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Development of Advanced Industrial Furnace Using Highly Preheated Combustion Air

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Results are presented on the thermal and chemical characteristics of flames using high-temperature combustion air and liquified petroleum gas (LPG) as the fuel. The stability limits of these flames are extremely wide as compared to any other method of flame stabilization. This study is part of the Japan national project directed to develop advanced industrial furnace designs that provide approximately 30% energy savings and hence CO_2 reduction, 30% reduction in the furnace size, and 25% reduction of pollutants including NO_x as compared to current designs. The objective here is to establish conditions that permit significant reduction in energy consumption, high efficiency, and low pollution from a range of furnaces. Data have been obtained on mean flame temperature and temperature fluctuations, flame emission spectra, emission intensity of C_2 and CH species from within the flames, and overall pollutant emission from the flames. The uniformity of temperature in the furnace was found to be far greater with low oxygen concentration combustion air preheated to 1000°C as compared to that obtained with room-temperature air or that found in conventional flames. Emission of NO_x and CO was much lower with combustion air preheated to high temperatures with low oxygen concentration. The chemiluminescence intensity of CH and C_2 radicals is significantly affected by the preheat temperature of the combustion air and oxygen concentration in the oxidant. The flame signatures revealed important flame characteristics under high-temperature air combustion conditions. The advantages of utilizing highly preheated combustion air (in excess of 1000°C) in various types of furnaces are given. The new and advanced furnace design utilizes high-efficiency regenerators and behaves essentially as a well-stirred reactor with uniform thermal and chemical characteristics. Because each furnace design requires unique features, it is imperative that each furnace must be optimized to satisfy the functional requirements of the furnace. In this paper a relatively simple diagnostic methodology is presented, which assists in a rational furnace design and optimization process.

Introduction

ONE of the most effective methods to reduce the emission of carbon dioxide from the combustion of hydrocarbon fuels, which is known to cause global warming, is to reduce the consumption of fossil fuel in all energy utilization sectors. The United Nations 3rd Conference on Parties on Climate Change held in Kyoto, Japan, during December 1997 (called the Kyoto Convention) imposes reduction of CO_2 from the industrialized nations. Accordingly, each country is developing its own strategy to reduce energy consumption and CO_2 emission, create new industries, and enhance public health and the environment. Any efforts to reduce CO_2 emission must also provide significant reduction of CO and NO_x when developing advanced high-efficiency industrial furnaces. Energy saving was placed on the priority policy by the Japan Ministry of International Trade and Industry (MITI, now called METI) in the 1992 fiscal year. A budget was appropriated from the 1993 fiscal year to develop high-performance industrial furnace as part of the Japan new energy saving policy for technical development. The goal of advanced high-performance industrial furnace development project was to develop new furnaces that have much higher thermal efficiency and provides energy saving of 30%, reduces the size of the equipment by about 25%, and reduces pollution by about 25%. This was quite an aggressive and challenging undertaking for the project.

It has been long recognized that significant savings of fuel from furnaces can occur by recycling heat (by preheating the combustion air using, e.g., recuperators or regenerators). In both the recuperative and regenerative methods heat is recycled from the exhaust gas and transported back into the furnace. The advanced high-performance industrial furnace development project utilizes high-temperature air for combustion using regenerative combustion principles. In this method air is preheated to a high temperature, in excess of 1000°C. According to this method, reduction in energy consumption greater than 30% (and hence CO_2) has been shown as compared to existing industrial furnace design practices.[1–30] Reduction of NO_x of about 50% as compared to existing low NO_x-type burners has also been shown.[6,7] This project, completed in 1999, has resulted in several publications from worldwide locations (see Refs. 1–30) and deals with fundamental and applied issues on high-temperature air combustion and potential applications of high-temperature air combustion to other areas. In this paper an industrial furnace making use of the high-temperature air combustion method is referred to as a high-performance industrial furnace or as a high-temperature air combustion (HiTAC) furnace.

Industrial furnaces use a variety of heating methods to heat the material. The combustion conditions inside the furnace vary widely depending on the materials to be heated or process employed. Examples include boilers for producing steam, continuous reheating furnaces for rolling the slab or billet, thermal-treatment furnaces for annealing materials, metal melting furnaces to melt aluminum, and tube-type heating furnaces for petroleum refining.[19–24,29,30] The predefined high-temperature air combustion conditions cannot be applied to every case because of the specific requirements imposed on each type. Optimum conditions should exist for each material

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to be heated. It is therefore important to establish a standard for combustion evaluation for each condition. The use of a suitable combustion diagnostic can result in higher performance of the combustion furnace.

The performance evaluation of high-temperature air combustion method in furnaces require determination of the characteristic flame features formed with high-temperature combustion air that are common to various types of furnaces. The characteristic features must provide good correlation with the combustion conditions in the furnace. The diagnostic tool can then be used for furnaces to provide design improvement and optimization using high-temperature air combustion principles.

Results on Flame Characteristics with High-Temperature Combustion Air

The test rig used here is shown in Fig. 1. The facility permits examination of the basic flame characteristics and performance of the furnace, which can then be used for application to furnaces of different designs. The furnace allows systematic variation of the input and operational parameters that are important for practical furnaces. Results are presented on the effect of air preheat temperature and oxygen concentration in the air on flame characteristics under diffusion flame conditions. The diluted air was obtained by mixing normal air with nitrogen. Flame features were examined with fuel jet injected normal to the high-temperature airflow (i.e., jet in crossflow arrangement). The supply of LPG fuel (consisting of 97% C_3H_8) was held constant at 0.053 m^3/h (1.380 kW thermal loading). The combustion airflow rate (diluted with nitrogen or carbon dioxide) was held constant at 15 m^3/h. The combustion air could be preheated to any desired temperature prior to its introduction into the test section. The momentum flux ratio between the two crossflows was kept constant at about 0.12. The fuel nozzle was insulated by a heat insulating material in order to prevent any temperature rise of the fuel prior to being injected into the test section having high-temperature airflow.

The effect of high temperature and oxygen concentration in combustion air (air diluted with nitrogen) on flame stability limit is shown in Fig. 2. The demarcation temperature between stable and unstable conditions appears to be near an air temperature of about 850°C over a large range of oxygen concentration in the combustion air. A decrease in air-preheat temperature below 850°C decreases the flame stability limits, in particular for the case of near normal oxygen concentration in the combustion air. At very low oxygen concentration in air, very high temperature of the air is required to obtain a stable flame. At very low oxygen concentrations in the combustion air, flameless or colorless oxidation of the fuel has been observed with certain fuels.[10,14,16,17] The observed colorless flame depends on the fuel property and combustion conditions.[3] The size and shape of the flames depend upon, among other parameters, the fuel property, flame type, and surrounding gas conditions.[3,16]

The autoignition limits for the fuel used are also shown in Fig. 2. The autoignition temperature of a fuel is usually a defined value for

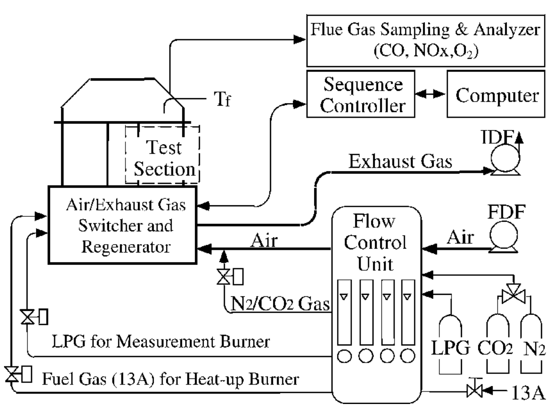


Fig. 1 Experimental setup for investigating the basic flame characteristics.

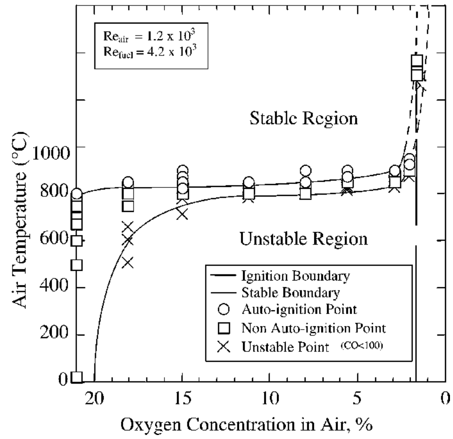


Fig. 2 Stable combustion region as affected by air preheat temperature and oxygen concentration in air (diluted air).

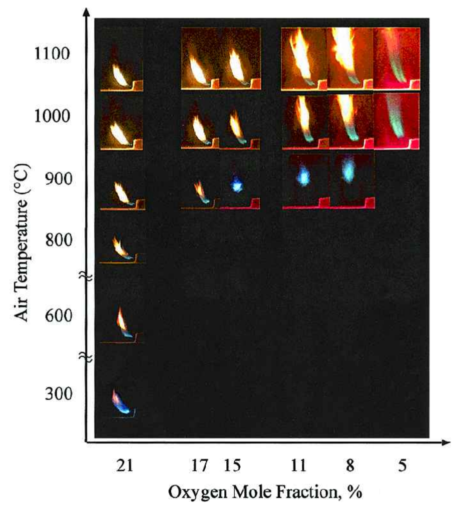


Fig. 3 Global flame features observed under stable flame combustion conditions at different air preheat temperatures and oxygen concentration in air.

normal concentration of oxygen in the air at a given pressure. The autoignition temperature depends on the fuel property and pressure so that for a given fuel the value of autoignition temperature is often provided with the air and fuel mixed under stoichiometric conditions. High-temperature air combustion occurs with combustion air temperatures in excess of the autoignition temperature under fuel-lean conditions. The results show that the flame stability limits under high-temperature air combustion conditions are indeed very wide. The fuel-lean stability limits extends to very low equivalence ratios with high-temperature air combustion conditions as compared to any other combustion conditions.

Figure 3 shows the global flame features of high-temperature air flames. Flame volume increases significantly at high temperature and low oxygen concentration in the combustion air. The brightness of visible flame increases with increase in air preheat temperature. Increased dilution of the air decreases the flame brightness while the flame volume and reaction zone increases. At temperatures higher than 1000°C and oxygen concentration below 5%, the flame is of **green color**. The green color of the flame becomes more pronounced at higher temperature and lower oxygen concentration in the combustion air. This green color of hydrocarbon flame at atmospheric pressure has not been observed before.

To analyze the characteristics of exhaust gases from the combustion volume, measurements were taken downstream of the flame zone for CO, NO_x, and O_2 using gas analyzers. Figure 4 shows the relationship between the temperature of the diluted air (diluted with either nitrogen or a mixture of nitrogen and carbon dioxide) and NO_x (ppm) concentration in the exhaust gas, using LPG as the fuel.

In all cases the NO_x value was recorded for stable combustion case and when CO value in exhaust gas was below 100 ppm. When the O_2 concentration in diluted combustion air was 4% by volume (using carbon dioxide as the dilution gas), the CO value was more than 100 ppm, and therefore this value was excluded from the measurement results. The measured results for NO_x can easily be converted to a fixed value of O_2 concentration in the air. The results are not presented in this form because the emphasis here is on the role of the dilution gas and air-preheat temperature. The results presented in Fig. 4 show that NO_x decreases with decrease in oxygen concentration and air preheat temperature. A closer examination of the results also reveals that NO_x emission value is smaller when air is diluted with carbon dioxide as compared to nitrogen for the same oxygen concentration in air. This suggests that exhaust gas recirculation into the furnace will be more effective for the reduction of NO_x.

Flame thermal characteristics have been obtained in the combustion chamber using a R type (Pt-Pt/13%Rh) thermocouple of 0.5-mm-diam wire. Measurements were obtained at 36 measuring points in the flame zone by traversing the thermocouple at 20-mm intervals in the x direction and 30 mm in the y direction. The wire was coated with ceramic coating to prevent catalytic reaction of platinum in the flame zone. High-temperature ceramic fiber material was used in the walls of the measurement chamber in order to insulate the heat in the combustion zone. The LPG fuel gas was injected into the furnace in a direction normal to the high-temperature airflow

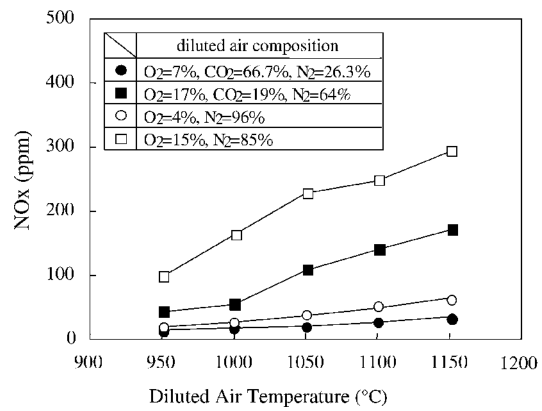
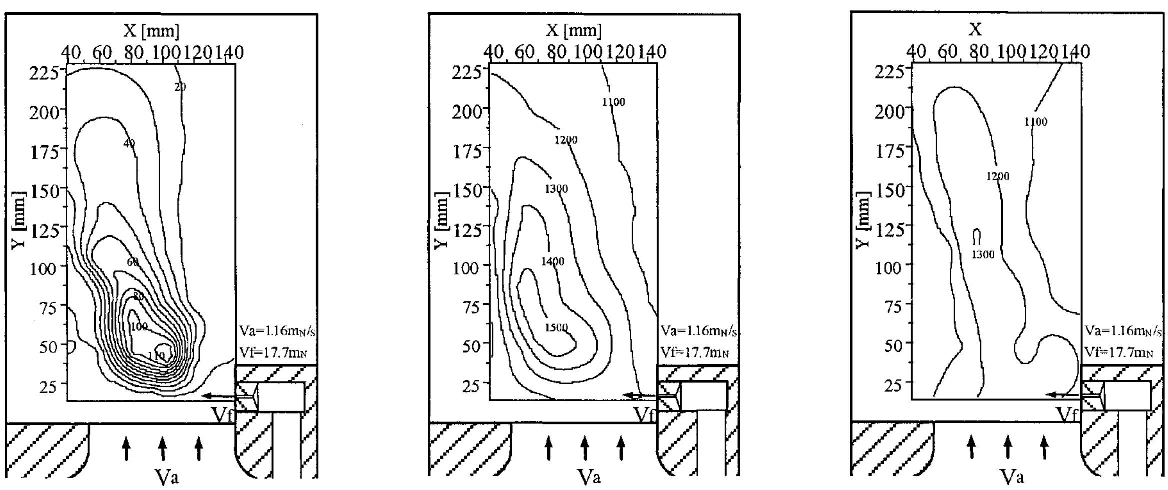


Fig. 4 Measured NO_x emissions as a function of diluted air preheat temperature.

using 1.0-mm-diam stainless-steel nozzle. The fuel flow was well insulated from the high-temperature combustion air prior to the introduction of fuel into the combustion chamber. In this study results are presented for the following three nominal conditions of the combustion air: 1) normal temperature air (air temperature, $Ta = 35°C$, $O_2 = 21\%$), 2) high-temperature combustion air (air temperature, $Ta = 1200°C$, $O_2 = 21\%$), and 3) diluted high-temperature combustion air (air temperature, $Ta = 1200°C$, O_2 concentration in the air using nitrogen as the dilution gas $= 4\%$).

Distribution of temperature in the furnace using normal ambient temperature air at 40°C having O_2 concentration$= 21\%$ by volume is shown in Fig. 5a. The temperature increases rapidly from $y = 15$ mm immediately downstream of the fuel nozzle exit and reaches a highest value of 1124°C near the location ($x = 100$, $y =$ 30 mm). The temperature decreases rapidly at downstream positions for $y > 30$ mm and in regions between $x < 60$ mm and $x > 120$ mm. At these locations the temperature difference (TD) between the maximum temperature ($T_{1\,\max}$) and minimum temperature ($T_{1\,\min}$) in the furnace ($T_{1\,\max} - T_{1\,\min}$) becomes$= 1104°C$. Using normal air ($O_2 = 21\%$ volume) at high temperatures (1200°C), combustion temperature rapidly increases to a very high value of $T_{1\,\max} = 1557°C$ near the location ($x = 80$, $y = 50$ mm) from the fuel nozzle exit (see Fig. 5b). At the location $y > 50$ mm and $x < 60$ mm or $x > 100$ mm, the temperature in the furnace decreases somewhat as compared that obtained with normal (ambient temperature) air flame. However, the TD is 512°C lower than that for the normal air case (i.e., the temperature difference in the flame between the maximum and minimum temperature decreases with air preheat). Reducing the oxygen concentration in combustion air ($O_2 = 4\%$ by volume) at high air preheat temperature of $Ta = 1200°C$ resulted in highest value of temperature in the furnace of $T_{1\,\max} = 1315°C$ near the location $x = 80$, $y = 100$ mm (see Fig. 5c). The TD for this low-oxygen-concentration case in the entire furnace is only 258°C. The temperature distribution is more uniform for the high-temperature and diluted air case as compared to the temperature distribution obtained with $T_{\mathrm{air}} = 1200°C$ and $O_2 = 21\%$ volume; compare Figs. 5b and 5c. This suggests that reduced oxygen concentration in the preheated air enhances thermal field uniformity in furnaces.

The magnitude of temperature fluctuation in diluted high-temperature air flames is lower than those obtained for normal air flames, compare Figs. 6a and 6b. The rms value of temperature fluctuation is less than about 4°C with the diluted high-temperature air case as compared to about 200°C for the normal-temperature air flame case. The temperature fluctuations have also been measured by compensating the thermal inertia of the thermocouple output

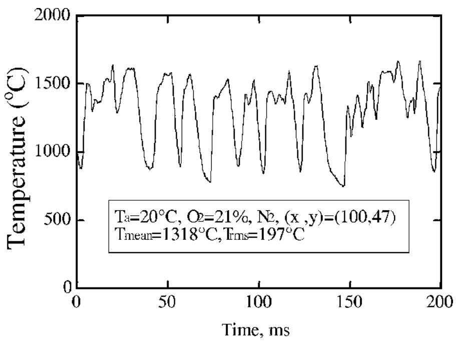


a) Diluted air temperature 35°C and O_2 concentration 21.0% (air ratio = 12.6)

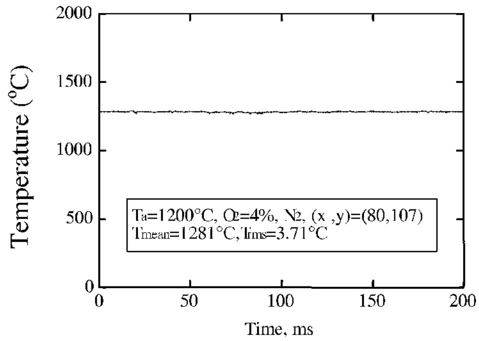
b) Diluted air temperature 1200°C and O_2 concentration 21.0% (air ratio = 12.6)

c) Diluted air temperature 1200°C and O_2 concentration 4.0% (air ratio = 2.4)

Fig. 5 Measured temperature profiles in the test section with a) left diagram: normal air (21% O_2 concentration in air) at 35°C, air ratio = 12.6; b) middle diagram: normal air (21% O_2 concentration in air) at 1200°C, air ratio = 12.6; and c) right diagram: diluted air (4% O_2 concentration in air) at 1200°C, air ratio = 2.4.



a) Diluted air temperature 35°C and O_2 concentration 21%



b) Diluted air temperature 1200°C and O_2 concentration 4%

Fig. 6 Measured temperature fluctuation at a location in the flame with a) left diagram: normal air with 21% O_2 concentration in air at 35°C; and b) right diagram: diluted air with 4% O_2 concentration in air at 1200°C.

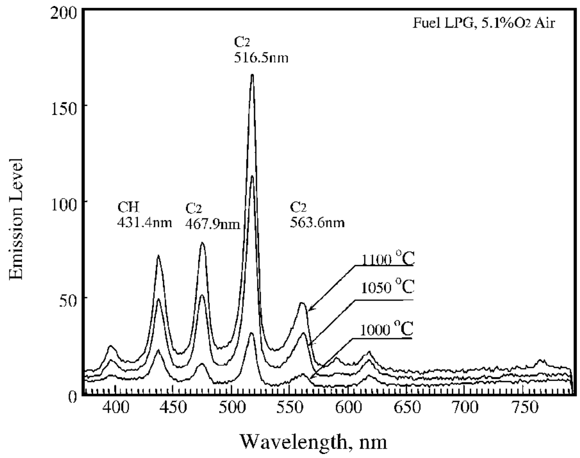


Fig. 7 Measured flame spectra of the LPG (propane) flames with diluted air (5.1% O_2 concentration in air) preheated to 1000, 1050, and 1100°C.

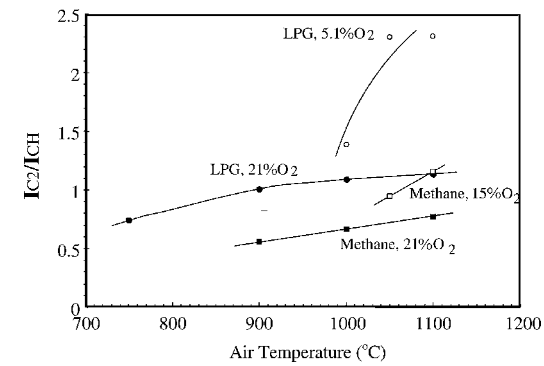


Fig. 8 Variation of C_2 and CH chemiluminescence intensity ratio at a location in the flame as a function of the air preheat temperature at two different O_2 concentrations in air for methane and LPG flames.

signal. The procedure provided higher frequency response of the thermocouple and was obtained by compensating the thermal inertia of the thermocouple using a time constant of 20 ms and filtering the signal with a low-pass (5-kHz) filter. This procedure extended the frequency response of the thermocouple in excess of about 1 kHz (Ref. 28). The temperature fluctuations with normal temperature air combustion have been found to be in excess of 200°C, whereas for high temperature and diluted air combustion case the fluctuations were found to be less than 10°C. Therefore, one can conclude that the thermal field uniformity is significantly enhanced, and the flame temporal fluctuations are significantly reduced under high-temperature air combustion conditions.

The chemiluminescence signal of CH and C_2 species from high-temperature and diluted air combustion conditions was recorded using a streak camera (Hamamatsu Photonics model C4187) coupled to an interference filter and UV lens. The filters had center wavelength of 515.5 nm for C_2 and 430 nm for CH species. The respective bandwidth of the two filters was 15 and 13 nm. This provided emission from C_2 and CH species at 515.5 and 431.4 nm, respectively. A total of 100 images were recorded at a framing rate of 20 ms/picture using a shutter speed of 1 ms. The results were stored in a PC and then processed. Figure 7 shows the chemiluminescence spectra at three airs preheat temperatures of 1000, 1050, and 1100°C. The oxygen concentration in the diluted air was held constant at 5.0%. Propane was used as the fuel. The signal intensity from the species was found to increase with increase in the air preheat temperature above 1000°C at all wavelengths examined. The rate of increase is higher from the green region at the C_2 swan band (at 515.5 nm) than the other bands (e.g., blue region from CH band at 431.4 nm). The C_2 peak at 467.9 nm also increased, but the rate of increase was not as high as compared to that at 515.5 nm. Slight increase in temperature to say 1125°C resulted in much more increase in C_2 emission at 515.5 nm. The observed green color is unique for the diluted high-temperature air flame using propane as the fuel. This green flame color with propane as the fuel has not been observed before.

To determine the role of reduced oxygen concentration and high air preheat combustion air temperature on the gradual transition from blue color flame to green color flame, one can examine the ratio of C_2/CH in flames because the CH species is indicative of blue region of the flame. An increase of this ratio at a given condition is indicative of the transition to green color of the flame and vice versa. Figure 8 shows the ratio of C_2 to CH luminescence intensity as a function of temperature at low (reduced) and normal O_2 concentrations in combustion air of 5.1 and 21%. The results are presented for propane as well as methane as the fuels. The intensity ratio does not change remarkably with normal air (21% O_2). However as the O_2 concentration is reduced to 5%, significant increase in the ratio of C_2 to CH signals occurs at higher air preheat temperatures. The results show significantly more increase with propane most part of (LPG) fuel as compared to the methane fuel (see Fig. 8 for methane at 15% O_2 in air). The flame was not visible (colorless flame) with methane for the 5% O_2 in air case. At oxygen concentration between 5 to 15% in air, visible color of the methane flame was not green. This reveals that fuel property has significant effect on combustion characteristics.

Distribution of C_2 and CH planar luminescence intensity from high-temperature diluted air (at 1050°C and $O_2 = 4\%$ volume) and normal temperature air (38°C and $O_2 = 21\%$ volume) flames have been measured and compared. The results showed that the emission intensity is locally concentrated for the normal temperature air flame, whereas for the high-temperature and diluted air case it is uniformly spread over a wider area in the combustion zone. The measured intensity ratio I_{C2}/I_{CH} in the flame was found to increase with diluted high-temperature air as compared to the normal-temperature air case. The results also showed uniformity of the green color effect throughout the flame for the diluted air case. The spatial distribution of luminescence intensity ratio as a function of air preheat temperature was also obtained by dividing the measured spatial average value of CH and C_2 chemiluminescence intensity at a location with the total sum of the chemiluminescence intensity. For any specific location in the flame, results similar to those shown in Fig. 8 were found. These results, therefore, suggest that the ratio of chemiluminescence intensity obtained at any location in the flame holds the same general characteristics of high-temperature air combustion flames.

The effect of green flame is to increase the intensity ratio of C_2/CH in laminar or turbulent diffusion propane/air flames at normal ambient pressure.[2,8,10,14,20] The chemiluminescence spectra were found to strongly depend upon the equivalence ratio (or air ratio). A decrease in air ratio (or increase in equivalence ratio) but still within the fuel lean region causes C_2 luminescence to increase and CH luminescence to decrease. Itoh[1] provided a correlation between air ratio and OH, CH, and C_2 radical luminescence intensity from the laminar premixed flames. Studies are also available on the flame color behavior as affected by fuel type[10,11] from laminar diffusion flame and evaluation of combustion condition based on the spectral analysis of heavy fuel-oil flames.[16] In some cases normal temperature air at 21% O_2 concentration was used to investigate the influence of air ratio in the range of 0.7–1.81.[2]

In this study high-temperature combustion air (in excess of 800°C) having low oxygen concentration (3%) has been examined for the effect of overall air ratio in the range 1.76–12.3. A diffusion flame formed with normal injection of the fuel into the high-temperature combustion air (jet in crossflow arrangement) is used to determine the chemiluminescence from C_2 and CH species. A region of locally low air ratio is caused in the combustion zone with the result of increased C_2 luminescence when the air ratio and combustion air temperature are held constant and the O_2 concentration in air is low. Increase of C_2 luminescence at high air preheat temperatures was observed with measurements made using a spectrometer.[3,7,11] Green color of the flame with high temperature and low oxygen concentration in combustion air can also be evidenced with the increased C_2 chemiluminescence from the flame see Fig. 3. Green color of the flame is a direct result of the high signal intensity from the C_2 specie at the swan band (at 515.5). This reveals that flame chemistry under high-temperature air combustion conditions is much different than that for the normal temperature air case. Under high-temperature air combustion conditions the preferred reaction route is via the enhanced production of C_2 specie. This issue on the reaction mechanistic pathways requires further examination and substantiation.

In this study high C_2/CH intensity ratio of 2.3 has been measured with air temperature of 1040°C and O_2 concentration of 5.1%, to result in air ratio of 2.99 (see Fig. 8). The results also show high combustion stability without any CO or soot, irrespective of the larger flame volume and C_2 intensity of the flame. Under normal combustion conditions, though the flame volume increases slightly as a result of decrease in the air ratio, combustion becomes unstable to result in higher emission of CO and soot. However no soot or CO emission has been found under high-temperature air combustion conditions using LPG or natural gas as the fuel. This might not be true with heavy fuel oils or other low-grade fuels. Because the autoignition temperature of most hydrocarbon fuels is much below the high-temperature air combustion conditions, the autoignition of the fuel occurs.[20] Because the air has been diluted with nitrogen in the ratio of 1:4.1, the flame temperature with high-temperature air is almost the same as that with normal air at room temperature. Although the reaction speed might increase because of the high air temperature, factors that decrease the reaction speed (e.g., diluted oxygen concentration) also exist at the same time. It is expected that under such conditions the influence of oxidizer preparation such as heating, thermal dissociation, dilution, etc., prior to the introduction of fuel increases C_2 luminescence and results in better combustion. Real chemical mechanism associated with the green flame color during combustion at high temperature and low oxygen concentration in air is an issue that should be further examined.

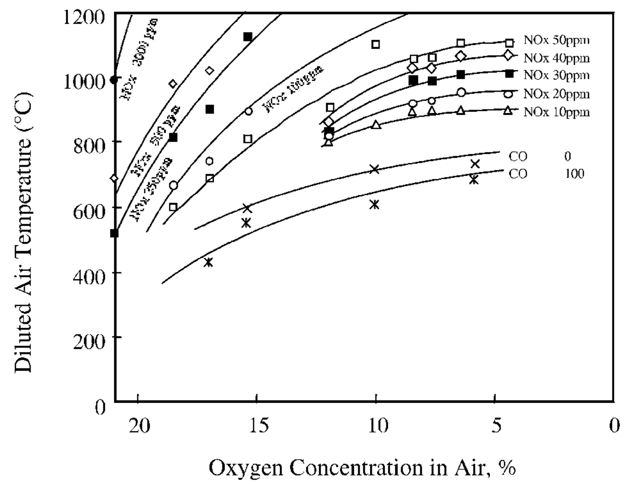


Fig. 9 Measured NO_x and CO emission as affected by O_2 concentration in air and air preheat temperature.

Figure 9 shows the measured results for NO_x and CO under high preheat temperature and low-oxygen concentration combustion conditions. The measurements were made at various spatial locations in the furnace with air preheat temperature in excess of 700°C and oxygen concentration in air ranging from 12 down to 5%. The measured value of NO_x is taken as NO_x volume generated under constant firing rate conditions, and hence no correction has been made to the measured concentration. The results also show the conditions when 0 or 100 ppm of CO are generated. The result also indicates the conditions when NO_x reduces from 50 to 10 ppm. Therefore, by knowing the properties of the combustion air (temperature and oxygen concentration of the diluted air) one can determine the NO_x concentration from a combustion system operating under high-temperature air combustion conditions. The results presented in this figure allow one to select the most desirable parameters for the combustion conditions in a furnace for specific application. However, further experimental studies must be carried out to determine the effectiveness and scaling issues associated with the high temperature and low-oxygen concentration combustion conditions.

Application to Other Types of Furnaces

Different industrial furnaces have their own desired design and operating conditions and unique combustion requirements. To determine the suitable HiTAC for various applications, one must be able to utilize the results presented here for different furnaces and boilers. A method of classification and global indication is required to generalize the application of the data for different types of furnaces. The temperature in the working section is of significant interest. As an example, the temperature range of interest for aluminum melting furnaces is much different than glass furnaces or boiler systems. For a specific application one must seek optimum and desirable HiTAC conditions. The optimum value for the combustion air temperature varies, among other parameters, on the application, which in turn depends on the furnace type, application, and range of operating conditions. In this regard we have attempted to provide a rather rudimentary method of selecting suitable condition for a specific application. One can subdivide the stable region of the flame formed with air preheat temperature T_{air} and O_2 concentration in the air into several discreet regions.

In this concept the design selection criteria assumes that furnaces having similar conditions must belong to a discreet region with regard to flame stability, O_2 concentration, and air preheat temperature. One can subdivide the combustion air preheat temperature to low, medium, medium high, high, and very high temperatures designated by L, M, HM, H, and HH in Fig. 10. In this figure L, M, H, and HH indicate low (up to 400°C), medium (400–800°C), high (1000–1350°C) and very high (above 1350°C) air temperature region, respectively. Normal oxygen concentration (21%) is designated with 1, whereas the low oxygen concentration in air is given a higher number (in this case 10 in the figure). So L1 represents normal

Table 1 Optimum HiTAC index for various types of industrial furnaces

Furnace type	Approximate furnace temperature, °C	Approximate air preheat temperature, °C	Suitable HiTAC index (see also Fig. 10)
Preheating furnace	1350	1250	HH6
Boiler furnace	1200	1050	H7
Heat treatment furnace	1100	1000	H5
Melting furnace	1100	1000	H3
Tube-type process heater	1000	900	HM5
Fuel reforming furnace for various types of fuels	1000–1200	900–1000	HM9 to H9

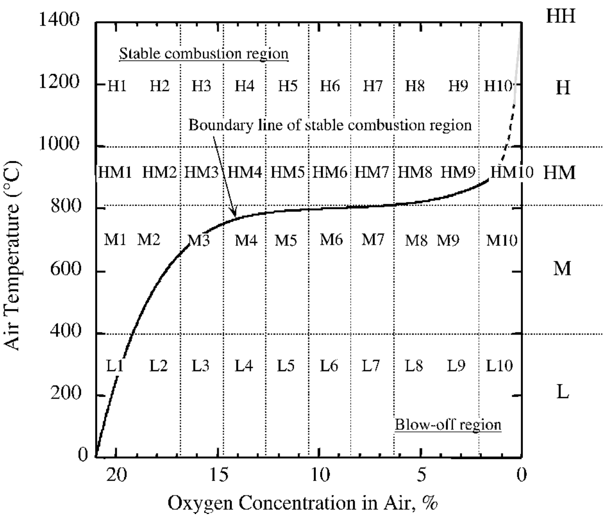


Fig. 10 Defined HiTAC index for identifying the degree of high-temperature air combustion conditions.

oxygen concentration of 21% and low air preheat temperature of say 400°C. Similarly for the high-temperature air the amount of oxygen concentration in the air can be subdivided into small discreet regions (e.g., H1 to H10). The HiTAC index involves identifying similarity in HiTAC conditions for different applications (see Fig. 10). Data obtained from the laboratory scale conditions can be utilized for specific practical applications by matching the appropriate desired conditions. The region above the curve is for stable flame, whereas that below the curve is unstable flame for a given fuel. The stable region curve has been obtained with LPG (propane) as the fuel. Similar curves can also be generated for other fuels.

The HiTAC index provides a convenient mean of classifying the extent of high-temperature air combustion conditions in furnaces based on air preheat temperature and oxygen concentration in the combustion air. Furthermore, the total air ratio in HiTAC diffusion combustion is larger than 1.0 (i.e., fuel-lean conditions). As an example, the region LM3 (low to medium temperature and about 15–17% O_2 concentration in air) is very appropriate for the aluminum melting system, whereas the H1 is appropriate for heat treatment furnaces when HiTAC technology is applied. Favorable conditions and applications can be achieved by the HiTAC index with knowledge of the actual required combustion condition in combustion furnaces. Though it is a simple approach to the more complicated high-temperature air combustion in the actual furnaces, it has provided many useful applications for furnace design and development.[20] Various types of furnaces use different temperature in the furnace for material processing. An example of the various temperatures desired in a furnace is given in Table 1. Also given here in this table is the HiTAC index along with the air preheats temperature. This index is also based on the information on flame characteristics and desired thermal field uniformity in the furnace experience.

To evaluate the HiTAC index for a given size furnace, one should first determine the type of industrial furnace (materials type to be heated, heated material temperature, etc.) and combustion conditions (fuel type, furnace temperature, air temperature, air ratio, etc.). The proper HiTAC index can then be evaluated based on the desired conditions for the specific application. This index must be verified by some other method. One approach is to measure or determine the chemiluminescence spectra at some point in the flame. The HiTAC index can then be calculated based on the ratio of CH and C_2 signals from the flame. The calculated index is then compared with the index already obtained. If the two values do not match, the cause is analyzed and corrections made. By repeating this iteration few times, the HiTAC index of the furnace is gradually brought to a proper value. The procedure described here has been found to be instrumental by designers of HiTAC furnaces.[19,29]

Conclusions

A new method of combustion involving high temperature and low oxygen concentration air is presented. The flame stability limits and thermal field uniformity in the combustion zone are much wider under high-temperature air combustion conditions. The flame characteristics are significantly different under high-temperature air combustion conditions. This combustion method has been shown to provide significant energy saving, improved heat transfer, higher performance, low pollution, and smaller size of the equipment or higher throughput for same size of the equipment. Reduced energy consumption in a furnace directly translated to CO_2 reduction from the system. The method has been applied to various industrial furnaces to improve their performance. To optimize and apply this method to various applications, analogy of the green flame effect caused by the high-temperature air combustion conditions is presented. When attempting to extend as a general combustion diagnostics to actual furnaces, many issues should be resolved. These include examination of combustion characteristics obtained by fundamental experiments, decision of measuring characteristic HiTAC index, and improving the index. This approach should provide applications to many different kinds of combustors and furnaces. Further advancements and developments should provide the desired tool to optimize the high-temperature air combustion method for each furnace application.

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