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DEVELOPMENT OF THE INDUSTRIAL SELF REGENERATIVE COMBUSTION SYSTEM

Yu Hyunseok*†, Lee Hyunchan*, Hong Seongho*, Dong Sanggeun**, Yang Jebok**

* Korea Gas Cooperation R&D Center, New Energy & Environment Team
** Korea Institute of Energy Research, Industrial Efficiency Center

† Correspondence author : hsyoo@kogas.or.kr

ABSTRACT

It is very important to develop an energy saving combustor for industrial furnaces, considering that energy use of industrial furnaces is about 22% of the total energy use in Korea. The objective of this research is the development of a self-regenerative combustion system using high airtight reverse valve to increase the thermal efficiency of a furnace system. Because a commercial regenerative burner consists of two burners, it is expensive and a relatively large installing area is needed. However, the self-regenerative burner operates with only one burner to thus have advantages in an economic and space point of view.

A self-regenerative burner has multi air nozzle in one burner, where half of them are for the combustion of fuel and preheated air and the rest of them are for the exhaust of combustion gas. Cycling in periodic combustion is performed in one burner. So, it drives internal recirculation flow in a furnace and causes the well mixing heat transfer between the flame and exhaust gas. This well mixing heat transfer makes the temperature in the furnace uniform and decreases NOx and CO.

To develop an optimum design, numerical analysis is performed with Fluent Code. Magnussen model (Hybrid Kinetics/Eddy Break-Up Model) is used. The result of the simulation is that strong internal recirculation flow forms in the furnace. The optimum design achieves and clearly predicts that low NOx and CO, and a uniform temperature will be formed in the furnace. To confirm the performance of the optimally designed self-regenerative burner, a 230 kW self-regenerative burner and a PLC for controlling the burner system have fabricated and experimented in the test furnace.

The result of the burner performance in the test furnace showed the flameless combustion made by strong internal recirculation flow. Though the high temperature air combustion is applied in the burner system, NOx and CO exhaust below 100ppm@11%O_2 in the range of 2~7% O_2 in the exhaust gas.

The thermal efficiency of self-regenerative burner and furnace system is noticeable at an exhaust gas temperature, i.e. in the case of a 1,250℃ furnace temperature, the temperature of exhaust gas is 150~200℃, which is the same as that of boiler exhaust gas. So, the thermal efficiency of a self-regenerative burner and furnace system much increase, comparing with a commercial furnace type burner.

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1. Introduction

It is very important to develop an energy saving combustor for industrial furnaces, considering that energy use of industrial furnaces is about 22% of the total energy use in Korea, and a self-regenerative combustion system is a solution. In a case where the capacity of an industrial furnace is below 1,000 kW, the conventional twin regenerative combustion system incurs excessive system costs with respect to the capacity. In this case, it is difficult to apply the conventional twin regenerative combustion system, and thus, there is a demand for a compact single self-regenerative combustion system. Therefore, this research has developed a compact combustor using high airtight reverse valve which guarantees an airtightness of up to 95% of air and exhaust gas at a temperature of about 200℃ and a regenerator. Here, the compact combustor is not only a small combustor, but is a combustor with high efficiency, high precision, and high controllability that is sufficient for efficient combustion within a limited space.

2. Theoretical review

A shape of a regenerative burner Is optimized by giving thermal property change with respect to a burner regenerator and simulating each of combustion flow field within a furnace corresponding to changes in fuel and air injection velocity by using a Fluent Code. In a burner, half of the regenerators and nozzles are set for the combustion of fuel and preheated air and the rest of them are set for the exhaust of combustion gas. Here, the Magnussen model, which is a hybrid kinetics/eddy break-up model, is employed.

$$R_{fu} = -\rho \frac{\epsilon}{k} MIN\left[Am_{fu,} \frac{Am_{ox}}{STOIC,} AB \frac{m_{pr}}{1+STOIC} \right]$$

Where

R_{fu} : fuel reaction rate

ρ : air/fuel mixture density

ε / k : eddy lifetime

m_i : i component mass fraction($m_{fu} + m_{ox} + m_{pr} = 1$)

$A = 32, B = 4$

$STOIC$ = stoichiometric

3. Experimental apparatuses and methods

3.1 Single regenerative burner capacity

Compared to a conventional regenerative combustion system including a pair of burners, a single self-regenerative burner may perform regenerative combustion by itself and the capacity of the single self-regenerative burner is 250,000 kcal/hr.

3.2 Single regenerative burner and test furnace system

FIG. 1 shows a completed single regenerative burner system and a test furnace for testing the same. In the single regenerative burner, the green piping supplies air for combustion and the black is for exhaust gas. The air for combustion alternately flows into the right and left side of single regenerative burner via a 3-way valve, and exhaust gas is alternately exhausted by a high-temperature butterfly valve via the black right and left piping. The internal cross-section of the test furnace has a width of 1,500 mm, a height of 1,200 mm, and a length of 2,500 mm, and combustion occurs alternately at the left portion and the right portion of the test furnace. An R-type thermocouple is arranged at the center portion of a side surface of the test furnace in a lengthwise direction to measure the inside temperature of the test furnace, and the internal pressure of the test furnace is measured by a pressure sensor arranged at an end side thereof in a lengthwise direction. To measure the regenerating efficiency of the regenerator, K-type thermocouples are respectively arranged behind the regenerator to measure the temperatures of air for combustion and exhaust gas, and a K-type thermocouple is arranged on a piping of a final exhaust gas outlet. For analysis of exhaust gas, a gas sampling port is arranged at the center portion of a side surface of the test furnace in a lengthwise direction. All measured data is acquired by using an A/D board. The supply of air and fuel for combustion is controlled using control valves, and flow rate may be measured by using an orifice-type flowmeter. For controlling internal pressure of the test furnace, an exhaust fan with an inverter control is installed.

The burner is controlled using a PLC, and the main components of a control system include a timer for controlling cycling in periodic combustion, an exhaust fan controller for controlling internal pressure of the test furnace, various solenoid valves, and an ignition transformer switch.

FIG. 1 Self-regenerative burner system in the test furnace

4. Results and discussions

4.1 Simulation of self-regenerative burner performance

As shown in FIG. 2, strong internal recirculation flow occurs in the entire space inside the test furnace, wherein the upper portion is in combustion mode, the lower portion is in exhaust mode, combustion load is 250,000 kcal/hr, and air/fuel ratio is 1.05. Flow at the leading end portion of a nozzle is highly stable, a recirculation region is significantly larger as compared to a general case, and it is predicted that recirculation flow occurs through a distance corresponding to two-thirds of the combustion furnace length from a burner outlet. Therefore, stable combustion gas circulation, which is pursued in this research, may be expected, and the stable combustion gas circulation will enable low NOx combustion.

The distribution of temperatures inside the test furnace is from 1,000℃ to 1,800℃, and, except for the leading end portion of a burner from which high temperature air is jetted, the temperature is uniform overall, that is, 1,500℃ or above, and thus, an object may be uniformly heated in actual operation.

FIG. 3 shows O_2 mass fraction in the test furnace. As shown in FIG. 2, combustion occurs in the upper/right portion of the test furnace, whereas exhaustion occurs in the lower/left portion of the test furnace. Although the O_2 mass fraction forms symmetry in the test furnace, it is a result of termination of a combustion reaction due to injection of high temperature air, and the distribution of temperatures inside the test furnace is uniform due to internal recirculation flow.

Based on the analysis results states above, optimal performance of the self-regenerative burner designed in this research may be expected, and thus, the design is reflected to an experiment for proving actual performance.

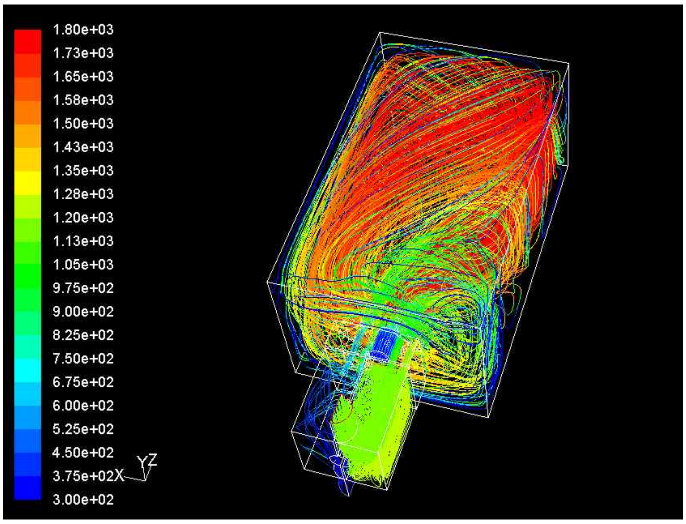

FIG. 2 Combustion flow path line of self-regenerative burner in the test furnace

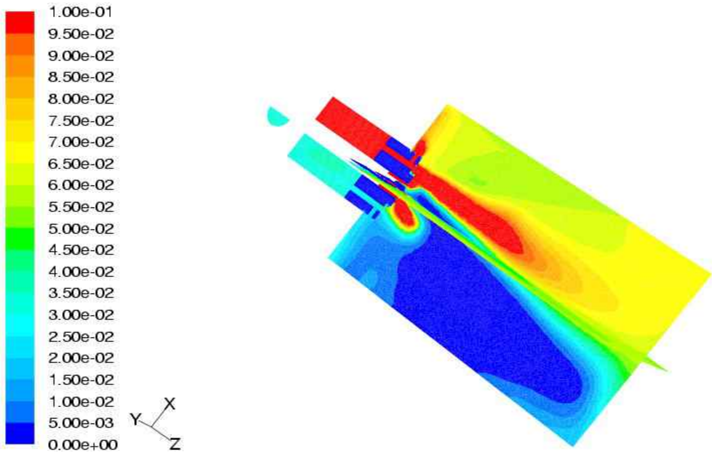

FIG. 3 O_2 concentration contour of self-regenerative burner in the test furnace

4.2 Experimental test of self-regenerative burner performance

- **Thermal efficiency**

FIG. 4 shows flameless combustion when the temperature inside the test furnace is 1,280℃. Strong internal recirculation flow due to high speed injection of high temperature air induces re-inflow of combustion products into a combustion region and causes flameless combustion. After the ignition, from 20% to 40% of the amount of the entire air flows in via primary and secondary air nozzles until the internal temperature rises to about 900℃. After the internal temperature rises above 900℃, a primary and secondary air amount, of which corresponds to only from about 5% to about 10% of the amount of the entire air, flows in, so that from about 90% to about 95% of the amount of the air for combustion regenerates. As a result, recirculation flow actively occurs due to FDI combustion.

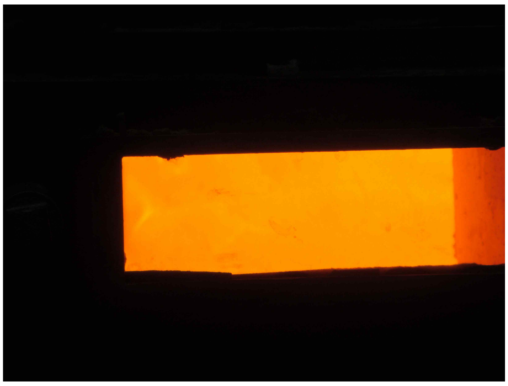

FIG. 4 Flameless combustion of the self-regenerative burner in the test furnace (O_2=3%)

FIG. 5 is a graph showing the temperature at the outlet of a regenerator and the temperature of the atmosphere inside the test furnace that are measured over time, where switching time of regenerative burners is 30 seconds. The temperature of the atmosphere inside the test furnace rises to about 1,250℃. The green line and yellow line indicate temperatures of exhaust gas after a regenerator, respectively. The variation of temperature of exhaust gas after the regenerator is from about 150℃ to about 170℃, and a fuel saving rate herein is about 50%. The balance of energy in the left portion and the right portion of a regenerator of a burner varies as much as a difference between the average values of the green line and the yellow line, that is, from about 5% to about 7%, as shown in the graph. The difference is based on subtle differences between weights of regenerative balls and flow paths of the left regenerator and the right regenerator. However, the difference does not significantly affect the actual efficiency and operation of the entire system. The leakage rate at a switching valve is below 5%.

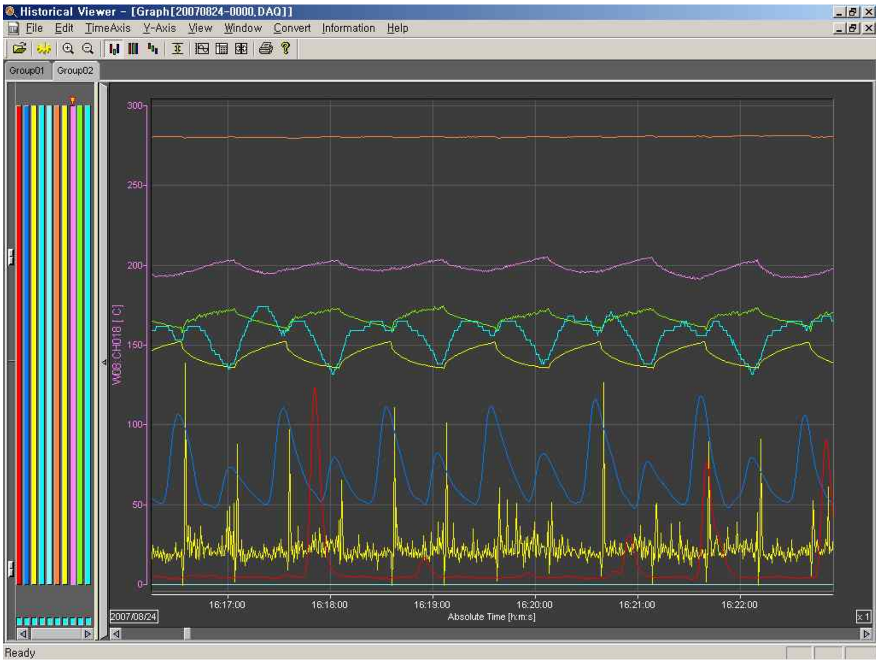

FIG. 5 Temperature variation of each point in the test furnace with respect to time

- **Emission performance**

FIG. 6 shows the change in NOx concentration according to change in O_2 concentration in exhaust gas. When the temperature inside the test furnace is 1,250℃ and the oxygen concentration in exhaust gas is from 1.0% to 3.0%, NOx concentration is from about 30 ppm to about 40 ppm, which is very low. The result shows that flameless combustion occurs in the test furnace. With respect to O_2 concentrations of 3% or above, NOx concentration increases linearly, which indicates that conditions for flameless combustion are not met. Therefore, it is preferable to maintain air ratio low for actual operation.

FIG. 7 is a graph showing exhaust correlation between O_2 and CO. At an oxygen concentration from 2% to 8%, CO concentration is below or equal to 10 ppm, and perfect combustion is obtained. Therefore, an oxygen concentration equal to or above 2% is a condition for perfect combustion without CO generation. Such excellent performance of combustion may be highly advantageous for controlling air ratio of a burner.

The optimal air ratio condition that may be determined based on exhaust composition of NOx and CO is from 2% to 3%.

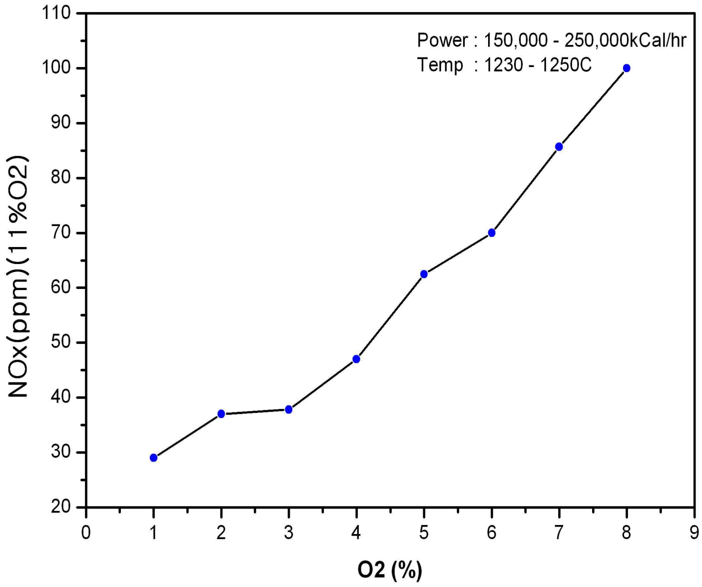

FIG. 6 The relation between NOx and O_2 in regenerative burner

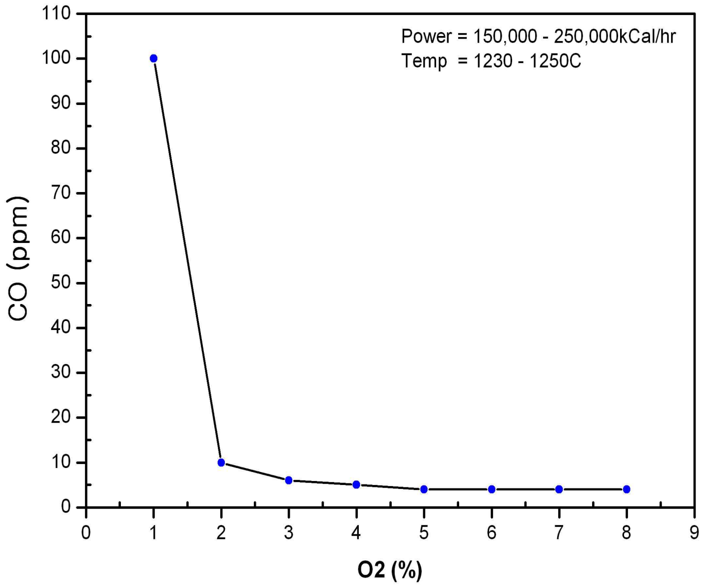

FIG. 7 The relation between CO and O_2 in regenerative burner

In a general burner, temperature significantly affects NOx exhaust. FIG. 8 shows exhausted NOx concentration according to temperatures inside the test furnace. The combustion load is from 140,000 kcal to 1,500,000 kcal, and oxygen concentration is 2%. As shown in

FIG. 8, NOx exhaust gradually increases according to temperature. However, at temperatures above 1,100℃, there is no dramatic increase in NOx concentration, because thermal NOx generation mechanism doesn't works due to flameless combustion. Considering that the temperature of operation in general furnace is from about 1,100℃ to about 1,200℃, the self-regenerative combustion is very effective in the aspect of NOx reduction.

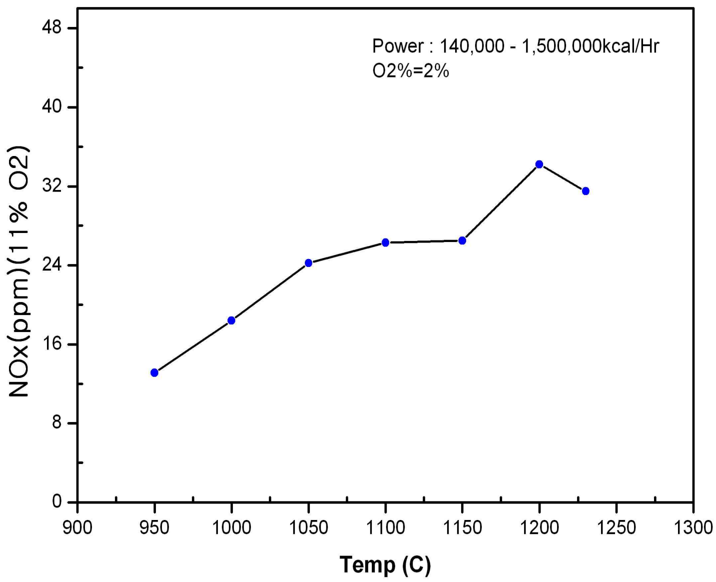

FIG. 8 The relation between NOx and temperature inside furnace

5. Conclusions

The optimal design of a self-regenerative burner is acquired via the simulation, and results, as shown below, are acquired via the experiment for proving actual performance.

(1) Via numerical analysis, it can be predicted that the self-regenerative burner generates strong internal recirculation flow inside the test furnace, and thus, embodiments of flameless combustion and reduction of both CO and NOx are expected.
(2) Via optimal designs of a burner head and a regenerator, high temperature exhaust gas in the test furnace of which a temperature is 1,250℃ is finally output as exhaust gas of which a temperature is below or equal to 200℃ via heat recovery of the regenerator. Thermal efficiency is significantly improved as compared to that of a conventional furnace burner.

(3) High temperature air combustion via a regenerator enabled high speed air injection, and thus, strong internal recirculation flow can be formed inside the test furnace. As a result, combustion products flow back to the flame reaction region, and thus, flameless combustion is embodied.

(4) Due to flameless combustion, when the temperature inside the test furnace is 1,250℃ and the O_2 concentration is from about 2% to about 3%, CO exhaust concentration is below or equal to 10 ppm, whereas NOx exhaust concentration is below or equal to 40 ppm (11% O_2). However, under the conditions in which O_2 concentration is 3% or above, NOx exhaust concentration tends to increase linearly. The result conflicts with the general tendency in which NOx concentration decreases when excessive air increases. Therefore, even if excessive air increases, the temperature inside the test furnace is sufficiently high, that is, about 1,250℃, and thus, a thermal NOx generation mechanism works. Furthermore, the result shows that a region corresponding to flameless combustion is relatively narrow with respect to the entire combustion region.

(5) Based on the conclusions above, the optimal condition for operating the self-regenerative burner is determined as O_2 concentration from about 2% to about 3%, where the range is relatively narrow with respect to the entire combustion region. Furthermore, a sequence and cycle of operating switching air and fuel valves according to alternating combustion, and load-balanced air ratio controlling techniques are important herein. Therefore, for an optimal embodiment of a self-regenerative burner, not only an optimal design of a burner, but also a technique for optimally controlling the regenerative burner system is required.

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