant metallic R/T (I.D. : 0.174m) was equipped in the furnace. Both ends of the R/T are attached to the R/T burner and the recuperator, respectively. The combustion method is pull type which prevails in real facilities. In the pull type system, atmospheric air is inhaled into the recuperator as the induced draft fan sucks out the combustion gas. Heat exchange occurs in the recuperator between the inhaled air and hot combustion gas. Therefore, the exhaust gas temperature is lowered and the air temperature goes up. The preheated air is supplied to the burner via connection tube. The floor of test furnace and fro and rear walls

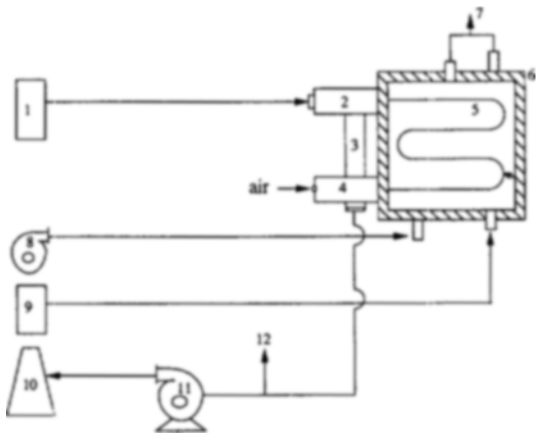

Fig. 1. Schematic diagram of the R/T burner test apparatus.

1. Fuel supply
2. R/T burner
3. Connection tube
4. Recuperator
5. Radiant tube
6. Test furnace
7. To atmosphere
8. Cooling air blower
9. Nitrogen supply
10. Stack
11. Induced draft fan
12. Sampling

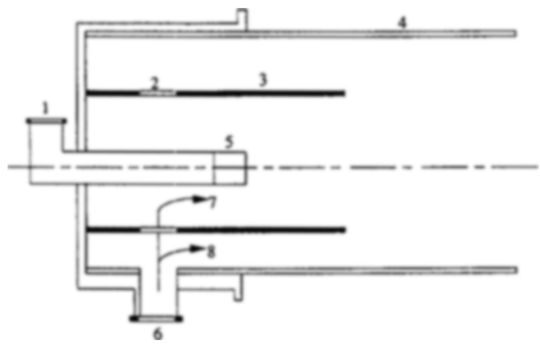

Fig. 2. Typical arrangement of the two-stage R/T burner.

1. Fuel inlet
2. Primary air port
3. Primary combustion tube
4. Radiant tube
5. Fuel nozzle
6. Air inlet
7. Primary air
8. Secondary air

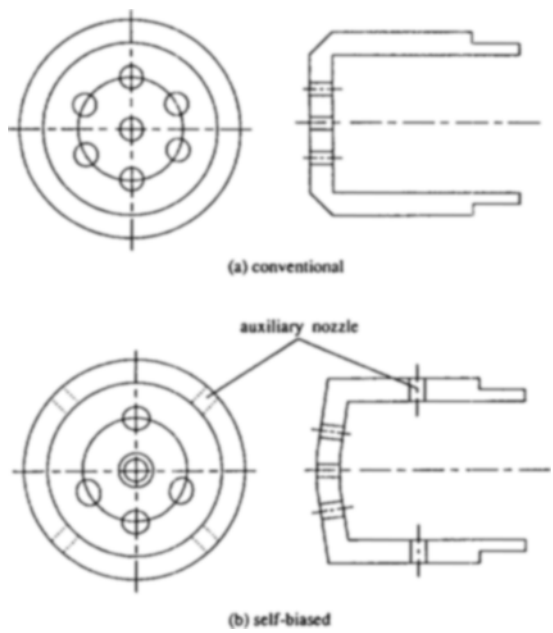

Fig. 3. Typical representation of the fuel nozzles.

supporting the R/T were made of refractory bricks. The ceiling of the furnace was covered by 0.1m thick ceramic board. Both side walls of the furnace were composed of air cooling chamber of 0.05m width to regulate furnace temperature. Ceramic fiber of 0.075m thickness was attached to the inside of the side walls. Furnace temperature could be controlled by adjusting cooling air flowrate in the cooling chamber as well as by introducing nitrogen gas directly into the furnace. Thermocouples were installed on the R/T to measure the longitudinal temperature distribution of the R/T. The location of each thermocouple is available in Fig. 7. The exact cumulative distance from the inside wall of the burner side to the center of curved sections is 1.919m, 3.593m and 5.267m, respectively. A sampling port for the analysis of exhaust gas composition was installed at the flue prior to the induced draft fan.

2. Experimental burner and fuel nozzles

Combustion tests with a conventional fuel nozzle and a self-biased one were carried out using a two-stage R/T burner (Fig. 2) as the basis. In the experimental burner, a fuel nozzle is coaxially placed in the center of the primary combustion tube. Fuel gas issuing from the fuel nozzle undergoes primary combustion in the primary combustion tube by the primary air supplied through primary air ports. Secondary combustion takes place in the R/T by the secondary air supplied through the annular space between the primary combustion tube and the R/T. For the experimental burner, 57% of total combustion air is fed as the primary air.

Fuel nozzles used in the experiment are shown in Fig. 3. In case of the conventional nozzle, fuel injection holes are arranged uniformly along the radial direction of nozzle tip. In the self-biased one, fuel is divided into main fuel and auxiliary fuel. To establish off-stoichiometric combustion, fuel injection holes of main fuel nozzle are arranged non-uniformly, that is, more

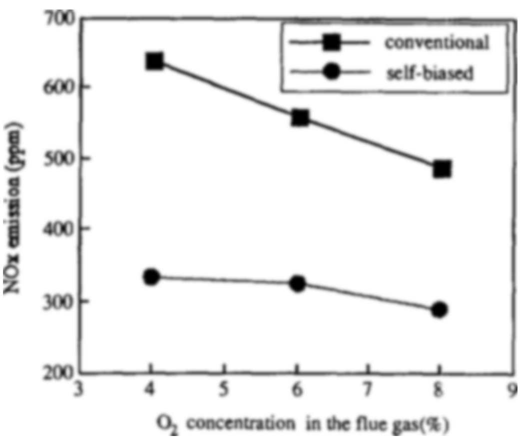

Fig. 4. Comparison of NO_x emissions between fuel nozzles.

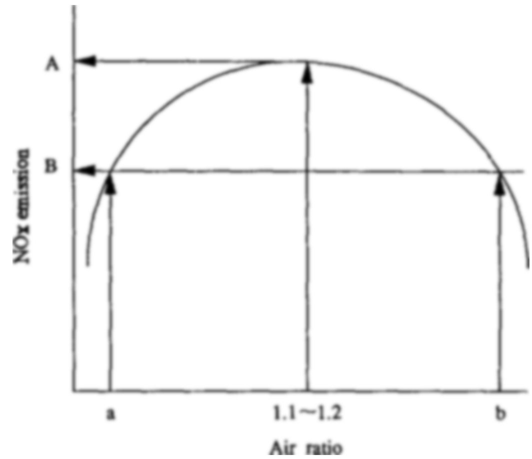

Fig. 5. Qualitative dependence of NO_x emission on the air ratio.

holes at the lower half of the nozzle to inject more fuel to the lower cross-section of the R/T. Auxiliary fuel is injected perpendicularly to the primary air stream through some holes located prior to the main nozzle. Flame stabilization was the primary objective of the auxiliary fuel injection.

3. Experimental procedure

Combustion tests for performance comparison of fuel nozzles and for optimization of the self-biased nozzle were carried out in this experiment. In combustion tests, emphases were given to the exhaust gas composition and the temperature distribution on the R/T. The combustion load was kept at 1.0×10^5 kcal/hr and the furnace temperature was maintained about 950℃. Temperature of preheated air at burner inlet was about 400℃ with minute fluctuation according to the experimental condition. Because the combustion air flowrate could not be measured in pull type system, oxygen concentration in the flue gas was selected as the experimental variable instead of the air ratio. The oxygen concentration was varied as 4%, 6% and 8% considering the normal operating range of the pull type combustion facilities. Coke oven gas (net heating value: 4,400 kcal/Nm^3) was used as the experimental fuel. About 3 hours after ignition, quasi-steady state was reached. Temperature was measured by K-type thermocouples and exhaust gas composition was measured by using flue gas analyzer (MRU 95/2D) and Orsat analyzer.

RESULTS AND DISCUSSION

1. Performance comparison of fuel nozzles

In the experiment to compare the basic performance of fuel nozzles, a self-biased nozzle with 5 holes for main fuel injection, 15° angle of main fuel injection hole and 30% of auxiliary fuel ratio was used.

1-1. NO_x emission

Fig. 4 shows NO_x emission of the experimental two-stage burner with the self-biased nozzle and the conventional one. Compared with the conventional nozzle, it is found that more than 40% of NO_x reduction is possible in case of using the self-biased one. It is thought that the NO_x reduction is mainly due to the off-stoichiometric combustion effect [4] of the self-biased nozzle. The availability of the off-stoichiometric combustion on NO_x reduction could be elucidated as follows.

In general, the dependence of NO_x emission on the air ratio shows a convex curve with a maximum value at a specific air ratio (Fig. 5). Although the air ratio which results maximum NO_x emission is somewhat different with fuel species, maximum value of NO_x emission is mostly found at the air ratio of 1.1-1.2 [5]. Let's consider air rich combustion with both nozzles at the total air ratio of 1.2. In case of using the self-biased nozzle, as shown in Fig. 6, the upper cross-section in the R/T becomes fuel lean state and the lower cross-section becomes fuel rich state. The upper cross-section corresponds to point b and the lower cross-section corresponds to point a in Fig. 5. Therefore, NO_x emission corresponding to point B is expected for the self-biased nozzle. For the conventional nozzle, however, it could be considered that all the cross-section in the R/T is maintained with a uniform air ratio, namely 1.2. As a result, a maximum value of NO_x emission (point A in Fig. 5) could be predicted

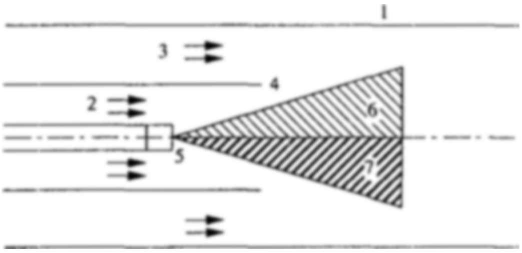

Fig. 6. Conceptual diagram showing the air-fuel mixing for the self-biased fuel nozzle.

1. Radiant tube
2. Primary air
3. Secondary air
4. Primary combustion tube
5. Fuel nozzle
6. Fuel lean
7. Fuel rich

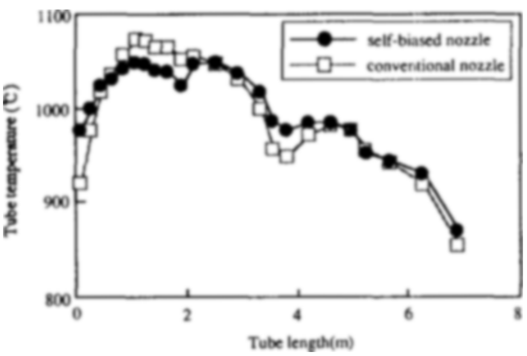

Fig. 7. Comparison of temperature distribution on the radiant tube between fuel nozzles.

for the conventional nozzle. Consequently, NO_x reduction of A-B (quantity basis) can be obtained for the self-biased nozzle. If the air ratio increases gradually, higher than 1.2, the upper cross-section of the R/T becomes more fuel lean state while the lower cross-section is transferred from fuel rich to fuel lean state. However, the off-stoichiometric combustion effect of the self-biased nozzle remains unchanged although reduction ratio in NO_x emission is slightly decreased with the increase of the air ratio. It could be considered that the NO_x reduction in the experiment (Fig. 4) is the reflection of the above-mentioned off-stoichiometric combustion effect.

1-2. Temperature distribution on the R/T

Comparison of temperature distribution along the longitudinal direction of R/T with each fuel nozzle is shown in Fig. 7. The oxygen concentration in the flue gas was 4% in this case. It is found that the highest temperature obtained for each nozzle appears at the rear part of the first straight tube. The mean temperature on the first straight tube with the conventional nozzle is much higher than that with the self-biased one. The peak temperature for the conventional nozzle was 1,073℃ and that for the self-biased one was 1,049 ℃ while furnace temperature was maintained equally as 950℃. Longitudinal temperature gradient was lowered in case of using the self-biased nozzle. Lowering of peak temperature is desirable for longer life of R/T and uniform temperature distribution on the R/T is effective for heating strip. From the above points of view, it can easily be seen that the self-biased nozzle is lucrative compared to the conventional one.

Temperature difference appears mainly at rear half of the first straight tube in which secondary combustion takes place. The lowering of peak temperature with the self-biased nozzle is thought to be due to the auxiliary fuel injection. When the auxiliary fuel burns, combustion gas of the auxiliary fuel flows along the inner surface of the primary combustion tube. The gas is finally ejected to the reaction interface between main fuel and the secondary combustion air. Surrounding the main fuel by the combustion gas effects retardation of the secondary combustion rate, and thus a mild secondary combustion takes place. This phenomenon suppresses the rapid rise of combustion temperature and contributes to the uniform temperature distribution on the R/T. On the contrary, main fuel and the secondary combustion air meet directly in case of the conventional nozzle to cause a rapid combustion. This results in the temperature rise on the first straight tube of the R/T.

Temperature profiles for other experimental conditions were similar to that in Fig. 7. Temperature difference between nozzles was reduced as the oxygen concentration in the flue gas went up. CO concentration in the flue gas was lower than 100 ppm for both nozzles, which indicates complete combustion with the practical view point.

2. Optimization of the self-biased nozzle

Since the basic performance of the self-biased nozzle, that is temperature distribution on the R/T and NO_x emission, was found to be superior to that of the conventional one, optimization test for the self-biased nozzle was performed. Number of main fuel injection hole, main fuel injection angle and auxiliary fuel fraction were selected as target variables. Temperature distribution on the R/T was found to be affected little by the variation of each variable, therefore, only the effect of each variable on NO_x emission will be mainly reviewed hereafter.

Fig. 8 shows the dependence of NO_x emission on the number of main fuel injection hole. In this experiment, two kinds of fuel nozzle, 3 holes and 5 holes

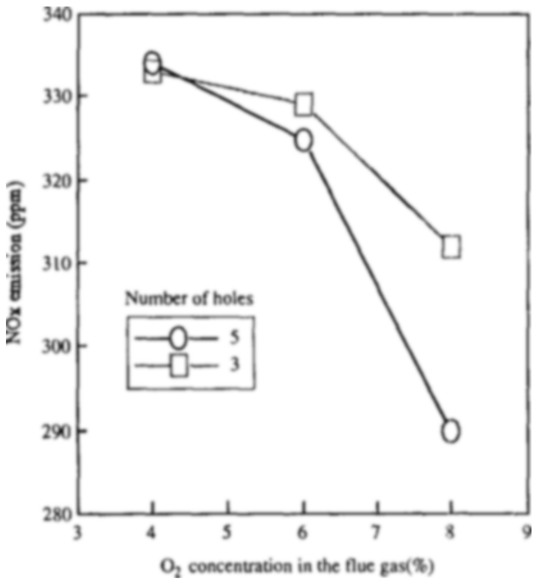

Fig. 8 Variation of NO_x emissions w.r.t. the number of holes of main fuel nozzle.

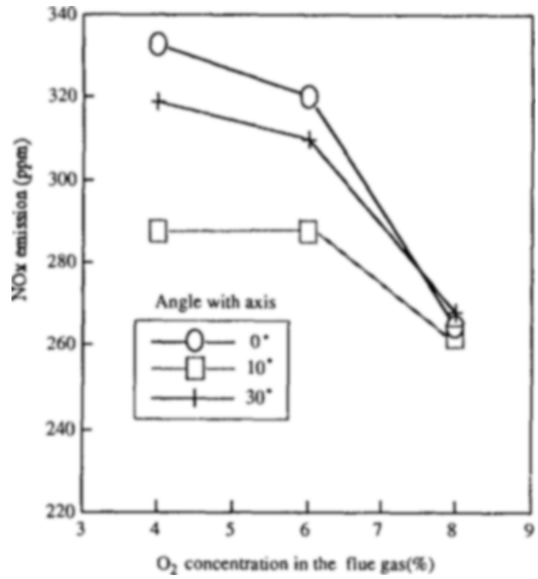

Fig. 9. Variation of NO_x emissions w.r.t. the injection angle of main fuel nozzle.

for main fuel injection, were tested because of the space limitation for arranging holes with self-biased structure at a small nozzle tip. For the nozzle with 3 holes, one hole was located at the upper half and the remaining two holes were arranged at the lower half of the nozzle. NO_x emission shows some reduction in case of the nozzle with 5 holes compared to the nozzle with 3 holes. This NO_x reduction could be explained by flame cooling effect. When fuel gas issues from a nozzle with some holes, several independent flames are formed according to the number of holes. As the increase of the number of holes, total surface area of the flames is enlarged and heat release from flame to bulk stream is enhanced. As a result, flame temperature is cooled down and NO_x formation is suppressed.

Fig. 9 shows the variation of NO_x emission with respect to the main fuel injection angle. NO_x emission with the nozzle angle is found to be in the order of $10° < 30° < 0°$, that is, consistent inclination or declination is not shown. The basic purpose of making angle was on the enhancement of air-fuel mixing for complete combustion. Generally, appropriate mixing is known to be effective in enhancing complete combustion and in reducing NO_x emission [7]. From the experimental result, it is thought that optimal mixing was achieved at the nozzle angle of 10°. The augmentation of NO_x emission in cases of 0° and 30° is considered due to poor mixing and radical mixing, respectively.

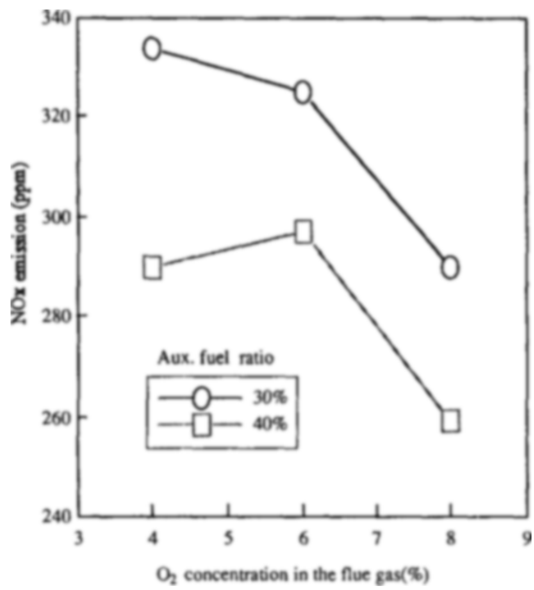

Fig. 10. Effect of auxiliary fuel ratio on NO_x emission.

Since the auxiliary fuel injection was found to be effective in promoting temperature uniformity on the R/T [6], combustion test was done to determine the upper limit of auxiliary fuel injection. In the experiment, 30% and 40% of auxiliary fuel injection were selected as potential limits. As shown in Fig. 10, NO_x

emission in case of 40% of auxiliary fuel injection was lower than that of 30% injection. It is considered that the NO_x reduction was effected by the retardation of secondary combustion as explained previously.

CONCLUSION

Full scale combustion tests for a conventional fuel nozzle and a self-biased one were carried out using a two-stage radiant tube burner as the basis. It was found that the self-biased nozzle is effective in reducing both NO_x emission and peak temperature on the radiant tube. It was considered that the temperature distribution on the radiant tube could be improved by the adoption of auxiliary fuel injection. The optimal design criteria of the self-biased nozzle were determined as 5 holes for main fuel injection, 10° angle of main fuel injection hole and 40% of auxiliary fuel ratio.

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