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# Spectroscopic Observation of Heavy Oil Luminous Flames in an Industrial Regenerative Furnace

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**A spectroscopic method has been applied to measure two-dimensional temperature distribution in luminous spray flames. A test furnace, incorporating a pair of regenerative burners, was used to examine the behavior of heavy fuel oil flames with very high-temperature combustion air. The spectroscopic method used here is based on the two-color thermometry, in which the ratio of spectral intensities of continuum emission is taken at two closely located wavelengths. The two-dimensional distribution of flame temperatures is obtained by the use of a charge-coupled device camera fitted with an optical bandpass filter to provide a much higher resolution compared to that measured with thermocouples. This method was applied to characterize the luminous flames formed under two different conditions during the combustion of heavy oil. The two different kinds of flames formed were either premixed or diffused by the use of air preheats to very high temperatures of 1373 K. A far more uniform temperature distribution was found for the diffusion flame case. In contrast, under premixed conditions, local high-temperature regions were found around the fuel injector exit. The concentration of $NO_x$ in flue gas has also been measured for the two different combustion conditions. The temperature distributions obtained from the premixed and diffusion flame conditions are discussed, as are the $NO_x$ emission levels from these flames. The results show lower $NO_x$ emission for diffusion flames as compared to premixed flames with high air preheats. These results are discussed because standards they provide new for uniform thermal field and ultralow pollution from flames with very high air preheats.**

## Introduction

RECENTLY, developments in regenerative combustion have provided higher efficiency, very low emission of $NO_x$ and other pollutants, and higher and uniform thermal field in furnaces using high-temperature air combustion principles.[1] The New Energy and Industrial Technology Development Organization (NEDO), under the auspices of Ministry of Economic Trade and Industry, provided major research and development support for this activity, to launch a major national project in Japan. The goal is to develop high-performance industrial furnaces. The use of regenerative burners has proven to provide very high thermal efficiency, uniform heat flux distribution, low pollution, and compact equipment size.[1–10] Under certain conditions, green-color flames resulting from the use of hydrocarbon fuels have been observed for the first time. This environmentally benign green flame color is only observed at low oxygen concentration in the combustion air.[2–4] At other combustion conditions, blue, yellow, or hybrid flame color is obtained.[4] The regenerative combustion principles utilize highly preheated air at low oxygen concentration for the combustion of fuels. Several recent studies on regenerative burners, utilizing high-temperature and low-oxygen concentration air for combustion, have reported that such burners exhibit very high efficiency, low $NO_x$ emission, negligible emission levels of CO and hydrocarbons, negligible flame fluctuations, and uniform temperature distribution in the combustion zone.[1–10] Regenerative burners are now increasingly used in many different kinds of commercial furnaces because of their effectiveness, with significant results on significant energy savings, lower pollution, compact size of furnace, and better quality of product in many applications.[1,2,7,10]

A test furnace facility was constructed at NKK Keihin Iron Mill that incorporated many of the features that are of industrial importance. Part of the objective of NEDO's high-performance

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industrial furnace development project was to provide performance and combustion evaluation tests by the use of detailed experimentation on the test furnace fitted with regenerative burners to supply high-temperature air for combustion. Measurements obtained with gaseous fuels provided uniform temperature distribution, higher and uniform heat flux distribution in the furnace, low $NO_x$ emission, very low heat losses associated with the exhaust gases from the stack, significant fuel energy savings, compact size of the furnace, and better quality of product from a process that uses regenerative combustion principles.[1,2] Negligible data are available on the combustion of heavy fuel oils in high-temperature air combustion. In this study detailed measurements have been made on the spatial distribution of temperature, $NO_x$ concentration, and other characteristics of the flames determined from within the regenerative combustion test furnace facility by the use of heavy fuel oil.

Thermocouples are commonly used to measure temperature distribution in industrial furnaces, for both test and commercial purposes, due to their ease of use, convenience, robustness, and low maintenance and costs. However, the spatial resolution of temperature data with thermocouples is often not sufficient to provide an accurate illustration of temperature gradient or detailed temperature distribution in a furnace because the number of thermocouples that should be installed in a furnace is often limited due to space and hardware limitations. Furthermore, the accuracy of thermocouples is affected by the luminous nature of heavy fuel oil flames. Although corrections for radiation can be made, the real temperature is often farther removed from the actual temperature measured with the thermocouples. In addition, the thermocouples suffer from both the amplitude lag and phase lag of the real gas temperature. Reliable, accurate, and sufficient quality data are not available from luminous spray flames for research and development purposes. Therefore, an alternative method to measure, simultaneously, the thermal field in a flame, or the entire furnace, is urgently needed. Ideally, this alternative method will allow on to better estimate the performance of industrial furnaces.

A spectroscopic method has been developed for use in laboratory size flames to measure the distribution of temperature in a nonluminous flame.[8] This method uses a charge-coupled device (CCD) camera to measure the spectral intensity at two discrete wavelengths emitted from $C_2$ radicals in the flame. The temperature is then determined from the ratio of these spectral intensities. The CCD sensor provides a two-dimensional D image of the flame in the furnace. The temperature is determined at each pixel location of the camera by measurement of the ratio of the two respective signals at two different wavelengths. This method provides a much higher spatial resolution than that obtained by the use of thermocouples. However, this method is not applicable to luminous flames during combustion of heavy fuel oils because the gray body radiation from soot and/or its precursors is too strong to separate out the weak emission signal from $C_2$ radicals.

In this study, the two-color thermometry was further developed to measure the temperature distribution in two-dimensional from with an industrial size test furnace that provided luminous flames during the combustion of heavy fuel oil. The furnace incorporated regenerative combustion principles in which the combustion air was preheated to 1373 K with exit gases from the furnace before the discharge of waste gases to the atmosphere. The facility allowed the formation of premixed or diffusion flames at same thermal loading. The spatial temperature distributions from within the furnace have been measured under the conditions of both diffusion combustion and premised combustion. The two-dimensional spectroscopic method has been used to measure temperature at a much higher resolution than those obtainable with conventional thermocouples. The results showed far more uniform thermal field or flat temperature distribution under diffusion flame conditions. However, under premixed combustion, local high-temperature regions were obtained. $NO_x$ concentration under the two different combustion conditions has also been obtained. The results show that, in contrast to the conventional flames that utilize room temperature air for combustion, low $NO_x$ is produced with diffusion flames as compared to the premixed flames using high-temperature combustion air. The $NO_x$ data are explained with relation to temperature distribution in the furnace for the premixed and diffusion flames.

## Experiments

### Regenerative Test Furnace Facility

A schematic diagram of the high-efficiency combustion test furnace equipped with regenerative burners is shown in Fig. 1. This

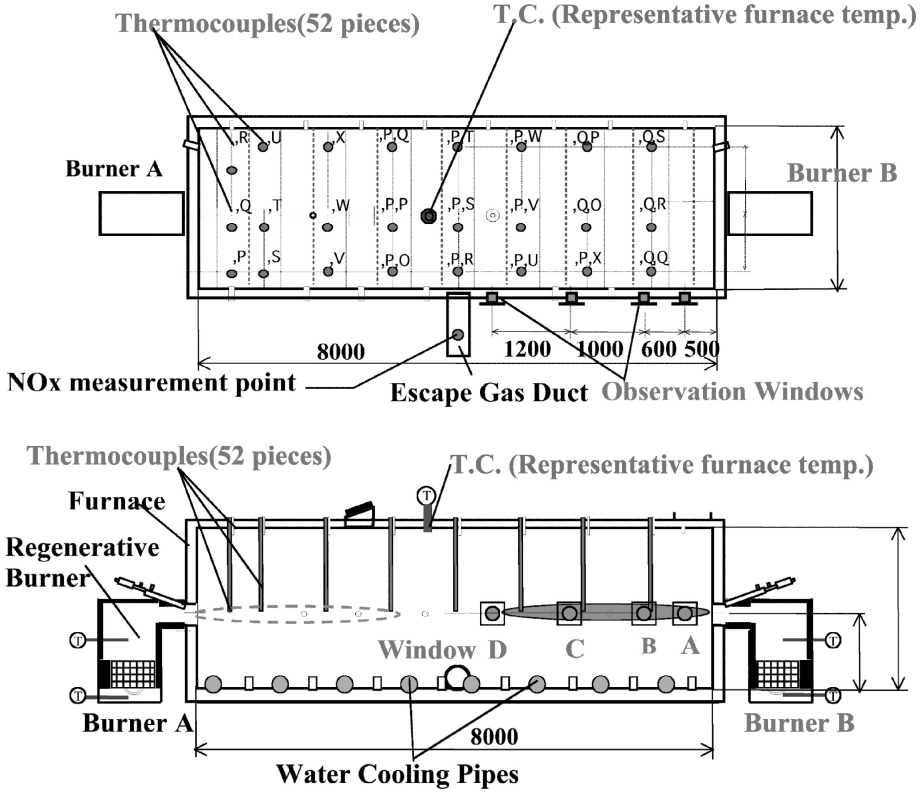



**Fig. 1 Schematic of the regenerative test furnace facility for oil combustion.**

**Table 1 Major specifications of the test furnace facility**

| Parameter | Value |
|---|---|
| Inner size | 8 m L × 2 m W × 2 m H |
| Max. furnace temperature | 1623 K |
| Nor. furnace temperature | 1573 K |
| Preheated air temperature | 1550 K (max.) |
| Max combustion load | 1163 kW |
| Fuel | Heavy oil |
| Load | Water cooling pipe |

**Table 2 Specifications of the heavy oil used**

| Parameter | Value |
|---|---|
| Lower calorific value | 46.7 MJ/kg |
| Kinematic viscosity | $4.0 \times 10^{-6}$ m$^2$/s (at 298 K) |
| Carbon content | 86.7% (weight) |
| Hydrogen content | 13.2% (weight) |
| Nitrogen content | 0.01% (weight) |

**Table 3 Major specifications of the burner**

| Parameter | Value |
|---|---|
| Max. oil consumption | 89.7 kg/h |
| Max. air consumption | 1206 Nm$^3$/h |
| Regenerator | Ceramic honeycomb |
| Consumption of atomization air | 49 Nm$^3$/h |
| Fuel nozzle | For premix × 2 pieces<br>For diffusion × 2 pieces |
| Injection speed of combustion air | 100 m/s (max.) |

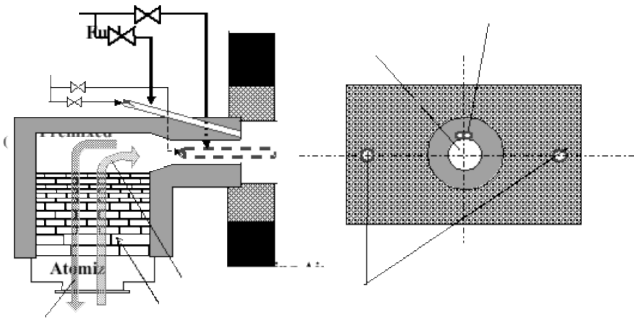



**Fig. 2 Schematic diagram of the regenerative burner.**

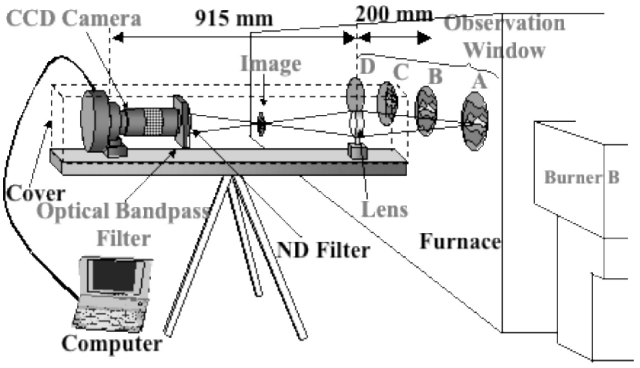



**Fig. 3 Apparatus used for spectroscopic measurement.**

industrial size test facility was used for the combustion of heavy fuel oil. Major specifications for this test furnace are given in Table 1. The internal dimensions for the furnace are: 8 m (length) × 2 m (width) × 2 m (height). A pair of regenerative burners (burners A and B, shown in Fig. 1), each having a capacity of 1163 kW, is installed on opposite-side walls (2 m × 2 m section) of the furnace, so that the distance between the burners is 8 m. The combustion of heavy fuel oil is switched between the two burners every 30 s. The regenerative burners incorporate ceramic honeycomb, which is used to extract enthalpy from the gases exiting the furnace test section. The maximum temperature in the furnace is 1623 K. The temperature in the entire furnace is fairly uniform (within about 50 K) so that one can classify the furnace as an isothermal reactor. The temperature of the preheated combustion air entering the furnace is about 1550 K at the furnace temperature of 1623 K. These conditions of high-temperature combustion air (at low oxygen concentration) and small temperature difference between the incoming combustion air and the furnace temperature are referred to as a high-temperature air combustion condition.

The thermal load to the test furnace was in the form of 16 water-heating tubes embedded in the furnace. Eight of these water tubes were fixed on floor of the furnace whereas the other eight water tubes were detachable, so that they could be incorporated when desired to simulate heavy load conditions.

The properties of the heavy fuel oil used are given in Table 2. The lower calorific value and kinematic viscosity (at 298 K) of the heavy oil used was 46.7 MJ/kg and $4.0 \times 10^{-6}$ m$^2$/s, respectively. No preheating system for the oil was necessary because the oil had good fluid flow properties without preheating it.

Figure 2 shows a schematic diagram of the burner used for the tests. Major specifications for the burner are given in Table 3. The fuel nozzle in the burner is designed to allow combustion under both diffusion and premixed conditions. For both the conditions, the combustion air is injected into the furnace at high speed, up to 100 m/s by the use of an air nozzle. For diffusion combustion, the fuel is directly injected into the furnace from the two fuel injection nozzles located on opposite sides of the air nozzle in each burner. The distance between fuel nozzle and air injection nozzle was constant for both the fuel nozzles. However, during the premixed combustion, the fuel is injected into the air jet stream from other two fuel nozzles installed on top of the air nozzle (Fig. 2). High-pressure air is used to atomize the heavy fuel oil.

The locations of temperature measurement points in the furnace with thermocouples are shown in Fig. 1. An array of 52 thermocouples (22 in the horizontal plan including the burner axis, 22 thermocouples 900 mm above the burner pairs, and 8 thermocouples near the furnace wall at the height of the burner axis) are used to obtain spatial distribution of temperature in the furnace. The test conditions were determined on the basis of a representative furnace temperature. This representative temperature was taken as the temperature measured with the thermocouple installed at the center (TIC in Fig. 1) of the horizontal plan in the furnace and 70 mm below the inside ceiling.

There are four observation windows (labeled as A, B, C, and D) in the longitudinal direction on one side of the furnace wall shown in Fig. 1. The flame conditions can be monitored via these windows. We have used a spectroscopic method to measure the spatial distribution of temperature at high frequency in the furnace via these windows.

### Spectroscopic Two-Dimensional Measurement of Luminous Flame Temperature

A schematic diagram of the experimental apparatus used to measure the temperature in the furnace spectroscopically is shown in Fig. 3. The optical system consists of a CCD camera used to detect the spectral intensity at a specified wavelength, which is emitted from soot and/or its precursor in the flame. The calculation of temperature is based on two-color thermometry principle, so that, by taking the ratio of spectral intensities at two different wavelengths (located close together so that the emissivity is independent of wavelength), one can obtain the temperature. The CCD camera takes two-dimensional images of the flame that allow one to determine temperature at each pixel location in the camera. This method, therefore, provides data on the distribution of temperature in the flame at a much higher spatial resolution and frequency than that obtainable with the use of themocouples.

**Table 4 Measurement conditions using spectroscopic diagnostics**

| Diagnostic | Description/Value |
|---|---|
| CCD camera | Santana Barbara Instrument Group<br>Model: SBIG ST-6UV |
| Number of pixels | 250 × 120 |
| Exposure time | 10 s (for averaged time)<br>0.01 s (for instantaneous time) |
| Optical band-pass filter | Wavelength 490 nm (half-width 28 nm)<br>Wavelength 531 nm (half-width 9 nm) |

**Table 5 Experimental test conditions**

| Parameter | Value |
|---|---|
| Furnace temperature (representative) | 1515 K |
| Preheated air temperature | 1373 K |
| Combustion load | 910 kW |
| Fuel | Heavy oil_(LHV = 46.7 MJ/kg) |
| Oxygen concentration in the furnace | 2.3% |
| Combustion-reverse cycle time between burners A and B | 30 s |
| Injection speed of combustion air | 70 m/s |
| Reynolds number of injected combustion air | $4.4 \times 10^4$ |

The CCD camera takes an image of the flame formed at the area of interest within the furnace with a converging lens, as shown in Fig. 3. If an optical bandpass filter is placed in front of the camera lens, so that only the radiation at a particular wavelength can pass through, one can obtain a two-dimensional monochromatic image of the flame. To determine the flame temperature, two images are taken at wavelengths of 490 nm (having a bandwidth of 56 nm) and 531 nm (having a bandwidth of 18 nm) by consecutively changing the bandpass filters. The temperature at each pixel location is determined by the use of the ratio of spectral intensities measured at these two wavelengths at each pixel location. This ratio is then converted to the temperature via a predetermined calibration curve.

The spectral intensity distribution is an average value over the exposure time used to measure the image with the CCD camera. In this experiment, we used both short and long exposure times of 0.01 and 10 s to obtain instantaneous and average intensity distribution. The image intensity was averaged over 10 s for the former case to obtain a direct comparison with the value from the later case.

The luminous flame temperatures were measured by the two-dimensional tow-color thermometry by the use of the flame observation windows A, B, C, and D, as shown in Fig. 1. Through these four windows, we were able to observe the upstream, middle, and downstream zones of heat flows in the flame when the burner B was on. The conditions used for the spectroscopic measurements are given in Table 4. Strictly speaking, we measure temperatures of soot and/or its precursors. Although we widely express temperature of luminous flame, or flame temperature, the real measured temperature here is surface temperature of soot and/or its precursor in luminous flames.

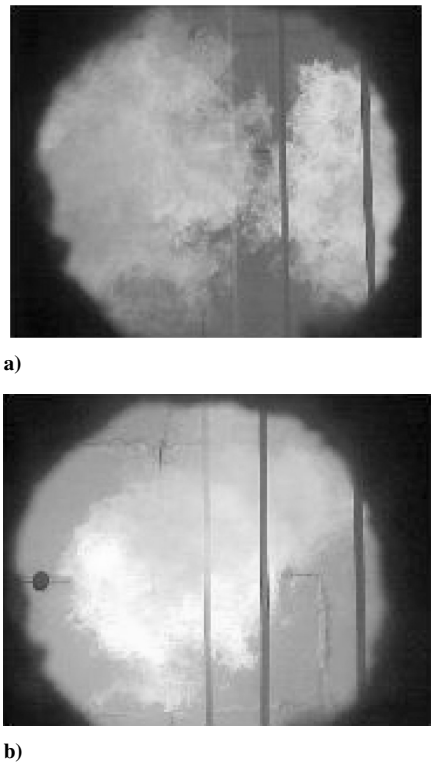
### Test Conditions

The test conditions used for the results presented here are given in Table 5. The representative furnace temperature was 1515 K. The oxygen concentration in the furnace was 2.3%, whereas the air preheat temperature was 1373 K. These conditions are routinely employed in slap reheating furnaces for the steel making process. The heavy oil with a lower calorific value of 46.7 MJ/kg is used as the fuel. The combustion load was 910 kW. The combustion cycle time of the regenerative burners was set at 30 s. The injection speed of combustion air was 70 m/s. The corresponding Reynold's number of combustion air was $4.4 \times 10^4$ at the injection port, so that the flames obtained are turbulent.

## Results and Discussion

### Luminous Flames

Figure 4 shows global photographs of the flames obtained during the combustion of heavy oil by the use of high-temperature combustion air in the test furnace. These photographs were taken through the window fitted with burner A on the wall, close to longitudinal direction of the flame. Figure 4a is for diffusion combustion condition whereas Fig. 4b is for a premixed combustion condition. As expected, there are significant differences in global flame shape and characteristics for the the two combustion conditions. The photographs show that heavy fuel oil burns with extremely bright flame radiation. In heavy fuel oil combustion, soot, carbon clusters, and other fine particles are generated and emit continuum radiation at high temperatures. Temperature distributions in these flames have been obtained to provide a quantitative measure of the difference in the flame characteristics between the diffusion and premixed flame conditions.



**a)**

**b)**

**Fig. 4 Flame photographs during diffusion and premixed combustion viewed axially: a) diffusion combustion flame, heavy oil, furnace temperature, 1515 K and b) premixed combustion flame, heavy oil, furnace temperature, 1515 K.**

### Temperature Measurement with Thermocouples

Initially, a rake of 22 R-type thermocouples, each having a wire diameter of 0.5 mm, was assembled. The thermocouple was enclosed in a ceramic thermoelectric casing. The inner and outer diameters of the casing were 8 and 10 mm, respectively. This thermocouple rake was used to measure the spatial distribution of temperature in the furnace under both diffusion and premixed combustion conditions.

Figure 5 shows the distribution of furnace temperature measured with the aforementioned thermocouple rake under both combustion conditions. The thermocouple was installed in the horizontal plan, including the burner axis (Fig. 1). The temperature readings were averaged over 120 s time duration, that is, a period of two switching cycles of combustion between the burners A and B. Significantly different temperatures in the furnace can be seen between the two combustion conditions (Fig. 5). The maximum temperature is seen during the diffusion combustion conditions at central region, near to flame tip of the furnace. In contrast, local maximum temperatures can be seen around the burner exit during the premixed combustion conditions. This difference can possibly be attributed to the difference in combustion velocity that is primarily controlled by the fuel/air mixing. This mixing is slow during the diffusion combustion and high during the premixed combustion.

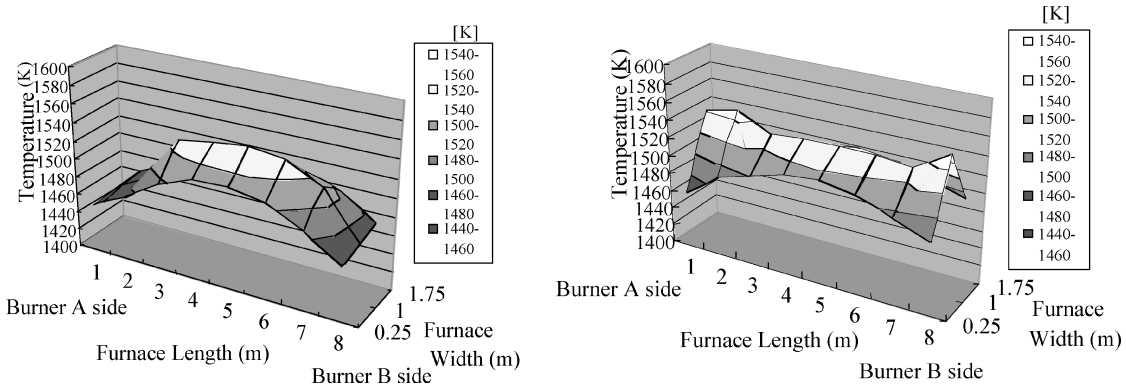



**Fig. 5 Temperature distributions under the a) diffusion and b) premixed combustion conditions measured using thermocouples (22 thermocouples in horizontal plain including burner axis).**

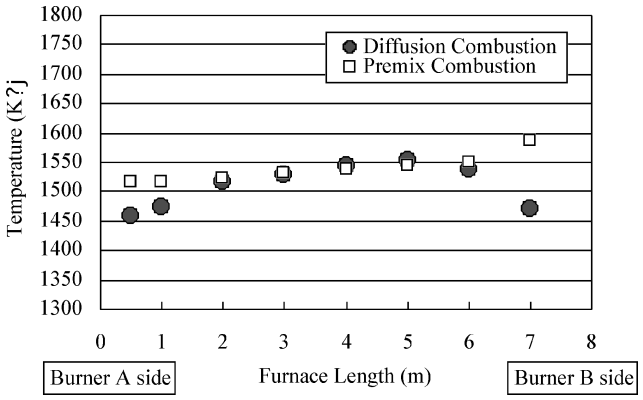



**Fig. 6 Temperature profiles on central axis of burner (averaged over 10-s time duration while burner B is operating).**

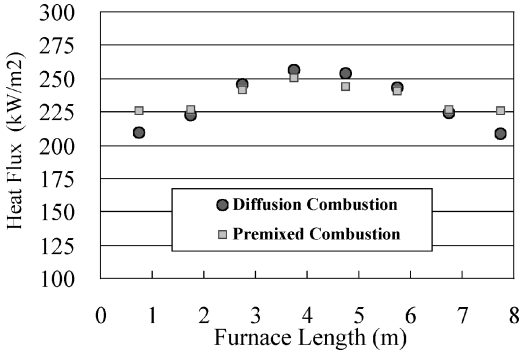



**Fig. 7 Heat flux profile on test furnace floor under burner axis under diffusion and premix combustion conditions; averaged over 5-s periods, representative furnace temperature, 1515 K.**

Figure 6 shows the profiles of flame temperature measured with eight thermocouples installed along the burner axis in the longitudinal direction of the furnace. These data show time-averaged temperature profiles of flame in the B side of the burner over a time duration of 10 s, within the time window from 10 to 20 s after the burner B was switched on. The circles and the squared in Fig. 6 represent the temperature under diffusion and premixed combustion conditions, respectively.

During the diffusion combustion, the lower temperature is near the nozzle exit of the burner where the fuel/air mixing is not sufficiently strong. A fairly flat temperature distribution is found around the central axis of the furnace. In contrast, higher temperature occurs near the burner nozzle exit for the premixed combustion condition. The maximum temperature measured with thermocouple is 1550 K during the diffusion combustion and 1590 K during the premixed combustion condition. The global flame thermal characteristics under both the combustion conditions can, therefore, be obtained from the thermocouple data. However, the thermocouple data lack detailed temporal and spatial resolution, so that if one wished to obtain temperature at higher frequency, some other diagnostic technique would have to be used (Fig. 6).

### Heat Flux Distribution on the Floor of Test Furnace

Figure 7 shows heat flux profiles at the floor of the test furnace under both diffusion and premixed combustion conditions. The circles and squares represent the diffusion and premixed combustion conditions, respectively. At the center of the furnace, the heat flux is higher by about 4% for the diffusion combustion than for the premixed combustion conditions. However, near the burner injector, the local heat flux is higher by about 6% during the premixed combustion than for the diffusion combustion. These trends are reasonable for the temperature distribution shown in Fig. 5. Quantitatively, however, this difference in heat flux is smaller than that expected from the difference in the temperature profiles. It is reasonable to suppose that the heat flux at the furnace floor is affected not only by the radiation from local flame, but also from the two flames and furnace walls, which reach the furnace floor. Therefore, the difference in the heat flux becomes smaller than that expected from the difference in flame temperature profiles.

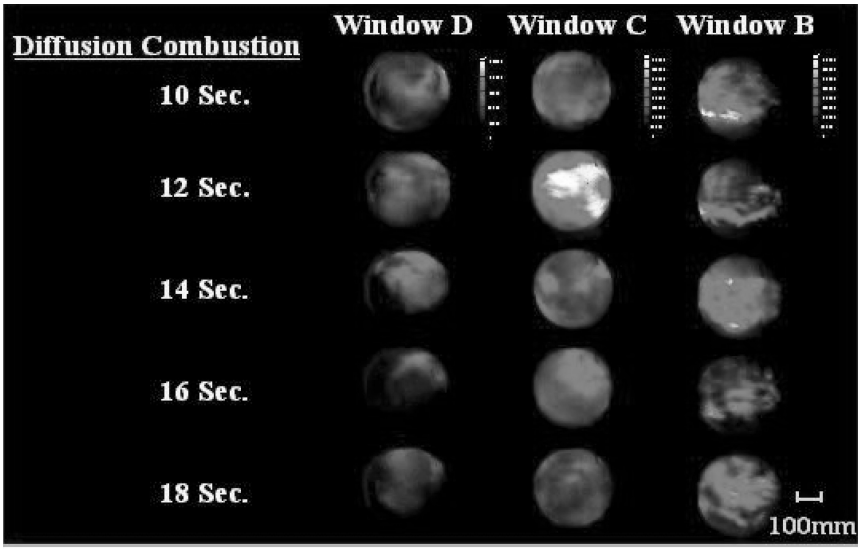
### Instantaneous Structure of Luminous Flames

To investigate the instantaneous structure of luminous flames, a short exposure time was used in the CCD camera to measure the spectral intensity of continuum radiation emitted from soot and its precursor. Under both of the combustion conditions, the data were collected for 0.01 s through windows, 10, 12, 14, 16, and 18 s after burner B was switched on.

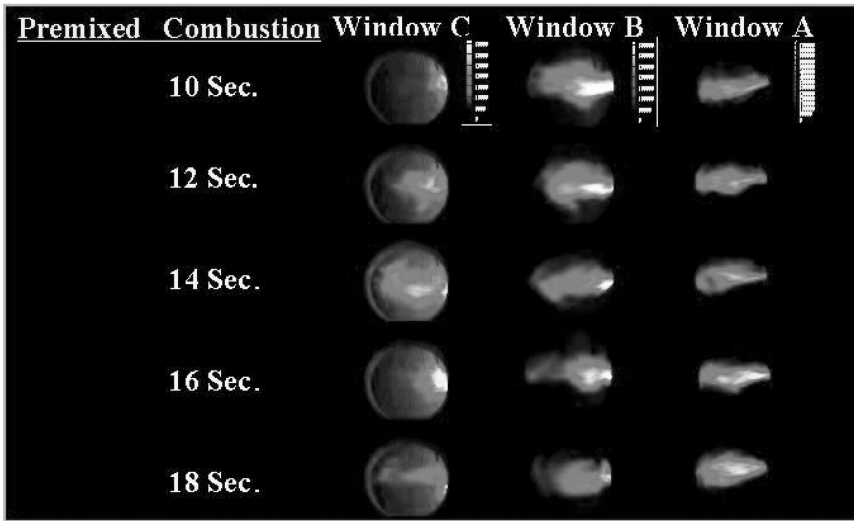
Figure 8 shows the two-dimensional distributions of spectral intensity emission measured through the top windows. Note that the instantaneous spectral intensity distribution for the diffusion combustion is significantly different at different measurements times. This may reflect the instantaneous fluctuations of temperature distribution due to the large-scale vortical structures of the turbulent field caused by slow diffusion of flows. In contrast, the fluctuations of temperature distribution are significantly less during the premixed combustion condition.

### Temperature Distribution in Luminous Flames Using Two-Color Thermometry

Figure 9 shows the two-dimensional distribution of flame temperature, measured spectroscopically with two-color thermometry with the burner B firing. These distributions of temperature were observed through the windows shown in Fig. 1, under both the diffusion and premixed combustion conditions. The exposure time was 10 s, between the time duration of 10–20 seconds after the burner B

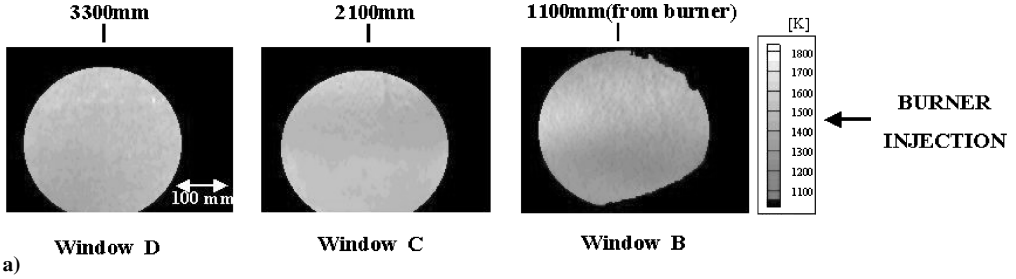



a)

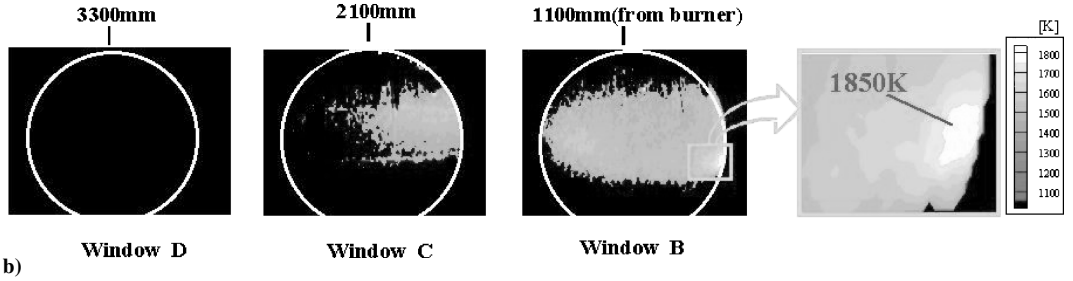



b)

**Fig. 8 Two-dimensional intensity distribution of continuum emission (exposure time = 0.01 s): a) diffusion and b) premixed combustion.**




a)




b)

**Fig. 9 Two-dimensional distributions of temperature measured spectroscopically: a) diffusion and b) premixed combustion, diameter of observational area window on burner axis is 300 mm, distance between nozzle of burner B and each window center is 1100 mm for window B, 2100 mm for window C, and 3300 mm for window D, respectively.**

was switched on. Thus, the temperature distribution is time averaged over an exposure time of 10 s.

The optical windows in the test furnace facility cover a 300-mm-diam field along the burner axis. The nondark regions in Fig. 9 represent the luminous flame areas. These results indicate that there is a conspicuous difference in the distribution of flame temperature between the two conditions. During the diffusion combustion, the luminous flames spread to exhibit a more uniform temperature over a wider area. Regions of high temperatures (in excess of 1500 K or higher) could be observed via window B. This area is near to the point where the air injected from the burner starts to mix with the fuel injected from the two fuel nozzles installed on both sides of the air nozzle. In contrast, uniform temperature distributions were observed through windows C and D.

The results presented in Fig. 8 show approximately uniform temperature in the entire diffusion flame with high-temperature combustion air (averaged over 10-s time duration). This is in contrast to the general observation for diffusion flames, which normally possess large temporal and spatial fluctuations with normal temperature combustion air.

During the diffusion combustion, the combustion air is injected at high speed, and the fuel is directly injected into the furnace, as shown in Fig. 2. Therefore, they mix while entraining the surrounding combustion gas to generate the conditions of diluted fuel and air. As the diluted fuel burns in the diluted oxidant, the combustion rate is low. Consequently, the combustion occurs over a larger distance and volume, so that the heat generated per unit volume becomes small. This, then, promotes uniform temperature distribution in the flame without causing and local high temperatures or hot spot zones.

In contrast, during the premixed combustion the luminous flames are limited to a small zone near to the burner axis. Near to the right corner of window B, a localized zone of high temperature could be observed as seen from the enlarged photograph. (See the right most portion of the flame in Fig. 9b.) The maximum temperature here is in excess of 1850 K, or about 335 K higher than the representative furnace temperature of 1515 K. Because no regions above 1850 K were observed through window A, the highest temperature of 1850 K or higher are likely to exist between the A and B view ports, where most of the intense burning occurs in the furnace. This region corresponds to a location of about 950 mm downstream from the burner nozzle exit. This is due to the droplet evaporation time before the onset of combustion in the furnace.

The highest temperature of the luminous flames, measured spectroscopically by the use of two-dimensional two-color thermometry, is 1600 K during the diffusion combustion and 1850 K during the premixed combustion. These vales are 50 and 260 K higher than those measured with the thermocouple under the diffusion and premixed combustion conditions, respectively. It is conceivable that the combustion reactions are more complicated both spatially and temporally in the flame. The thermocouples have a large thermal mass and heat capacity, and, therefore, they do not have the capability to measure the complicated thermal field that changes rapidly with time. In addition, the spatial resolution is limited because of the finite number of thermocouples used in the rake for temperature measurement. It is likely that heat radiation from the surrounding combustion field gives significant errors in measurements with thermocouples. Although these errors can be accounted for, the results showed much higher temperatures with premixed combustion than diffusion combustion. The results obtained show that complex thermal field in luminous flames can be extracted and visualized in two dimensions by the use of the two-color nonintrusive spectroscopic diagnostics developed here.

### $NO_x$ Concentration

The $NO_x$ concentrations were measured in the exhaust gas by the use of a chemiluminescent analyzer (Shimadzu Model: NOA7000). The results obtained for both premixed and diffusion condition at the same furnace operating conditions are presented in Table 6. In both cases, the air-preheat temperature was 1373 K and the representative furnace temperature was 1515 K. The results are given at 11% $O_2$ concentration in the exhaust gas. The $NO_x$ concentration was 30 ppm for the diffusion combustion and 120 ppm for the premixed combustion. Thus, the $NO_x$ during diffusion combustion is only about 25% of the value obtained for premixed combustion. This is presumably due to the delocalization of maximum temperature (no hot spot zones under diffusion conditions), as confirmed by the spectroscopic measurement. The alleviation of local maximum temperatures suppresses the formation of thermal $NO_x$, which is predominant in high-temperature zones.

**Table 6 $NO_x$ concentration in the exhaust gas[a]**

| Combustion condition | $NO_x$ concentration,[b] ppm |
|---|---|
| Diffusion | 30 |
| Premixed | 120 |

[a]Representative furnace temperature, 1515 K; $O_2$ concentration in exhaust gas, 2.3%.
[b]$NO_x$ concentration value is converted 11% $O_2$ in air.

The results of the distribution of flame temperature and NOx emission from premixed and diffusion combustion condition allow one to conjecture some relationship between NOx concentration in the exhaust gas and local NOx generation in the flames. The thermal NOx formation in flames is known to vary exponentially with the absolute local temperature in flames. Although the local high-temperature area under premixed condition resides in a very small flame region, the thermal NOx generated in this high-temperature zone is very high due to its exponential variation with temperature. Therefore, it seems that the significantly higher thermal NOx found in the exhaust gas under premixed condition is due to the local high temperatures associated with the flame. In contrast, under diffusion combustion, the flames spread very wide in the furnace to cause much lower thermal NOx formation over a wider area in the furnace. No local temperature peaks could be seen in diffusion combustion. Temperature distribution in the furnace is almost equal to the representative furnace temperature for the entire furnace zone. This, in turn, results in lower NOx in the exhaust gas. These findings are consistent with the preceding findings that high-temperature air combustion technology results in uniform thermal field.

## Conclusions

In this study, tests on heavy fuel oil combustion have been conducted with a high-efficient, industrial size, regenerative test furnace facility that uses highly preheated air for combustion. Spectroscopic measurements have been conducted to obtain two-dimensional temperature distribution from within the luminous diffusion and premixed flames using two-color thermometry. The results showed the following.

1) The spectroscopic method developed in this study has been proven to be effective to obtain a two-dimensional spatially resolved distribution of temperature in luminous flames from an industrial size regenerative combustion test furnace.

2) During diffusion combustion conditions, uniform temperatures over a significantly wider area in the furnace were found for the luminous flames. However, for the premixed combustion, the flame was confined to smaller region around the central injector axis. This resulted in local peak temperatures with the premixed combustion.

3) Spectroscopic measurements indicated that the flame structure fluctuates locally during the premixed combustion.

4) Spectroscopic measurements provide higher spatial and temporal resolution. This is particularly beneficial for detecting local high temperatures in flames that have complicated flame configurations and for which the traditional thermocouple methods cannot be used.

5) The heat flux profiles during both the diffusion and premixed combustion depend on the temperature distribution. The two combustion conditions provided finite differences in the local value of heat flux between them.

6) The $NO_x$ concentration in the exhaust gases from a premixed combustion condition is significantly higher than that in the diffusion condition. The local high temperatures associated with the premixed combustion are the main source of high thermal $NO_x$ under these conditions.

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