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Investigation of Regenerative Combustion Using a Heavy Fuel Oil

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A heavy-fuel-oil-fired regenerative burner has been under development. The objectives, at an early stage of the project, were to evaluate the NO_x emission level and the performance of the heat regenerator and to solve problems such as plugging of heat regeneration media, coking of atomizers, and flame stability at cold startup. Utilization of a honeycomb-type ceramic regenerator resulted in high air-side temperature efficiency, averaging 92%, and high preheated-air temperature, above 1000°C at a furnace temperature of 1200°C. Staging-fuel technology adopting two secondary fuel atomizers angled 30 deg with the airflow and an internal flue gas recirculation induced by the preheated-air jet helped to reduce NO_x emission from 429 ppm without staging-fuel to 153 ppm using 100% staging-fuel, that is, a 64% reduction, at a furnace temperature above 1200°C.

Introduction

INDUSTRIES in Taiwan have been experiencing increasing pressure to reduce energy consumption and pollutant emissions.[1] It recently became urgent after the third meeting of the Conference of the Parties for United Nations Framework Convention on Climate Change held in Kyoto, Japan, 1997. Development and application of a combustion system with higher efficiency and lower emission is, therefore, a responsibility of local combustion researchers and engineers.

Combustion of fuel gas with highly preheated air has been studied and in service in Europe and United States for years.[2–12] A high cycle regenerative combustion system (HRS) incorporating a ceramic honeycomb as heat regeneration media was developed at Nippon Furnace Kogyo, Japan. Temperatures of preheated air were reported being within 100°C of furnace temperatures. It contained three major components, a pair of burners, a honeycomb-type ceramic regenerator, and a cross exchange mechanism for reversing air and flue flows. Optimum regeneration of heat was achieved by alternating firing with a cycle less than 1 min. These characteristics led to impressive energy efficiency and better controllability and uniformity of temperature in furnaces.[13–16] It was estimated that there was a 30% energy saving rate over the past case where there were no provisions for waste heat recovery; the thermal efficiency of the furnace was more than 50% greater; and the waste heat, recovery rate was more than 60% higher.[17]

Heavy fuel oils has the following API (American Petroleum Institute) specifications at 60°F: gravity—12, flash point—150°F, viscosity (at 122°F)—200, sulfur content—2.0 wt%, carbon residue—15 wt%, and water 0.5 vol.%. Heavy fuel oil is the most popular energy source in local industry. Therefore, the combustion of this oil, using regenerative burners, is of great interest to local industry. Very limited information is available in the open literature on the combustion of heavy fuel oils using highly preheated air with regenerative burners. In this paper we present experimental results from a pilot scale facility using heavy fuel oil in regenerative burners. Results presented include information on fuel spray characteristics, regenerator performance and emission of NO_x.

Experimental Apparatus

It is known that combustion with preheated air correspondingly emits more NO_x pollutants. The higher the temperature of the air is, the higher the level of NO_x emission. This is because a higher peak flame temperature is generated, which provides a suitable environment for thermal NO_x formation.[18] To design a low-NO_x burner, generally the means of introducing air and fuel are modified to delay mixing, reduce the availability of oxygen, and reduce the peak flame temperature. Commercial staged-fuel gas burners have 40–50% NO_x reduction capability compared to a standard gas burner.[19] In this study, one primary fuel atomizer and two secondary fuel atomizers were integrated to the regenerative burner as shown in Fig. 1. To ensure the contact of the secondary fuel and air, the secondary fuel atomizers were angled 30 deg with the airflow. To solve problems of plugging of regenerators and cold startup, prefilming and plain-jet air-blast atomizers were adopted for primary and secondary fuels, respectively, for their capability to produce fine spray and through mixing of a large amount of atomizing air and fuel.[20] For a detailed description of the atomizers is provided by Lefebvre.[20]

A honeycomb-type ceramic regenerator was employed for the large specific surface area and small pressure drop.[13] The overall dimensions of the ceramic honeycomb for each burner were 300 mm length × 150 mm width × 200 mm height. The burners with the maximum capacity of 18 l/h alternated firing with a constant period of 30 s. They were mounted on a test furnace with inner dimensions of 1.85 m width × 1.55 m depth × 0.97 m height (shown in Fig. 2). A system consisting of oil pump, electrical heater, and piping for oil circulation was utilized to ensure fuel was preheated above 90°C before entering the atomizers. A forced draft fan and an induced fan were used to supply air and to suck flue gas out of the test furnace. A damper in the exhaust line was automatically adjusted to maintain furnace pressure.

An imaging system composed of a 5-W argon-ion laser, a disk-type scanner, and a charge-coupled device (CCD) video camera module (Sony Model XC-27) was utilized to capture water spray images. A laser sheet was generated by introducing the laser to mirrors mounted on the rim of the scanner rotating at 10,000 rpm. The laser sheet was then directed to the central line of the spray with its normal perpendicular to the flow direction. The water spray images were recorded with the CCD video camera. Shades of gray were then transformed from digitized intensity of the image through image processing software. Though the shades of gray could not give any information about size or number of drops, they reflected relative concentrations by volume of drops.

Sauter mean diameter (SMD) and axial velocities of drops from spray were measured with an optical system. It consisted of four subsystems, namely, a piping system for supplying water and atomizing air to the atomizer, a three-axis traversing mechanism for mounting and positioning the atomizer facing downward, a two-component phase Doppler particle analyzer (PDPA), and an exhaust system. Pressures and flow rates of both water and atomizing air were adjusted with regulators and flowmeters, respectively. The traversing

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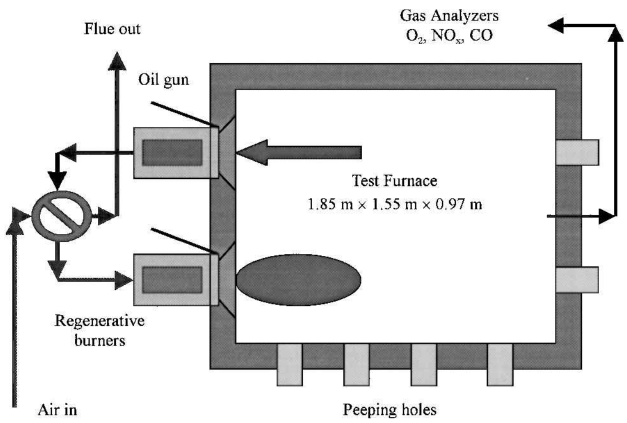

Fig. 1 Schematic diagram of experimental apparatus.

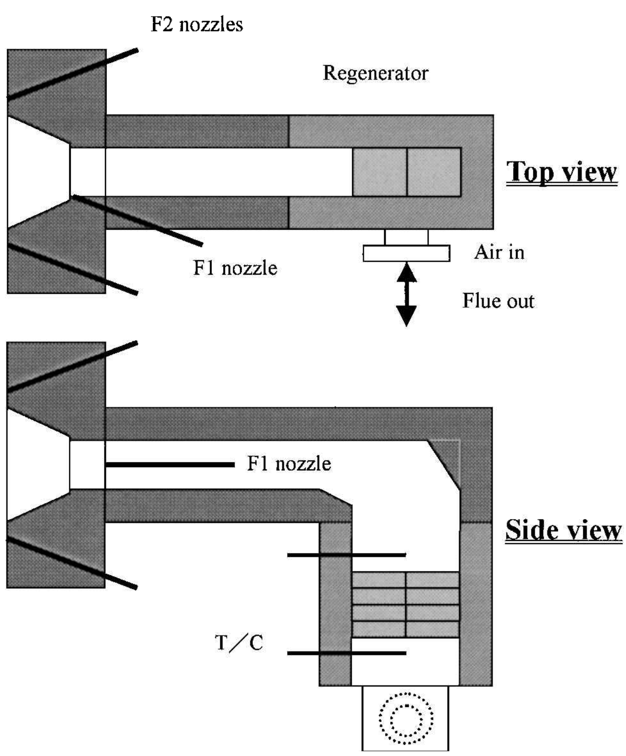

Fig. 2 Schematic diagram of regenerative heavy-fuel-oil-fired burner.

mechanism was positioned with step motors controlled by an IBM-compatible personal computer. For a single measurement, 30,000 scans from the PDPA were averaged. Flow reversal causing measuring error was eliminated by introducing a uniform curtain flow around the test section. The accuracy of SMD and axial velocity measurements was estimated at 5 and 2%, respectively.

Two 0.13-mm-diam, R-type (platinum 13%, rhodium vs platinum, Omega), unsheathed fine-gauge thermocouples were inserted into the top and bottom of the regenerator for each burner to measure air and flue gas temperatures instantly. The temperatures of the flue and exhaust for the burner in the firing mode and the temperatures of fresh air and preheated air for the burner in the exhausting mode were then simultaneously recorded. The temperatures were sampled every 0.5 s and averaged for each half-cycle. Because the air and the flue gas were relatively clean, the unsheathed thermocouple beads used in this study were not coated. On the other hand, because the air/flue gas paths inside the burner were insulated, the temperature measurements were not corrected for radiation heat transfer due to the small temperature difference between the thermocouple beads and walls.[21]

A stainless steel sampling probe was inserted on the wall opposite to the regenerative burners to suck furnace gases to a cooler to condense the water vapor. The gases were then directed to gas analyzers to deduce concentrations of O_2, NO_x, and CO. The instruments used were Model 755A Beckman Industrial, Model 951A Resemount Analytical, and Multor 610 Maihak, respectively, the accuracy of which is 1.0% of the reading. On-site calibrations with standard gases were conducted during the measurements.

Results and Discussion

Prefilming Air-Blast Atomizer

Water spray images from the CCD video camera of the prefilming air-blast atomizers are presented in Figs. 3–5 at atomizing air pressure, P_a at 0.5, 1.0, and 1.5 kg/cm^2, respectively, with a constant water flow rate of 300 cm^3/min. The nonsymmetric spray due to machining was noticed and did not cause any trouble during experiments. Spray cone angle as shown decreases from 60 to 45 deg with increasing P_a from 0.5 to 1.0 kg/cm^2. Further increasing P_a has no effect on the spray cone angle. Results of image processing of Figs. 3–5 are shown in Figs. 6–8. The spray images are marked with numbers from 1 to 256 to show the relative concentrations by

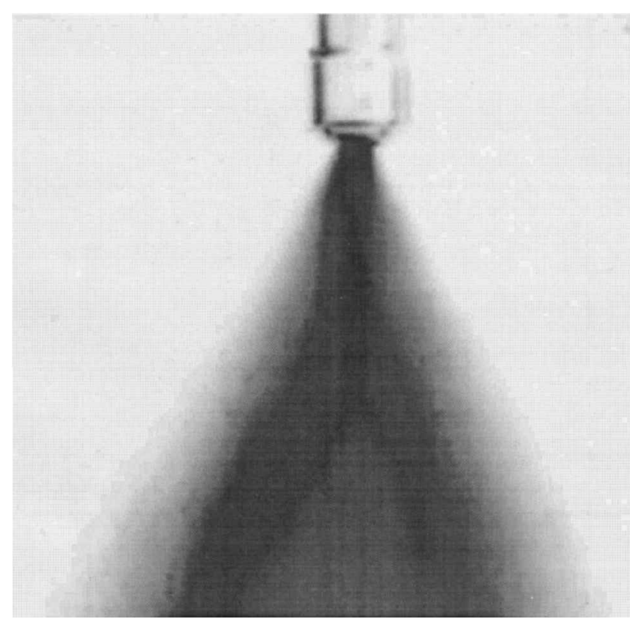

Fig. 3 Spray image of prefilming air-blast atomizer, 0.5 kg/cm^2.

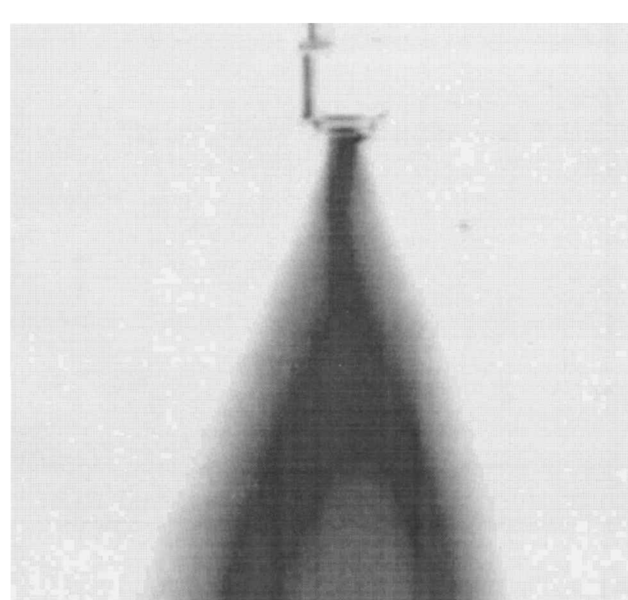

Fig. 4 Spray image of prefilming air-blast atomizer, 1.0 kg/cm^2.

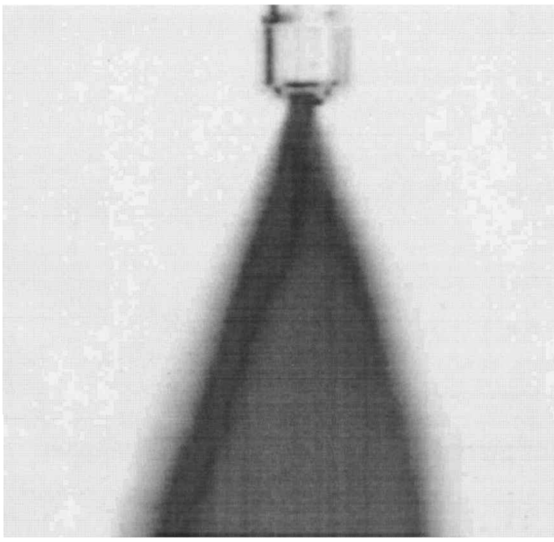

Fig. 5 Spray image of prefilming air-blast atomizer, 1.5 kg/cm^2.

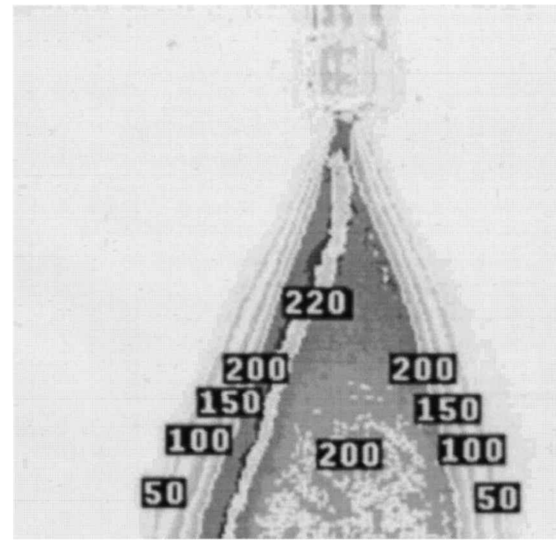

Fig. 8 Relative concentrations by volume of spray, 1.5 kg/cm^2.

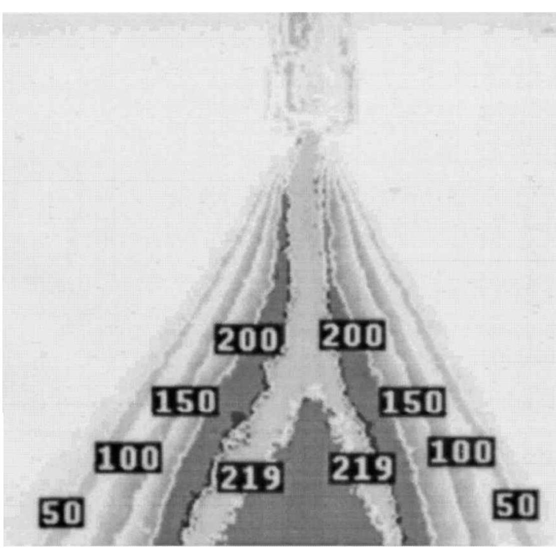

Fig. 6 Relative concentrations by volume of spray, 0.5 kg/cm^2.

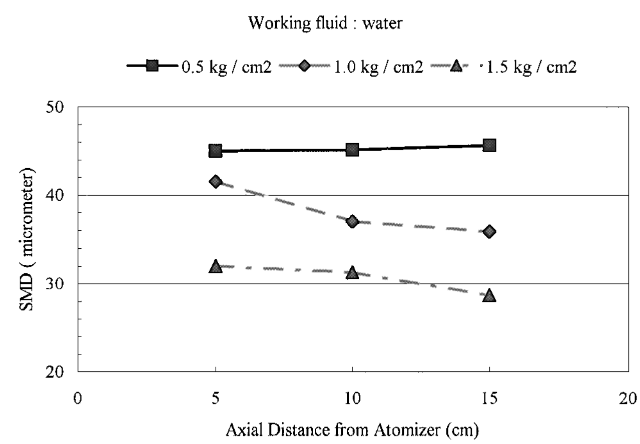

Fig. 9 Axial distribution of SMD of drops from prefilming air-blast atomizer.

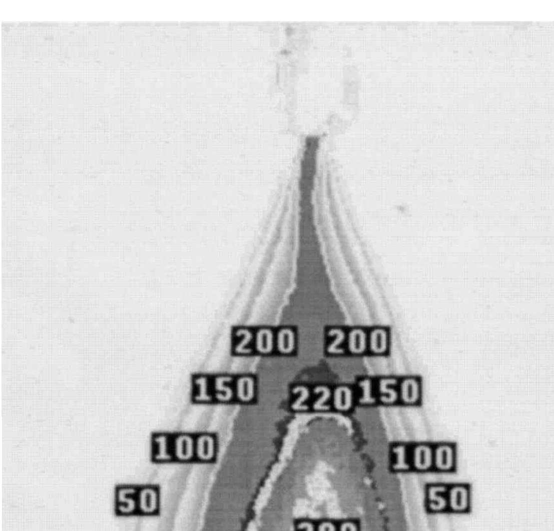

Fig. 7 Relative concentrations by volume of spray, 1.0 kg/cm^2.

volume of water drops. The larger the number, the higher the relative concentration. Lower relative concentrations are shown near the edges in all three cases, as expected. The cases where P_a is 0.5 and 1.5 kg/cm^2 are examples of the nonuniformity of the sprays. In the former case, shade 219 occupies a considerable part inside shade 200. In the latter case, it becomes a stream of water drops. On the other hand, the case where P_a is 1.0 kg/cm^2 shows the best uniformity (relatively) among the three cases; therefore, it is taken as a reference for the combustion experiments.

Both the SMDs and axial velocities of drops along the central line of the spray are shown in Figs. 9 and 10, respectively. The operating conditions are exactly the same as those in Figs. 3–5. Measurements were conducted at three locations, namely, 5, 10, and 15 cm downstream from the atomizer. The SMDs from all measurement ranges from 25 to 55 μm. Increasing atomizing air pressure clearly results in smaller SMDs and higher axial velocities of drops. On the other hand, axial velocities of drops decrease with increasing axial distance from the atomizer and decreasing atomizing air pressure. Radial distributions of SMDs and axial velocities of drops at axial distances of 5, 10, and 15 cm from the atomizer were also measured. Nevertheless, measurements of full width to check the symmetry of the spray were not conducted. The results of applying a pressure of 1 kg/cm^2 for the atomizing air are shown in Figs. 11 and 12. A uniform radial distribution of SMDs and axial velocities was achieved 10 cm away from the atomizer.

Carbonization of heavy fuel oil inside the atomizers exposed to a high-temperature environment was experimentally avoided by locating solenoid valves for cutting off fuel supply as close to the

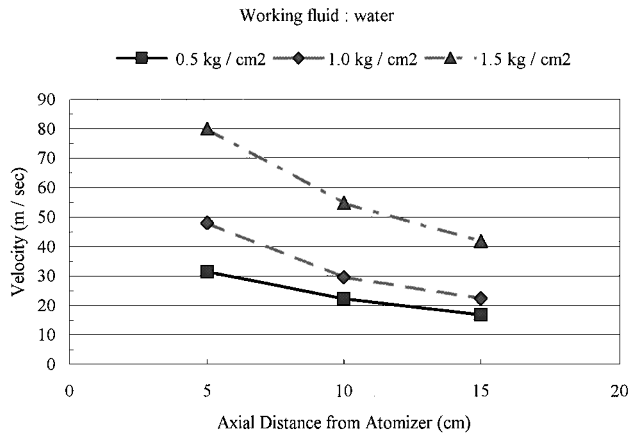

Fig. 10 Axial distribution of velocity of drops from prefilming air-blast atomizer.

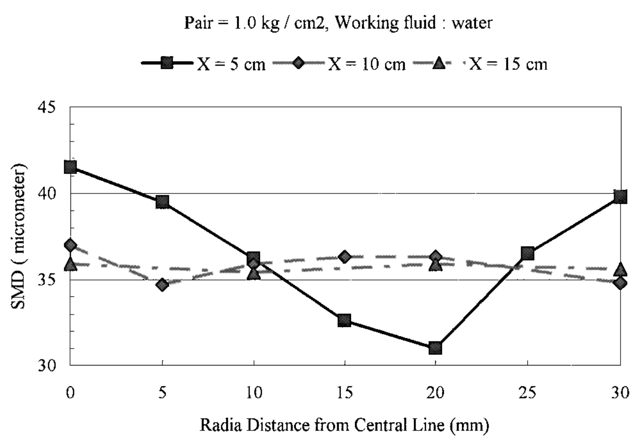

Fig. 11 Radial distribution of SMD of drops from prefilming air-blast atomizer.

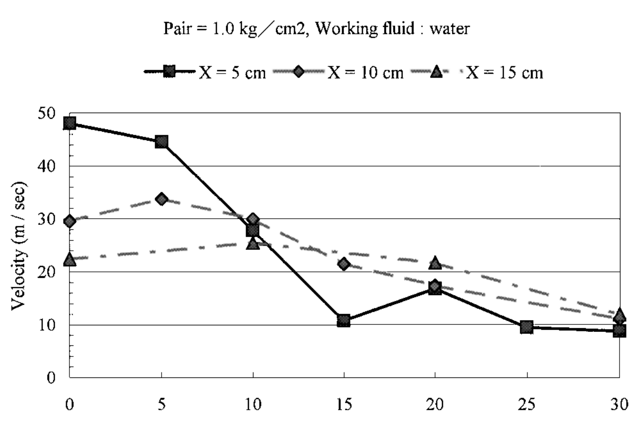

Fig. 12 Radial distribution of velocity of drops from prefilming air-blast atomizer.

atomizers as possible and flowing atomizing air continuously regardless of the burner being in a firing or an exhausting mode. The flowing of atomizing air resulted in a small loss in heat recovery rate because the atomizing air was not preheated. A pressure of 0.8 kg/cm^2 for atomizing air was applied to all experiments conducted in this study when considering atomizer performance and heat regeneration efficiency.

Honeycomb-Type Ceramic Regenerator

The authors had no trouble with cold startup but found a serious deposition on the top layer of the regenerators. It is attributed to the dripping of heavy fuel oil from the atomizers of the burner in the exhausting mode. Cutting the fuel off 1 s before switching solved the problem; nevertheless, the burner capacity decreased by about 3%.

Temperatures of the flue, T_{flue}; preheated air, $T_{\text{preheated}}$; and exhaust, T_{exhaust} at various furnace temperatures are presented in Fig. 13. The corresponding air-side temperature efficiency η is also shown in Fig. 13 and is defined as

$$\eta = \frac{T_{\text{preheated}} - T_{\text{cold}}}{T_{\text{flue}} - T_{\text{cold}}} \tag{1}$$

In Eq. (1), T_{cold} is fresh air temperature of 30°C. Compared with a value of 50°C for a gas-fired HRS,[22] heavy-fuel-oil-fired regenerative burner showed a larger temperature difference of 100 ~ 125°C between T_{flue} and $T_{\text{preheated}}$. It was due to the mixing of flue gas and atomizing air that continuously flowed. Though the temperature efficiency of the regenerator was not influenced, the thermal efficiency of the burner or the test furnace decreased.

NO_x Emissions

Effects of temperature of the preheated air on NO_x emission are shown in Fig. 14. Numbers at the top of Fig. 14 indicate the percentage of total fuel input that was input from the secondary atomizers. For example, 0% means no fuel input from the secondary fuel nozzles, called nonstaging-fuel, and 100% means no fuel input from the primary fuel nozzles, called 100% staging-fuel. The data of NO_x concentrations in parts per million were corrected to 6% O_2 by volume. Oxygen concentration in the flue was kept between 2 and 4% by volume. Note that NO_x emission increases monotonically from 240 to 460 ppm with increasing furnace temperature from 930 to 1230°C. This implies that, in that temperature range, the

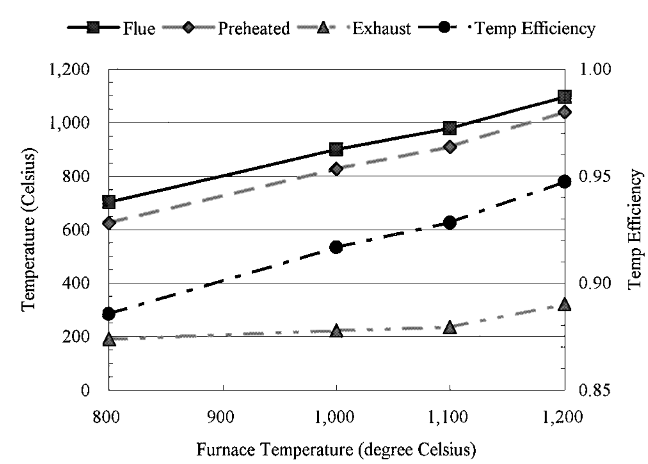

Fig. 13 Temperatures of gases and air-side temperature efficiency of honeycomb-type regenerators.

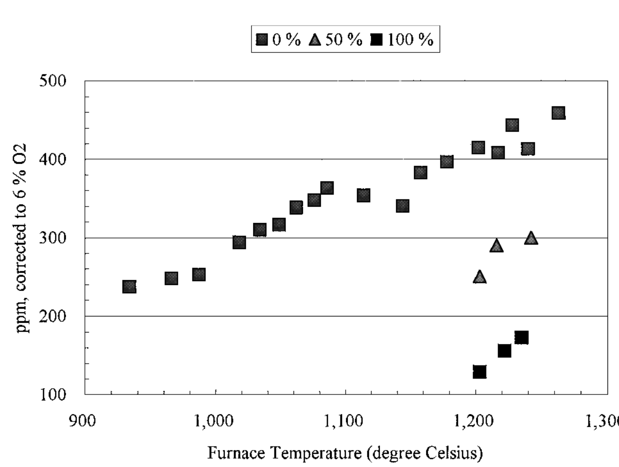

Fig. 14 NO_x emission of heavy-fuel-oil-fired regenerative burner.

highly preheated air increased the flame temperature dramatically and that hot spots inside the flame induced the generation of the thermal NO_x. Because the fuel drops from the primary atomizer vaporized and mixed with the preheated air and were ignited before they left the burner tile, the internal flue gas recirculation induced by the high-speed preheated-air jet showed little effect on reducing the NO_x emission.

Local standard of NO_x emission from a heating system firing heavy fuel oil is 250 ppm corrected to 6% O_2 by volume. Experimental data with furnace temperatures above 1200°C are also shown in Fig. 14. At such high temperatures, the preheated-air temperature was above 1000°C, the ignition and stable combustion of heavy fuel oil could be achieved and sustained without using the pilot burner. It is shown that NO_x emission decreased with increasing percentage of staging-fuel. The combination of a fuel-lean primary combustion zone, extended secondary combustion zone, and internal flue gas recirculation effectively decreased peak flame temperature and local oxygen concentration that resulted in less amount of NO_x emission. For the furnace temperatures between 1200 and 1250°C, the averaged NO_x emission could be reduced from 429 ppm without staging-fuel to 280 ppm with 50% staging-fuel. Nevertheless, the local standard of NO_x emission can only be conformed using 100% staging-fuel to achieve an averaged value of 153 ppm.

Conclusions

1) Air-blast atomizers showed acceptable performance when integrated to the heavy-fuel-oil-fired regenerative burner, although they required a considerable amount of atomizing air. Stable combustion could be sustained at cold startup. The atomizers exposed to high-temperature environment would not be plugged with coke if the atomizing air flowed continuously.

2) Honeycomb-type ceramic regenerators showed an impressive capability of heat recovery. They absorbed the sensible heat from the flue gas when the burner was in an exhausting mode and heated the combustion air when the other burner was in a firing mode. The temperature differences between the flue gas and preheated air were in a range of 100 ~ 125°C for the furnace temperatures between 800 and 1200°C. These resulted in promising temperature efficiency with an averaged value of 92%. Plugging or deposition of the regenerators could be avoided by stopping the oil dripping of the burner in the exhausting mode.

3) For heavy-fuel-oil-fired regenerative burner without using any combustion modification to reduce NO_x emissions, the NO_x emission increased monotonically from 240 to 460 ppm corrected to 6% O_2 by volume with increasing furnace temperatures from 930 to 1230°C. Two secondary fuel nozzles angled 30 deg with the airflow and internal flue gas recirculation induced by the preheated air jet helped to reduce the NO_x emission level at high furnace temperature up to 1250°C. For example, the averaged NO_x emission could be reduced from 429 ppm without staging-fuel to 280 ppm with 50% staging-fuel, that is, a 35% reduction. It could be further reduced to 153 ppm using 100% staging-fuel, that is, a 64% total reduction.

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