FLAME CHARACTERISTICS AND CHALLENGES WITH HIGH TEMPERATURE AIR COMBUSTION

Ashwani K. Gupta
University of Maryland, Department of Mechanical Engineering, College Park, MD 20742, USA
e-mail: akgupta@eng.umd.edu

Abstract

Results are presented on the thermal characteristics of propane-air diffusion flames using high temperature combustion air. Global flame characteristics are presented using several different gaseous fuels. A specially designed regenerative combustion test furnace facility, built by Nippon Furnace Kogyo, Japan, has been used to preheat the combustion air to elevated temperatures. A heat recovery system equipped with a honeycomb type regenerator could preheat the combustion air to temperatures of about 1300°C. The difference in temperature between the furnace and incoming combustion air could be 50°C or less. The oxygen concentration in combustion air was varied from 21% by volume (normal air) to 2%. The flame signatures were found to be very different with high temperature combustion air (in excess of 1000°C) and with different fuels than near room temperature combustion air. The flames with highly preheated combustion air were much more stable and homogeneous (both temporally and spatially) as compared to room-temperature combustion air. Stable flames were obtained at remarkably low equivalence ratios, which would not be possible with normal temperature air. The global flame features showed flame color to change from yellow to blue, bluish-green and green over the range of conditions examined using propane as the fuel. In some cases hybrid color flame was also observed. Under certain conditions flameless or colorless oxidation of the fuel has also been observed for some fuels. Some fuelss provided purple color flame under similar operational conditions. Information on the flame spectral emission characteristics, spatial distribution of OH, CH and C_2 species and emission of pollutants has been obtained. Low levels of NO_x along with negligible amounts of CO and HC were obtained with high temperature combustion air. Experimental results have been complemented with numerical simulations. Calculated results showed flame features similar to those obtained experimentally. The thermal and chemical behavior of high-temperature air combustion flames depends on fuel property, preheat temperature and oxygen concentration of air. High temperature air flames provide much higher heat flux than normal air, which helps to save energy and the subsequent reduction of greenhouse gases to the environment. The high temperature air combustion technology provides significant energy savings (up to about 60%), downsizing of the equipment (about 30%) and pollutants reduction (about 25%). Energy savings translate to reduction of CO_2 and other greenhouse gases to the environment. The challenges and opportunities with high temperature-air combustion technology are also described.

Key Words: High temperature air combustion, Energy savings, Reduction of NO_x, CO_2 and greenhouse gases, Advanced energy conversion and Pollution control.

Introduction

The desire to preheat the combustion air or reactants has been significant in almost all types of practical combustion systems[1]. Various methods of heat recirculation used in combustion systems are given in Table 1[2]. In swirl flows the heat is transported internally from downstream of the flame to upstream region, near to the root of the flame. It has been long recognized that significant savings in fuel can occur with energy recovery from the furnace exit gases using recuperator, regenerator or some other heat exchange method. Preheating the combustion air using the exit gases from a furnace provides many benefits, such as, enhance efficiency and flame stability, and reduce pollutant's emission and save energy. Recuperators provide low temperature air preheat as compared to regenerators. The maximum air preheat achievable with recuperators is around 600°C so that the fuel savings are only marginal. The regenerators used by North American Company showed that packed with ceramic balls increases the combustion air temperature up to about 1000°C using a switching cycle time of about 30 seconds. Weinberg[3,4] provided the idea on excess enthalpy combustion which could raise the flame temperature using heat-recirculating combustion. Figure 1 shows a schematic diagram of the temperature histories of premixed combustion both without and with heat recirculation[3]. Maximum temperature of the flame with heat recirculation is affected by the amount of heat recirculated to the flame, heating value of the fuel and equivalence ratio. The significance of excess enthalpy lies in convenient approach to burn very low heating value fuels without any auxiliary fuel. The method also provided means to increase the maximum flame temperature. Of course oxygen in place of air can also be used to increase the flame temperature[5]. However, the cost increases with the use of oxygen. Any efforts to develop combustion systems for increased efficiency and substantial energy savings must not be at the expense of increased pollution, equipment size, system reliability and costs. In conventional burners as the temperature of incoming combustion air is increased the NO_x emission increases.

Major thrust in all kinds of furnaces used in boilers, melting, reheating, soaking, heat treatment is to reduce production costs, improve product quality. The reduction of pollutant's emission is part of the production costs. Fuel costs represent a major cost element in furnace operation. Furthermore Treatment of exhaust gases to reduce pollutant's emission is not desirable as this increases the capital investments and added equipment maintenance costs. The development efforts made by Nippon Furnace Kogyo Kaisha Ltd.(NFK) since the early 1990's, under the leadership of late President Ryoichi Tanaka, were focussed on about 30% increase in efficiency and energy savings, 30% reduction in pollutant's emission (including NO_x and CO_2), and 30% reduction in equipment size using regenerators and the excess enthalpy principles. Pilot plant and full-scale studies have demonstrated this goal to be a reality[6,7]. In some cases the energy savings in excess of the original goal have been shown[8]. In the North American design, ceramic balls were used in the regenerator to preheat the combustion air with gases exiting from the furnace. The use of ceramic balls in a packed bed provided much higher temperatures of the combustion air. These temperatures were much higher than those achieved previously by recuperators. In the NFK High Temperature Air Combustion (HiTAC) technology a honeycomb regenerator is used. The honeycomb regenerator is much more compact than the packed bed with ceramic balls, have low thermal inertia and results in a very low pressure drop[6]. In the HiTAC technology high temperature and low oxygen concentration air is used for combustion air. In conventional burners increasing the air preheat temperature increases NO_x emission levels. However, in high temperature air combustion, the temperature of combustion gases in the furnace or reactor is small (only about 50 to 100^oC above the incoming combustion air at high temperature). The oxygen concentration in the combustion air is very low (only about 2 to 4%). Under these conditions the thermal field distribution in the combustion zone is very uniform with high temperature combustion air. The peak temperatures in the combustion zone are suppressed to result in very low NO_x emission levels. The heat flux from the flame with high temperature combustion air is also very high to provide large energy savings of about 60%[8]. A schematic diagram of the conventional flame, high temperature air flame and HiTAC flame as well as the distribution of heat flux is shown in Fig. 2.

During the past decade exponential development has taken place on excess enthalpy combustion. Many different applications of excess enthalpy combustion share a common element of highly preheated combustion air, although the design features are significantly different. A major program on the advanced energy conversion of fuels to save energy and reduce pollution, using High Temperature Air Combustion (HiTAC), was led by Nippon Furnace Kogyo (NFK), Japan, under the aegis of NEDO. Many companies and universities from Japan, and the University of Maryland Combustion Laboratory were involved in this program. Fuel savings provide a corresponding reduction of CO_2 and greenhouse gases to the environment. Most of the studies have been carried out on gaseous fuels (LPG, propane, methane and low heating value gases). Recently, some studies have also been carried out on heavy fuel oil[9], light oils and waste fuels. The fundamental studies provided an insight on the thermal, chemical and fluid dynamical behavior of the flames while the applied research provided optimal utilization of the technology for some specific application (e.g., heating, melting, heat treatment, soaking, boiler).

During the past few years several independent studies carried out on laboratory, pilot and full-scale units suggest many distinct advantages of high temperature air combustion as compared to any other combustion method[1-18]. The thermal and chemical behavior of HiTAC flames is significantly different than that of normal air flames[19]. The differences include increased thermal field uniformity in the combustion zone, high efficiency and reduced emission of pollutants with HiTAC[6,7,19]. Further examination of the technology have revealed other advantages, such as, high performance, low fuel consumption, very low emission of NO_x, CO, soot, hydrocarbons, CO_2 and other greenhouse gases[20]. Furthermore, low heating value fuel can be utilized without any auxiliary fuel. Smaller size of the furnace for performing the same function means savings in materials and resources. This in turn means further energy savings and pollutants reduction. This technology has been shown to provide large energy savings in industrial furnaces and power systems[9-11,20]. Further insights on HiTAC technology will reveal potential applications of this technology to various applications. Some of these potential applications as well as the associated challenges associated with HiTAC are presented here.

It is generally recognized that waste heat from the exhaust end of any power plant represents one of the large energy losses, which in most applications is used to preheat the combustion air to relatively low temperatures or to preheat water for heating and steam generation. In some cases the exhaust gases at moderate temperatures are simply discharged to the atmosphere. The use of waste heat from the combustion products to preheat the air or water assists in saving energy. This energy recovery to raise the air preheat temperature increases the adiabatic flame temperature and thermodynamic efficiency by operating the plant at higher temperatures. This in turn increases the NO_x emission from the system. The spatial distribution of heat flux from the flame remains essentially unchanged, having maximum value downstream of the burner exit and decays with axial distance further downstream from the burner exit. The spatial distribution of heat flux is, therefore, not uniform both along the flame and transverse to the flame. In general the maximum heat flux is found close to the burner exit and minimum farther downstream or radially displaced away form the flame axis. The maximum flame temperature is limited by the critical temperature of the fuel used and materials used for furnace construction. Although the increase in flame temperature (using, for example, air preheat or oxygen enriched combustion air) enhances thermal efficiency, the problem of non-uniform heat flux distribution in the furnace still remains. Recent developments in high-temperature air combustion technology have demonstrated high and uniform heat flux distribution in the combustion chamber[10-14].

In the HiTAC technology, preheated combustion air under controlled condition results in high and uniform distribution of flame temperatures in the combustion chamber so that the temperature difference in the entire furnace zone is extremely small. The furnace operation temperature can be made very close to the limits dictated by the materials used for the furnace construction. Uniform furnace temperatures are desired not only for higher thermal efficiency but also to improve performance and process control. Therefore, in order to achieve uniform heat flux in a furnace, redistribution of thermal field in a furnace is desired. This requires innovative means of using flame in the furnace so that there is no axial or radial variation of the temperature. The use of low oxygen concentration (via the use of exhaust gases, for example) with high temperature combustion air has been shown to provide the same average flame temperature (or even lower) than that obtained with normal combustion air. The use of oxygen-enriched combustion air raises both the furnace temperature and gradients in the spatial distribution of mean temperature. The relative gradients of mean temperatures with oxygen-enriched combustion air remain essentially the same as with normal air.

In this paper the thermal and chemical features propane-air flames are presented using high temperature combustion air. The combustion air is preheated to 1150^oC. The oxygen concentration in air is varied from 21% (normal air) to 2%. Under normal combustion conditions stable flame cannot be obtained with 2% O_2 in air. However, with high temperature combustion air, flameless oxidation of fuel (flame without any color) has been observed under certain conditions. Fuel property has a effect on the flameless oxidation[13,17,21]. The flame thermal characteristics are significantly different with low oxygen concentration and high temperature combustion air as compared to normal or moderately preheated air. The narrow window of low oxygen concentration and high temperature air combustion provides significant advantages on energy savings, down sizing of the equipment, and reduction of emissions from almost all power systems using any type of fossil fuel[1-22]. One of the challenges in high temperature air combustion is to determine the true features of the flame including the case of flameless oxidation.

Regenerative combustion provides convenient means of obtaining high temperature air for combustion[6,7,20]. In this system heat is extracted from one preheated regenerator while the other regenerator is heated with hot gases prior to exiting the furnace. Most regenerative combustion systems use a pair of burners. The burner pair is equipped with a ceramic honeycomb, which has been proved to be most efficient regenerator with negligible pressure drop as compared to ceramic balls packed in a bed. The regenerator extracts and stores energy for its use in the subsequent cycle.

High Temperature Air Combustion

A schematic diagram of high-temperature air combustion furnace, incorporating a pair of honeycomb type regenerator[11], is shown in Fig. 3. This type of regenerator offers very large surface area to volume ratio. Furthermore, it possesses significantly less thermal inertia as compared to a packed bed with ceramic balls. This is a heat recirculating furnace and the combustion alternates between burner A and burner B after prescribed time duration. The temperature difference between the incoming combustion air temperature and furnace gases can be only 50^o or less with negligible temperature variation[12] in the furnace at temperatures of about 1600 K in the furnace. The velocity of the gases inside the furnace is very high due to large recirculation of the exit gases. This reduces the oxygen concentration in the combustion air. A complex flow pattern is set-up inside the furnace due to periodic switching of the flow from left burner to right burner and vice versa. Precise information on the vortical structure of the flow is not yet fully understood. Several pilot plant and full-scale facilities have been built and used with the basic configuration similar to that shown in Fig. 3. The characteristics of the flame obtained with this set-up are quite unique and different to those obtained with normal air temperature. Figure 4 shows a schematic representation of high-temperature air combustion flame. The flame combustion characteristics are much affected by the flow recirculation, fuel property and the air preheat temperature.

Experimental Facility

A simulated high temperature air test furnace facility, developed and built by NFK, Japan, has been used to determine the features of HiTAC flames, see Figure 5. The facility consists of two burners, each firing in furnace section A and B. The facility has two main components of furnace and control unit. The furnace has two combustion chambers, each equipped with a ceramic honeycomb regenerator at upstream section of the burner in each chamber. The computer control unit provides the desired flow and switching sequence. Further details on this test facility are given in refs. 6 and 13. When burner in the furnace section A is firing, heat-up fuel at ambient temperature is supplied to burner A. Combustion air gets heated up while passing through the regenerator located downstream of the furnace section B. Furnace gases in chamber B are, therefore, directly drawn by regenerator B to store heat. The exhaust gases, after passing through the regenerator, are released to the environment via a 4-way-valve. After prescribed time duration (about 30s) the system is switched so that the burner in chamber B is firing and the regenerator located upstream of the furnace section A gets heated. The above process is repeated again with the burner A firing while the regenerator B gets heated up. By repeating this cycle several times, more and more heat is stored in the regenerators. When the desired temperature of the regenerator is achieved the air is passed over the regenerator. The air gets heated to the desired high temperature. The air with this facility can be heated to temperatures close to the furnace temperature. The test fuel is then introduced into the test section of furnace chamber section A.

Characteristics of High Temperature Air Combustion Flames

The flame characteristics are then examined with the high temperature combustion air using several advanced diagnostics. The flame stability as a function of air-preheat temperature and oxygen concentration in air is shown in Fig. 6. The flame stability limits increases significantly at high temperatures and low oxygen concentration, see Fig. 6. Under HiTAC conditions the flame stability are infinite.

The flame characteristics were found to depend on fuel property, preheated air temperature and oxygen concentration in the air. The diagnostic facility used here include direct photography, spectrometer, an ICCD camera coupled to narrow band filters for signatures on OH, CH and C_2, and gas analyzers for NO_x, CO, CO_2 and hydrocarbons. Numerical simulation of the flow and thermal field at pertinent conditions has also been obtained using a CFD code. Both experimental and calculated data show good agreement and contribute to our understanding on the structure of flames using high temperature air combustion. In this paper experimental data on non-premixed propane-air turbulent flames are presented using high temperature combustion air. Global flame features are also provided using other fuels.

The regenerator can preheat the incoming air to temperatures greater than 1600K. Furthermore, it is possible to dilute the air with any gas or the combustion products using simulated exhaust gas recirculation (EGR). The fuel was injected via a nozzle (about 1 mm diameter) in a direction normal to the heated airflow so that the initial mixing of the fuel and air is in the form of a jet in cross-flow. This form of jet mixing is known to be very efficient. Oxygen concentration in the air was varied from 21% (normal air) to below 2%. Thus the equivalence ratio was varied from ϕ = 0.83 (with 2% O_2) to ϕ = 0.079 (with 21% O_2) for the propane-air flames examined here. By changing the fuel from propane to methane and maintaining the same momentum of the fuel jet (for providing similar mixing patterns between the fuel and air) the equivalence ratio would change 0.3 (for 2% O_2 in air) and 0.03 (for 21% O_2). The results presented here have been with constant momentum to the fuel jet.

The combustion air supplied to the test section of the furnace was preheated to temperatures ranging from 900^{o}C to 1100^{o}C with oxygen concentration ranging from 21% to 2%. Flame photographs were obtained with a 35-mm camera using very short exposure times. From these photographs the flame color and flame area was analyzed using a computer program. Flame photographs with air preheat temperature of 1100^{o}C and oxygen concentration of 21, 8 and 2% in air are shown in Figures 7 (corresponding to N of 0.079, 0.21 and 0.83 respectively) using propane as the fuel. The flames showed four distinct colors of yellow, blue, bluish-green, and green, see Fig. 7. Under certain conditions colorless flame (flameless oxidation of fuel) has also been observed[22]. The green color observed for propane flames at low oxygen concentration and high air-preheat temperatures is unique. This green flame color has not been observed for methane flames over the range of conditions examined[13,22]. This suggests the important role of fuel property on the thermal and heat transfer characteristics of flames.

The size and color of the flame depends on air preheat temperature and oxygen concentration (obtained, for example, by changing the amount of gas recirculation) in the combustion air. All flames showed a unique structure as the air-preheat temperature was increased and the oxygen concentration was reduced from 21% to 2%. The flame volume was found to increase with increase in air temperature and decrease in O_2 concentration in the combustion air. At any fixed temperature, the total flame size decreased with increase in oxygen concentration from 2% to 21%. No yellow color flame was found at temperatures less than 950^{o}C and oxygen concentrations less than 15%. The size of blue color region in the flame decreased with increase in oxygen concentration (up to about 15%) and temperature. Between 900^{o}C to 950^{o}C and O_2 concentrations between 5 to 15% all flames were of blue color. For very fuel-lean mixtures and at high air preheat temperatures (1100^{o}C), the luminosity of the flame (and hence the heat flux) was found to be very high. Further discussions on flame features are provided in refs. 13,19 and 22.

At low air preheat temperatures as the overall flame equivalence ratio is increased the ignition delay increases. The color of the upstream region of the flame becomes blue. Increase in air preheat temperature at this equivalence ratio resulted in hybrid color of the flame (blue followed by a yellow). At 1100^{o}C the flame was completely of yellow color with 21% O_2. This suggests that the reaction pathways and the intermediate species formed are very different with different air preheat temperature. Understanding of the detailed chemistry is an issue in high temperature air combustion. Increase in heat flux distribution from HiTAC flames also requires examination. Detailed insight will provide better information on the various ongoing processes and subsequently allow one to tailor a process for a specific application.

Less penetration of air into the fuel stream, due to low density of air or less diffusion of the fuel into the air, results in an increase in flame length. This trend could be observed at all the examined equivalence ratios. This behavior can also be supported by the observation that at high equivalence ratios the flame stand-off distance is higher than that found at low equivalence ratios. At lower oxygen concentration in air and low temperatures the reduced availability of oxygen near to the fuel nozzle exit contributes to the ignition delay and hence the higher stand-off distance of the flame. However, at higher temperatures increased dissociation of the fuel may allow penetration of the evolved gases into the surrounding air, thus stabilizing the flame closer to the nozzle exit. This issue requires further examination.

At high air preheat temperatures and low oxygen concentration, e.g., around 2-5 % oxygen concentration in air, the flame was found to be of greenish color. The greenish flame color pronounces at higher air preheat temperatures and low oxygen concentration in the air. This suggests high levels of C_2 species (swan band) from within the flames under these conditions. The results also show that the flame volume increases dramatically under conditions of low oxygen concentration and high air preheat temperatures, see Fig. 7.

At very low O_2 concentration in air (less than 2%) no visible flame color could be observed. We call this condition as flameless (or colorless) oxidation of fuel. Determination of pertinent species under flameless oxidation conditions will allow one to postulate the mechanistic pathways. The fuel chemical property has an effect on the flameless oxidation of fuel[14,22]. Further studies are required for determining the thermal and chemical behavior of flameless oxidation. Advanced non-intrusive diagnostics can help determine the flame characteristics under flameless oxidation conditions.

The increase in green color for propane flames, obtained by using a computer program sensitive to the color in the flame photographs shown in Fig. 7, at low oxygen concentrations can be seen from Fig. 8. This program allowed determination of flame length and volume associated with different colors in the flame under various operational conditions. The total yellow flame volume increases with increase in O_2 concentration in the air. The increase in flame temperature increases the yellow fraction of the flame at high O_2 concentrations over the range of temperatures examined. The flame volume associated with green color of the flame increases sharply at O_2 concentrations less than 5% in the combustion air, see Fig. 8. Similarly the flame volume associated with other colors in the flame can be determined. The flame radiation associated with different colors is very different. In some applications high radiant flux is desired while for other applications it is undesirable. Therefore one can select the desired operating parameters from the information presented here. This type of information, therefore, assists in providing design guidelines on the use of High Temperature Air Combustion (HiTAC) technology for various applications.

Emission Spectra

The spatial distribution of C_2, OH and CH from within the flames has been obtained using a ICCD camera having transmission at the appropriate band for the specie. Figures 9 show the effect of oxygen concentration (2% and 15%) and air preheat temperature (980^{o}C and 1070^o C) on the distribution of C_2 from the propane flames. Results were also obtained at other oxygen concentrations and air-preheat temperatures. At high air preheat temperatures and low oxygen concentration, the flames appear to have two regions of high concentration of C_2, both regions being near to the upstream portion of the flame. With increase in oxygen concentration the flame structure becomes more symmetrical. Note that the color scale used for the various flame cases presented in Fig. 9 is different. At high oxygen concentration the higher concentration region increases for both methane and propane flames. This may be due to enhanced mixing with the oxidant. It was observed that flame fluctuations were negligible at high temperature and low oxygen concentration in the combustion air. Quantitative data on flame fluctuation at high air preheat temperatures and low oxygen concentrations are given in refs. 16 and 20.

The emission spectra of the flames under different HiTAC operational conditions have been obtained at selected positions in the flames. Sample results with 4% O_2 concentration and air preheat temperatures of 970^{o}C, 1030^{o}C and 1100^{o}C taken at one location in the flame (X = 3 cm and Y = 1.5 cm) are shown in Fig. 10. These results correspond to simulated exhaust gas recirculation (EGR) of 426%. These results were obtained using a spectrometer by scanning the flame in 100 nm wavelength intervals so as to enhance the resolution. Thus, one flame condition required 5 scans to scan between 250-750 nm. No significant species were found beyond 750 nm for the examined flames. The results show a significant increase of OH, CH, C_2 and H_2O emissions with increase in air preheat temperatures. The relative amount of various species present at various positions in the flame was different. As mentioned above the flame color at low oxygen concentration changes from blue to bluish-green with increase in air preheat temperature. This suggests an increase in the emission of C_2 radicals. At 516.5 nm the increase factor is 1.9 from 970^{o}C to 1030^{o}C and 2.4 from 970^{o}C to 1100^{o}C. Similar results were found for other species. The green color of the flame is directly attributed to the increase of C_2 (swan band) emission. Further downstream of the flame negligible amounts of CH and C_2 species were detected.

Emissions

In order to determine whether the HiTAC conditions would adversely affect the emission of NO_x and other greenhouse gas, measurements of various gaseous species have been made. Figure 11 shows the NO_x emission for two air preheat temperatures of 21% and 2% O_2 in air. The emission of NO_x increases with temperature under normal combustion conditions. However, at high air preheat temperatures and low oxygen concentration very low NO_x emission is observed. NO_x emission at air preheat temperature of 1150°C decreased from 2800 ppm with 21% O_2 to 40 ppm with 2% O_2 in air.

Numerical simulation

The computational domain, representing the test section, was divided into 14976 cells (26x32x18 in x, y, z directions, respectively) using non-uniform mesh. Heat transfer, turbulence, radiation, and chemical reactions are considered in the physical model. For conduction and convection heat transfer, temperature was calculated as representative variable. Because of good insulation materials used in the experiment apparatus, adiabatic boundary conditions are assumed in the heat transfer model (i.e., zero heat flux and wall temperature of 300K). For turbulence, two-equation k-ε model was used. The parameters used in this model are Cmu=0.09, c1=1.44, c2=1.92. For radiation heat transfer, discrete transfer method was adopted. Number of divisions in θ and φ are both 2, and the radiation model was solved for every 10 iterations. Converged conditions are reached once the relative differences between two iterations are less than 10^{-4}. For chemical reactions, both single-step and two-step reaction mechanisms have been tested. However, in this paper only the results from one-step reaction are presented. The parameters used for these reactions to calculate specific reaction rate constant, such as pre-exponent factor, active energy and powers of temperature and constituent, are given in Ref. 16. Nitrogen was regarded as inert specie. The data on Arrhenius-type rate constants used in the model are also given in Ref. 16. Thermodynamic data for the fluid, such as, density, viscosity, Molecular weight, thermal conductivity, specific heat and formation enthalpy of species have been used from Ref. 21. Thermodynamic data at temperatures other than standard conditions were obtained using polynomial expressions and/or extrapolation.

The boundaries of computation domain consisted of 7 adiabatic walls, namely, w-front, w-back, w-up, w-down, w-left, w-right and w-nozzle. In addition two inlets, named as inlet-air and inlet-fuel, and one outlet were used. For each adiabatic wall, heat flux was assumed to be zero and temperature 300K. To determine the effect of air-preheat and dilution, the inlet air conditions were changed. As an example, for air preheat temperature of 1400K and O_2 diluted to 8% by nitrogen, the O_2 mole fraction of 0.08 was used in the model. The v-velocity of inlet air (in y-direction) and u-velocity of fuel inlet were calculated based on inlet and nozzle geometry as well as its thermodynamic state. For instance, to calculate the air inlet velocity at 1400K, its volume flow rate at room temperature, i.e., $15m^3/h$, was converted to that at 1400K based on the state equation of ideal gas.

In order to calculate reactive flow, non-reactive flow case was performed to facilitate convergence. Typically 300-500 iterations were enough for initializing approximate inputs of reactive flow. Once the non-reactive flow field had been obtained, the combustion case calculations were performed using a small value of 'under relaxation factors' (about 0.2). Typically, at least 5,000-10,000 iterations were required to get convergence with residual less than 10^{-4}.

The calculated flame temperatures with air preheat temperature of 1400K and 1200K and O_2 concentration in air of 21, 15, 8, 5 and 2% are shown in Fig. 12. For the cases of 1400K air preheat the maximum temperatures in the flame at O_2=21% is about 3819K while at O_2=2% it is about 3631K. Comparing the volume of high temperature zone for various cases, it can be seen that the flame volume is significantly larger at high temperature and low oxygen concentration, similar to that observed experimentally. The calculated results provide important information on the features of high temperature air combustion.

Effect of Fuel Property on Global Flame Characteristics

Several different fuels have been examined to determine the effect of fuel property on the flame characteristics. Sample results with CO and hydrogen are given in Figs. 13 and 14, respectively. In all cases the fuel jet momentum was the same as that for the propane fuel. This provided the jet similarity to yield similar mixing patterns. The similarity in flame features between methane and CO to those observed for propane is quite striking. In all cases a larger flame volume under HiTAC conditions is also observed. The results showed flameless oxidation conditions under low oxygen conditions using hydrogen as the fuel. Both the fuels provided no evidence of the presence of green color flame for the range of conditions examined. This suggests that the combustion mechanism is much different with different fuels. Flameless oxidation with methane as the fuel has also been observed[13]. Measurements on the flame spectra with methane fuel showed no peaks at the swan band. The global characteristics of the flame can therefore help decide detailed diagnostics on the flames.

Applications of High Temperature Air Combustion

Most of the HiTAC technology efforts have been for furnaces and boilers. The technology has tremendous potential for application to many applications. Some of the near term applications (or potential applications) include the following:

- Furnaces used for melting, heat treatment, soaking, petrochemical reformering heater, glass melting, steel reheating, process heater, aluminum melter, dryer, boilers, ceramic heater and domestic boilers and heaters

- waste incineration/waste thermal destruction of solid and liquid wastes including animal, chicken, industrial, municipal and yard wastes, mixed wastes, gasifying of wastes and conversion of wastes to useful energy
- fuel reforming and energy transformation. The water gas shift reaction can be easily realized.
- Gas turbine combustion using low calorific value fuels, PF fuels, waste fuels

It is anticipated that additional applications will evolve with further R&D efforts on high temperature air combustion. Several efforts are now in place on the use of light and heavy fuel oils. They have provided useful insights for practical applications.

Challenges in High Temperature Air Combustion

The old practice used to be to develop a system for specific application. While this trend is the same in principle, there are many additional conditions imposed now. The engineer must pay close attention to the life cycle costs, product disposal after useful life, environmental issues, health issues, legal issues, reliability, and simplicity for diagnostics and maintenance. The near term challenges include determining suitable conditions for specific application using various fuels. Systematic fundamental studies will provide optimum design guidelines for specific application. Some of the near term challenges include the following:

- What is the role of fuel property on combustion, emission and energy savings
- What is the maximum heat flux achievable for a specific application.
- What is the effect of initial injection 'puff' of fuel or air injection from the burner on combustion and emission
- What is the role of flow dynamics in the reaction zone on the flame chemical and thermal behavior. What is the role of flow behavior on flame signatures and thermal time scales
- What is the role of fuel injector design on fluid residence time, flame thermal signatures and emissions
- What are the flame characteristics under flameless oxidation conditions
- What are the health effects of flame under HiTAC conditions
- What are the limits on the maximum achievable energy saving, pollutants reduction and down sizing of the equipment with HiTAC for some specific application

The fundamental and applied studies will help us gain insights into the HiTAC technology in addition to providing data base for mathematical modeling and model validation.

Summary

The following conclusions can be drawn for the highly preheated air turbulent diffusion propane flames. Green flame color increases with decrease in oxygen concentration and increase in air-preheat temperature. This green color is only observed for propane flame. Use of other fuel may not provide the same features. The observed yellow flame color was found to increase with increase in temperature and oxygen concentration. At air preheat temperature of up to 1000^{o}C and O_2 concentration from 5 to 15%, blue flame color predominates. The flame size increases with decrease in oxygen concentration and increase in air temperature. The flame standoff distance from the nozzle exit (ignition delay) was found to decrease with an increase in air preheat temperature. Two-stage combustion region was observed under low oxygen concentration and high temperature air flames. The emission of NO_x was significantly lower at high temperatures and low oxygen concentration as compared to low temperatures and high oxygen concentration. Fuel property has an effect on the flame thermal and chemical behavior. Flameless oxidation of the fuel (colorless flame) has been observed under certain conditions. Thermal uniformity of flame is significantly enhanced with high temperature and low oxygen concentration of air. Flame signatures can be significantly changed with change in fuel property, EGR, air preheat temperature and O_2 concentration in air. This allows one to design and develop highly preheated air combustion technology for various applications. Calculated results with single-step model showed good qualitative agreement with the experimental data. Main features of the HiTAC have been captured with the numerical code. Further numerical studies on HiTAC will assist in understanding the flame structure, which are necessary for improving design and wider application of high temperature combustion technology. Data are urgently needed for further understanding the HiTAC Technology. This data should include fuel property effects as well as the fluid dynamics and chemical kinetics of HiTAC. Challenges and potential of this technology presented here suggests significant advantages for further understanding of HiTAC to various applications.

Acknowledgements

The experimental facility used here was built and provided by NFK, Japan. Support of this project by NSF and NFK is greatly appreciated. Technical discussions, support, and friendship provided by Mr. Toshiaki Hasegawa and late President R. Tanaka, both of NFK, are gratefully acknowledged. The assistance provided by S. Bolz, K. Jagnow, Li and Xin are also appreciated.

References

1. Gupta, A.K., Lilley, D.G. and Syred, N.: Swirl Flows, Abacus Press, Tunbridge Wells, Kent, England, 1984.
2. Gupta, A.K.: Excess Enthalpy Combustion, Report to NFK, Japan, May 17, 1995.
3. Weinberg, F.J.: Combustion Temperature, The Future, Nature, Vol. 233, pp.239-241, 1971.
4. Weinberg, F.J.: The First Half-Million Years of Combustion Research and Today's Burning Problems, 15th Symposium (Intl.) on Combustion, The Combustion Institute, PA, 1975, pp.1-17.
5. Gupta, A.K, Presser, C.: Effect of Oxygen-enriched Atomization Gas on Spray Combustion Characteristics, Accepted for Publication in J. Propulsion and Power, 1999.
6. Mochida, S., Hasegawa, T. and Tanaka, R.: Advanced Application of Excess Enthalpy Combustion Technology to Boiler Systems, Paper presented at the 1993 AFRC International Symposium, Tulsa, OK. Also available as NFK Tech. Note 0929-93, Yokohama, Japan, 1993.
7. Hasegawa, T., Tanaka, R. and Kishimoto, K.: High Temperature Excess-Enthalpy Combustion for Efficiency Improvement and NO_x Abatement, Paper No. 9E, Paper presented at the 1995 AFRC Japan-USA Meeting, Hawaii, October, 1995.
8. Weber, R., Verlaan, A.L., Orsino, S., and Lallemant, N.: On Emerging Furnace Design Methodolgy that Provides Substantial Energy Savings and Drastic Reductions in CO_2 , CO and NO_x Emissions, J. Institute of Energy, U.K., September, 1999, pp. 77-83.
9. Suzukawa, Y., Sugiyama, S. and Mori, I.: Heat Transfer Improvement and NO_x Reduction in an Industrial Furnace by Regenerative Combustion System, Proc. 1996 IECEC Conference, pp.804-809, Paper No. 96360, 1996.
10. Hasegawa, T. and Tanaka, R.: Combustion with High Temperature Low Oxygen Air in Regenerative Burners, Paper presented at the 1997 ASPACC, Osaka, Japan, 1997.
11. Katsuki, M. and Hasegawa, T.: The Science and Technology of Combustion in Highly Preheated Air, Proc. 27th Symposium (Intl.) on Combustion, The Combustion Institute, PA, 1999, pp. 3135-3146.
12. Kitagawa, K., Konishi, N., Arai, N., and Gupta, A.K.: Two Dimensional Distribution of Flame Fluctuation During Highly Preheated Air Combustion, Proc. ASME Intl. Joint Power Generation Conference (IJPGC), Baltimore, MD, August 23-26, 1998, ASME FACT Vol. 22, pp. 239-242.
13. Gupta, A.K. and Li, Z.: Effect of Fuel Property on the Structure of Highly Preheated Air Flames, Intl. Joint Power Generation Conference, Proc. IJPGC-97, Denver, CO, November 3-5, 1997, ASME EC-Vol. 5, 1997, pp. 247-257.
14. Gupta, A.K. Bolz, S. and Hasegawa, T: Effect of Air Preheat and Oxygen Concentration on Flame Structure and Emission, Proc. ASME J. Energy Resources and Technology, Vol. 121, September, 1999, pp. 209-216. Also presented at IJPGC, Baltimore, MD, August 23-26, 1998, ASME FACT Vol. 22, pp. 193-206. Also published in ASME J. Energy Resources and Technology, 1999.
15. Wen-Chen, C. and Wei-Min, C.: An Investigation of Regenerative Combustion using #6 fuel oil, Proc. 2nd intl. Symposium on Advanced Energy Conversion Systems and Related Technologies, Nagoya University, Japan, December 1-3, 1998, Paper 2B4.
16. Ishiguro, T, Tsuge, S., Furuhata, T., Kitagawa, K., Arai, N, Hasegawa, T., Tanaka, R., and Gupta, A.K.: Homogenization and Stabilization During Combustion of Hydrocarbons with Preheated Air, 27th Symposium (Intl.) on Combustion, The Combustion Institute, PA, 1999, pp. 3205-3213.
17. Plessing, M., Peters, N., and Wunning, J.G.: Laser Optical Investigation of Highly Preheated Combustion with Strong Exhaust Gas Recirculation, Proc. 27th Symposium (Intl.) on Combustion., The Combustion Institute, Pittsburgh, PA, 1998., pp. 3197-3204.
18. Gupta, A.K. and Hasegawa, T.: The Effect of Air Preheat Temperature and Oxygen Concentration in Air on the Structure of Propane Air Diffusion Flames, 37th AIAA Aerospace Sciences Meeting, Reno, NV, January 11-14, 1999, Paper No. AIAA 99-0725.
19. Gupta, A.K. and Hasegawa, T.: High Temperature Air Combustion: Flame Characteristics, Challenges and Opportunities, Proc. Symposium on High Temperature Air Combustion, Beijing, October 18-19, 1999, pp. 10-28.
20. Hasegawa, T., Tanaka, R. and Niioka, T.: High Temperature Air Combustion Contributing to Energy Savings and Pollutants Reduction in Industrial Furnaces, , Proc. Symposium on High Temperature Air Combustion, Beijing, October 18-19, 1999, pp. 101-114.
21. Ishigure, T., Itoh, S., Matsumoto, K., Kitagawa, K., Arai, N., and Gupta, A.K.: Mass Spectroscopic Detection of Neutral radicals and Ions by Alkali Element ion Attachment and Application to Highly Preheated Air Combustion, Paper to be presented at 1999 IJPGC Conference, Burlingame, CA, July 25-28, 1999.
22. Gupta, A.K. and Hasegawa, T.: Air Preheat and Oxygen Concentration Effects on the Thermal Behavior of Propane and Methane Diffusion flames, High Temperature Air Comb. Sym, Jan. 20-22, 1999, Kaohsiung, Taiwan.
23. Westbrook, C.K., and Dryer, F.L.: Combustion Science and Technology, Vol. 27, 1981, pp.31-43.
24. Yuan, J. and Naruse, I.: Energy & Fuels, Vol. 13, 1999, pp. 99-104.

25. Kiga, T., Hanaoka, R., Nakamura, M., Kosaka, H., Iwahashi, T., Yoshikawa, K., Sakai, M., Muramatsu, K., and Mochida, S.: Combustion Characteristics of Pulverized Coal using High Temperature Air, 37th AIAA Aerospace Sciences Meeting, Reno, NV, January 11-14, 1999, Paper No. 99-0730

Table 1. Various Methods of Heat recirculation Used in Combustion Systems

Heat Recirculation Methods	Internal Recirculation Methods	Steady	Convection	Central Toroidal recirculation (swirl flows, wake flows) flames, corner recirculation zone flame (comb. Eng.) [Internal-external recirculation]
			Conduction	Combustion in porous media (Takeno & Sato, 1979)
			Radiation	Cyclone combustors
		Unsteady	Convection	Pulse combustion
			Conduction	No trials
			Radiation	No trials
	External Recirculation Methods	Steady	Convection	No trials
			Conduction	Swiss roll burner (Llyod & Weinberg. 1974) Burner with heat exchanger (Kawamura, 1983)
			Radiation	Porous media (Echigo, 1982) Rotary Regenerators
		Unsteady	Convection	No trials
			Conduction	No trials
			Radiation	Regenrative combustion

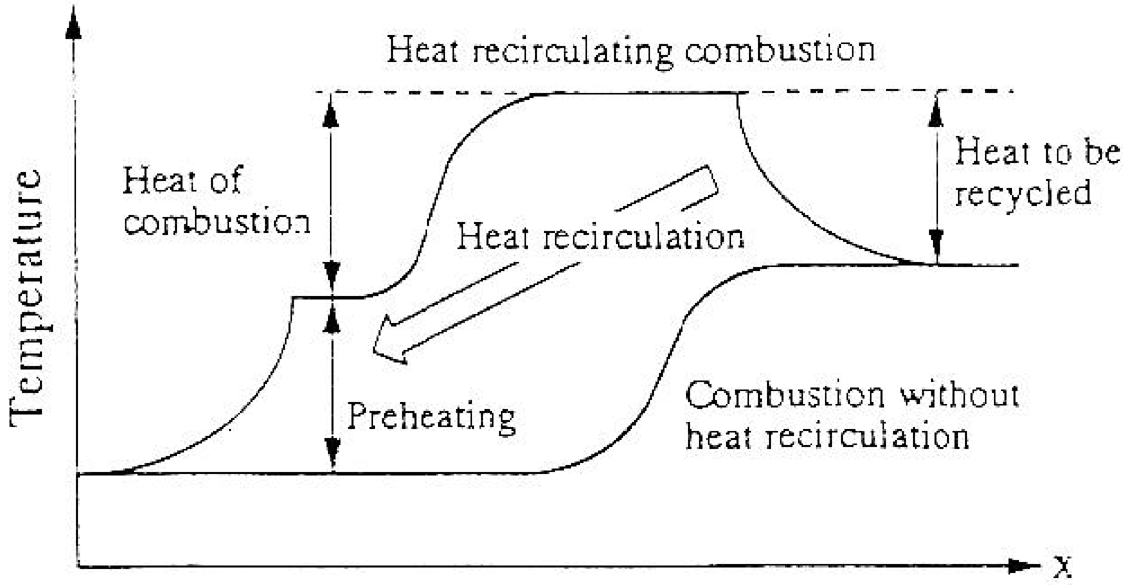

Fig.1. Change of flame temperature with heat recirculation[12].

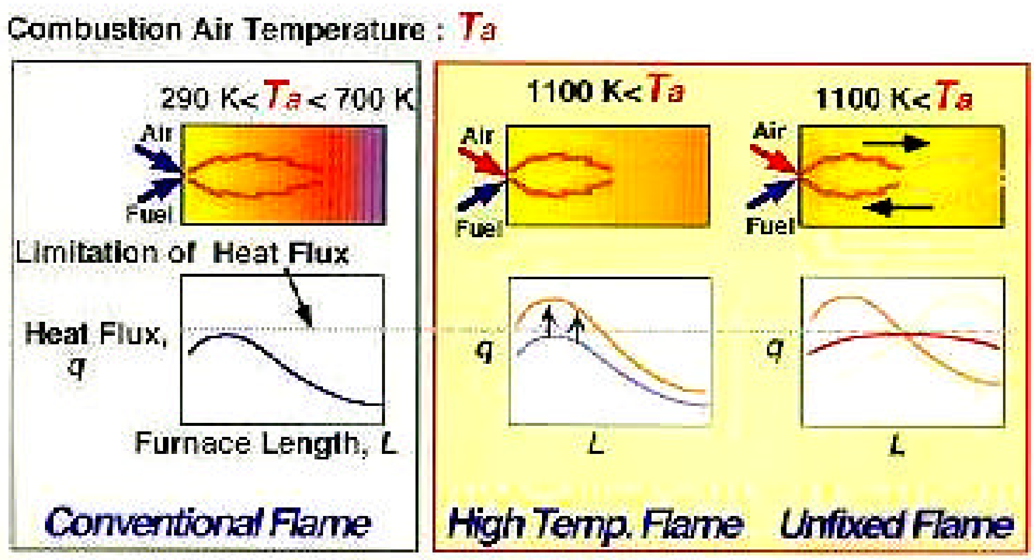

Fig.2. A Schematic diagram of flame and heat flux distribution in a furnace with low temperature combustion air, high temperature air and HiTAC.

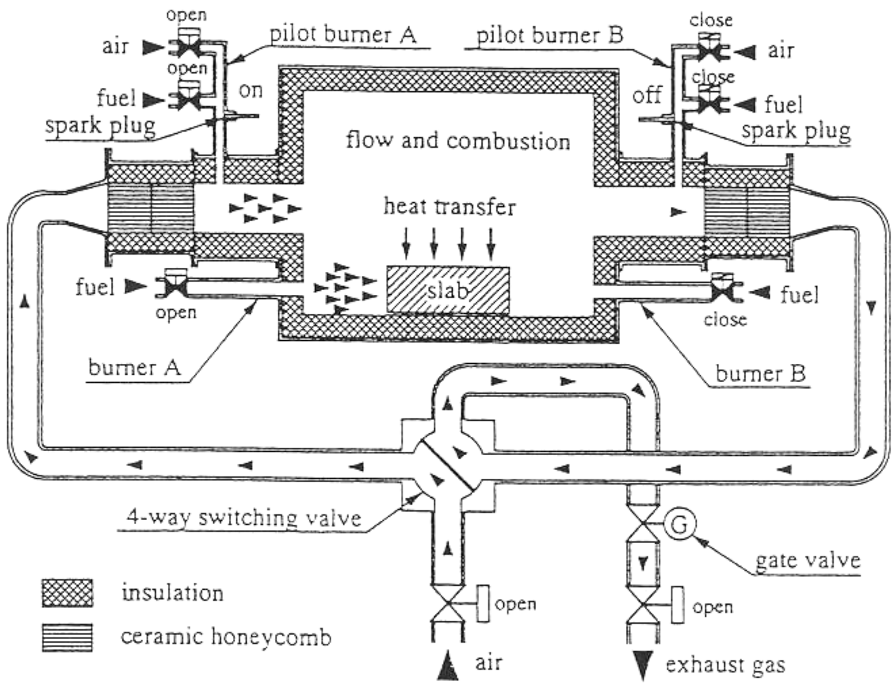

Fig.3. A schematic diagram of heat-recirculating furnace equipped with a pair of ceramic honeycomb burners[11].

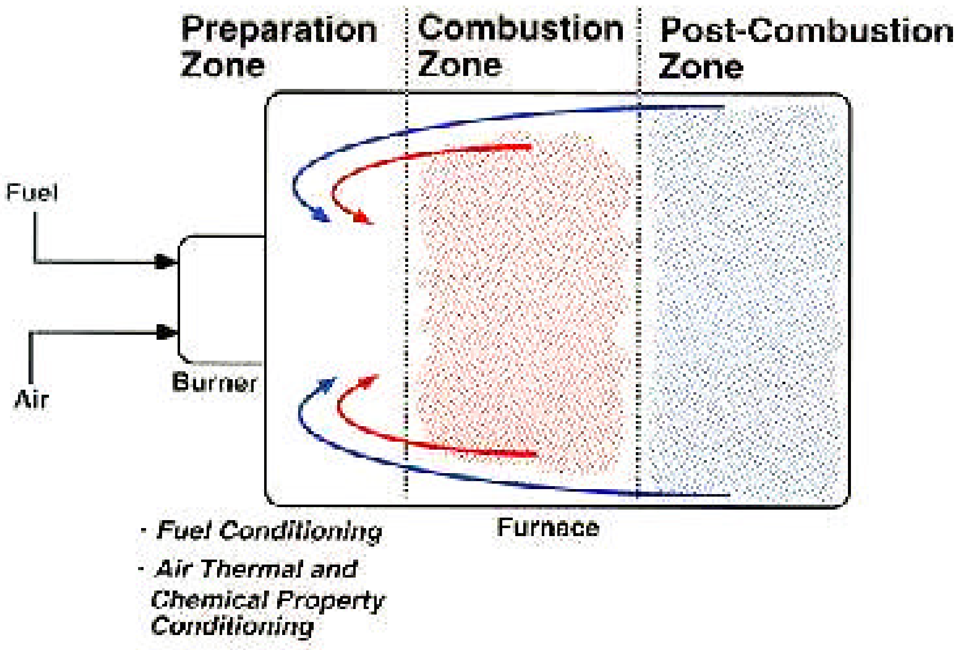

Fig.4. A schematic representation of HiTAC flame

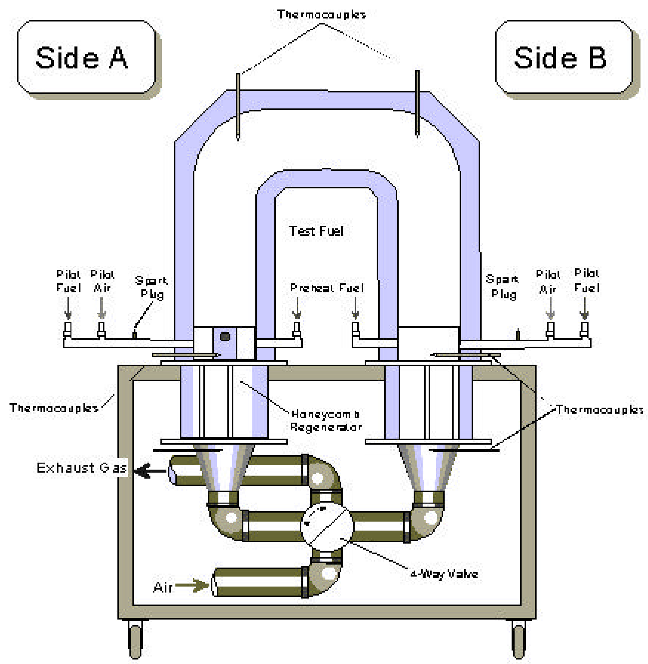

Fig.5. A schematic diagram of the experimental test facility

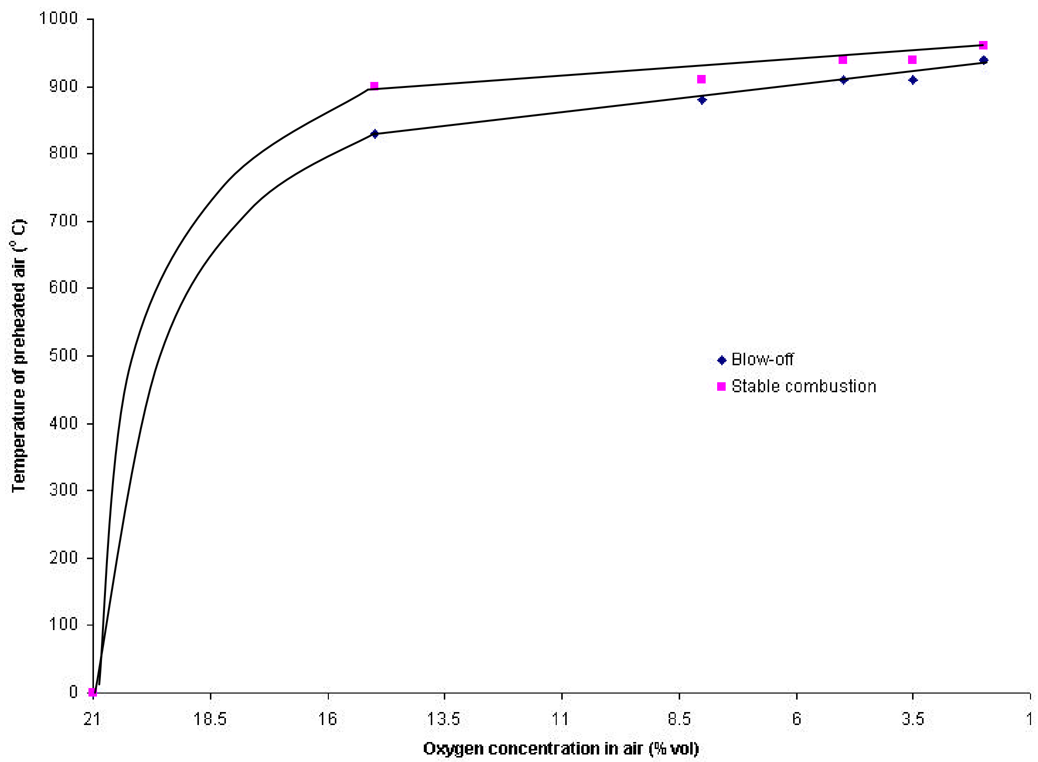

Fig.6. Stability limits of propane flames

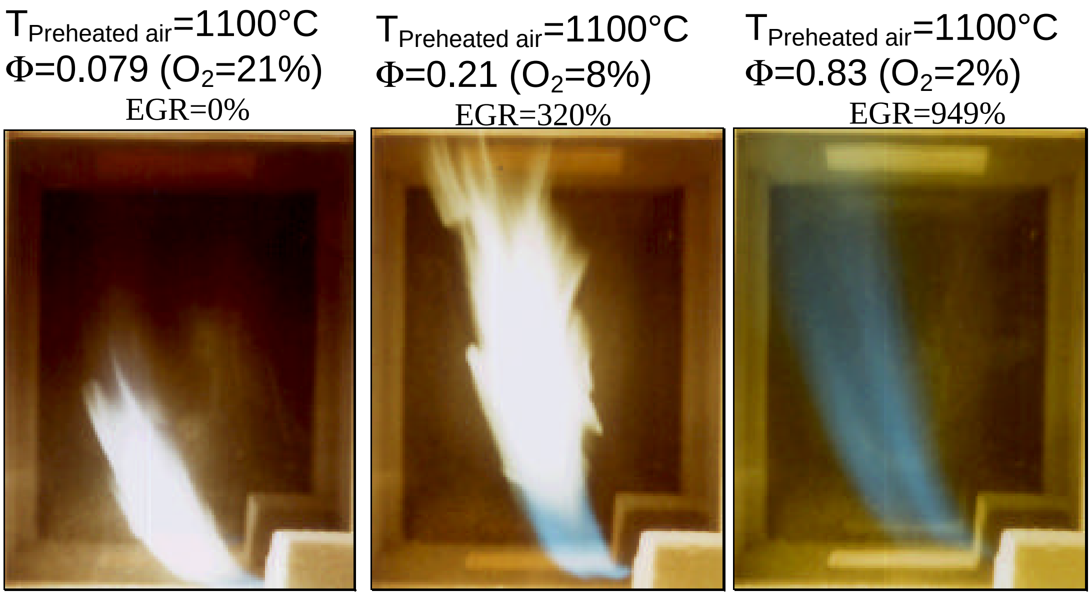

Fig.7. Flame photographs with combustion air temperature of 1100°C and oxygen concentration of 21%, 8% and 2%

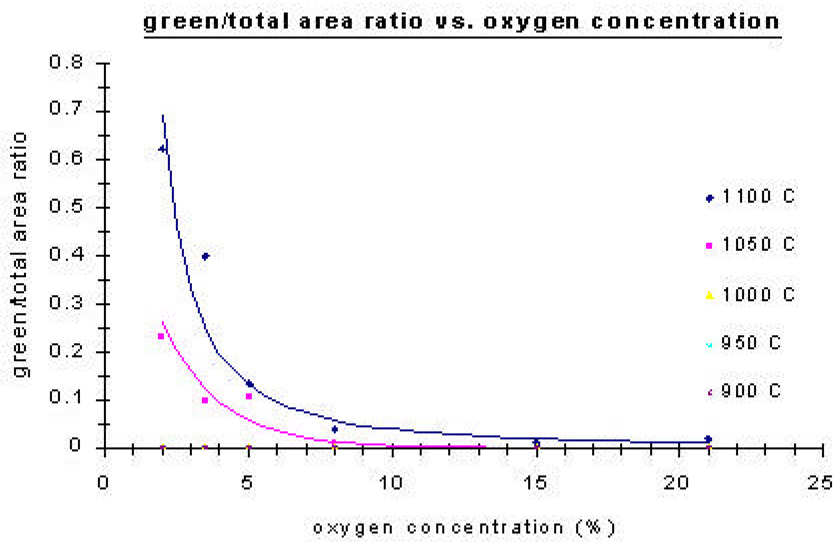

Fig.8. Increase in green flame volume with drecrease in oxygen concentration and increase in air-preheat temperature

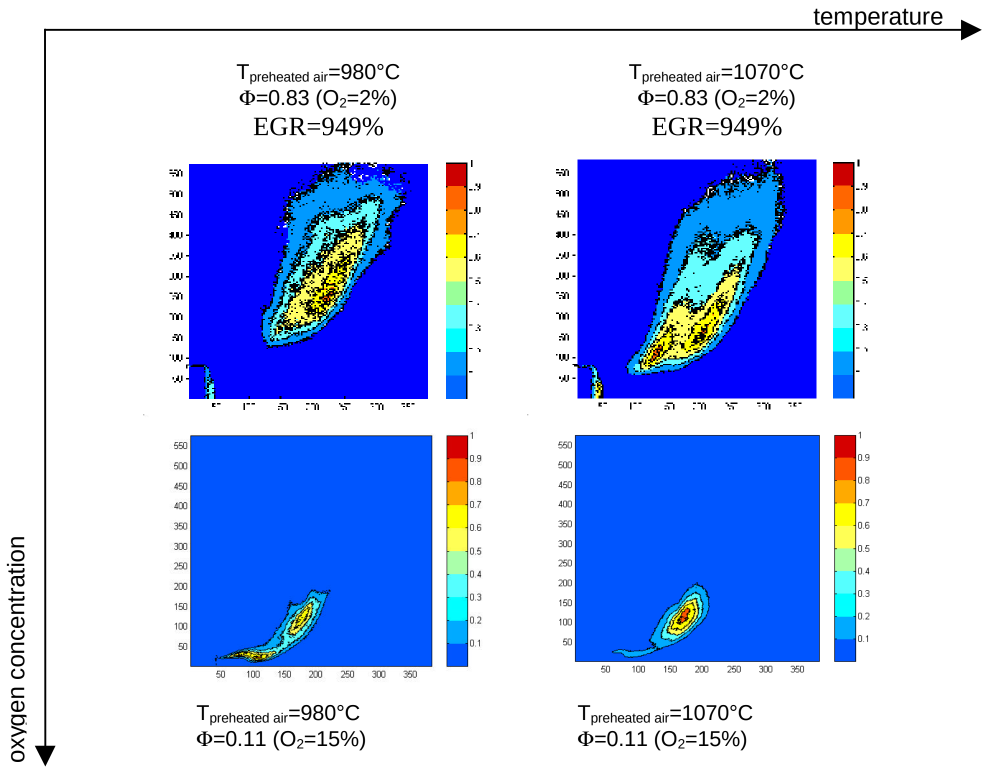

Fig.9. Distribution of C_2 in flames at 1070°C air temperature and oxygen concentration in air of 15% and 2% (Nitrogen as the dilution gas)

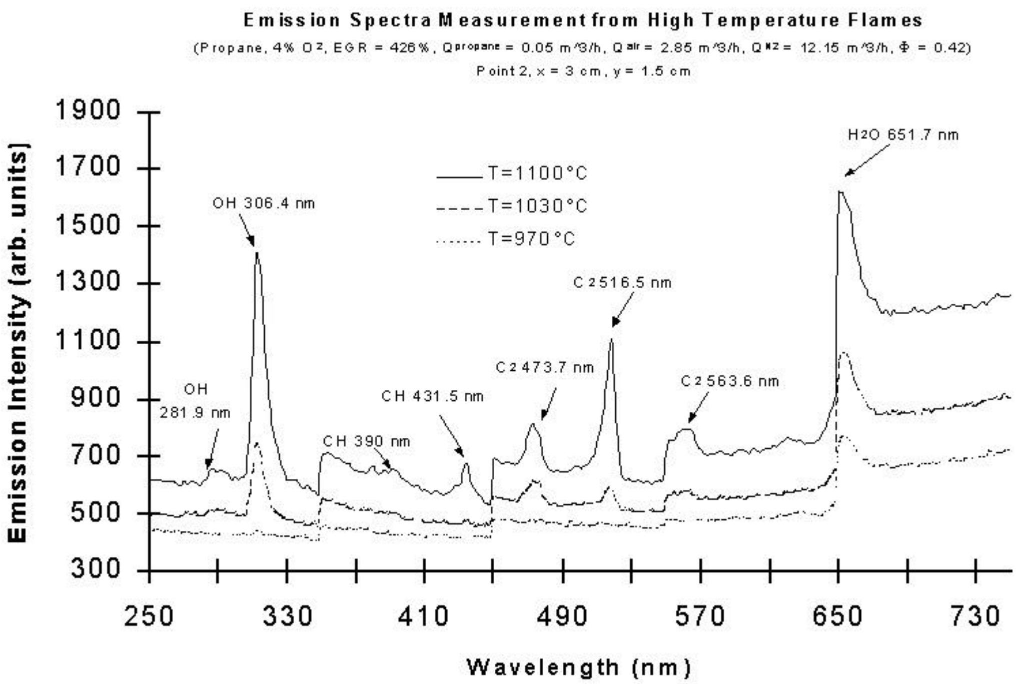

Fig.10. Flame emission spectra at one point in flame (x=3cm and Y=1.5cm) and three air preheat temperatures (Nitrogen as dilution gas)

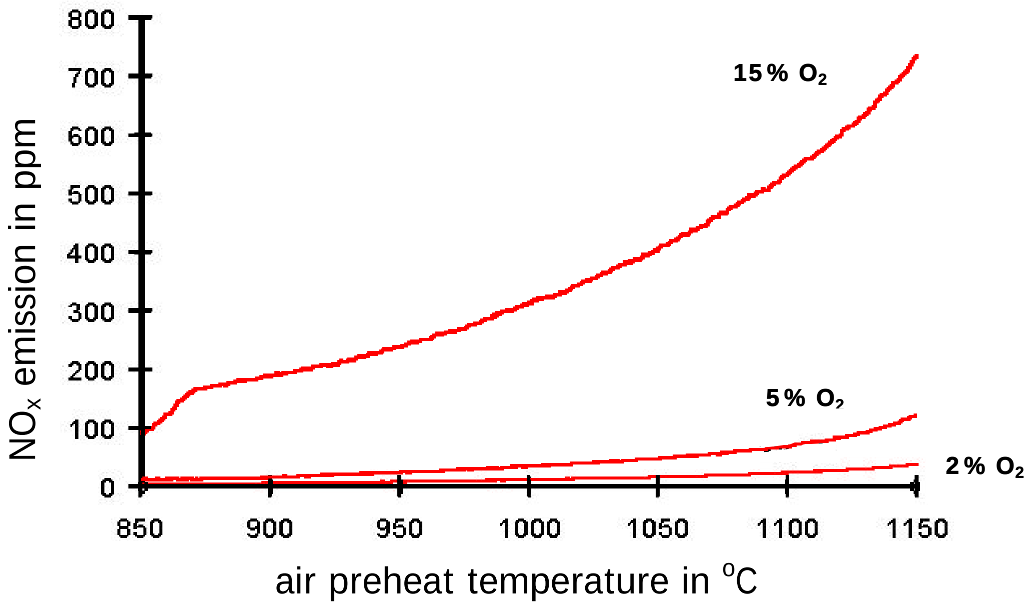

Fig.11. Emission of NO_x at 15, 5 and 2% O_2 in air with various air-preheat temperatures (Nitrogen as the dilution gas)

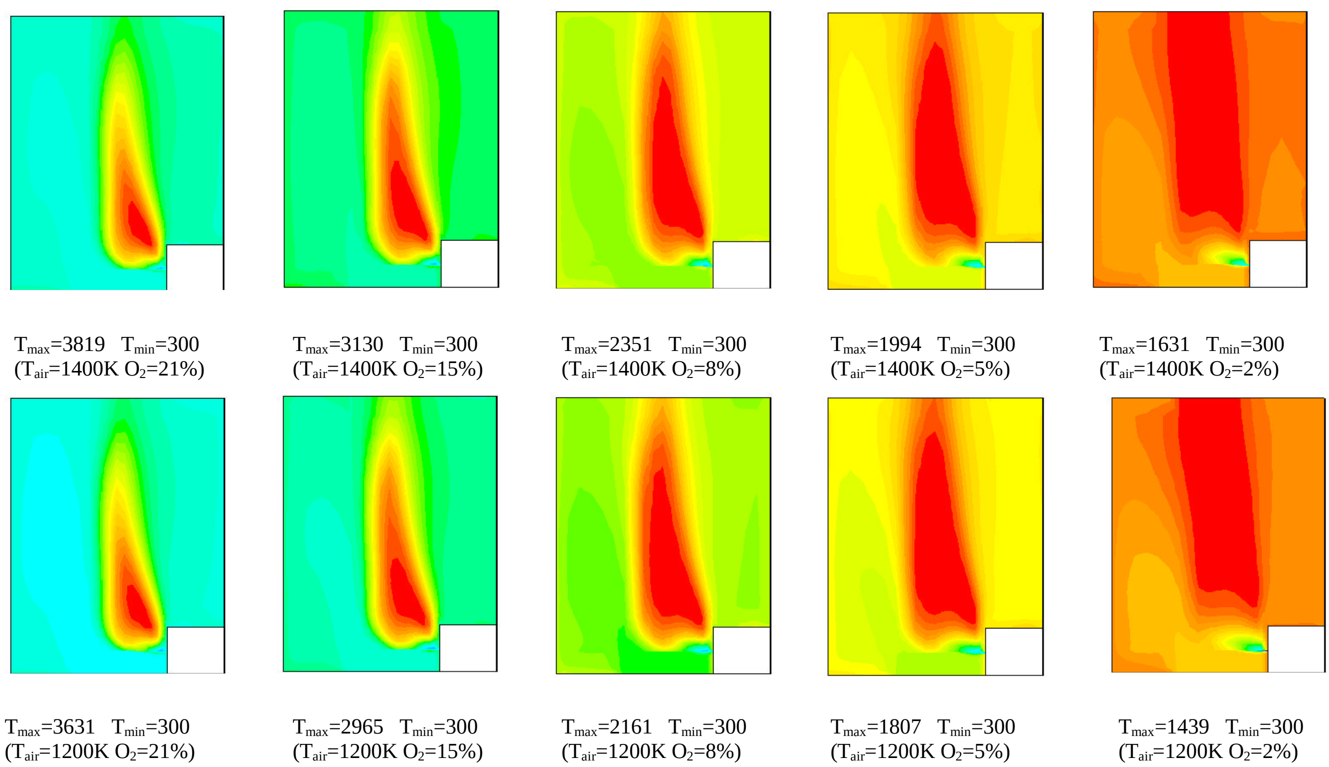

Fig.12. Calculated results on the effect of air preheat temperature (1400K and 1200K) and oxygen concentration (21,15,8,5 and 2%) on the distribution of mean temperatures in propane flames.

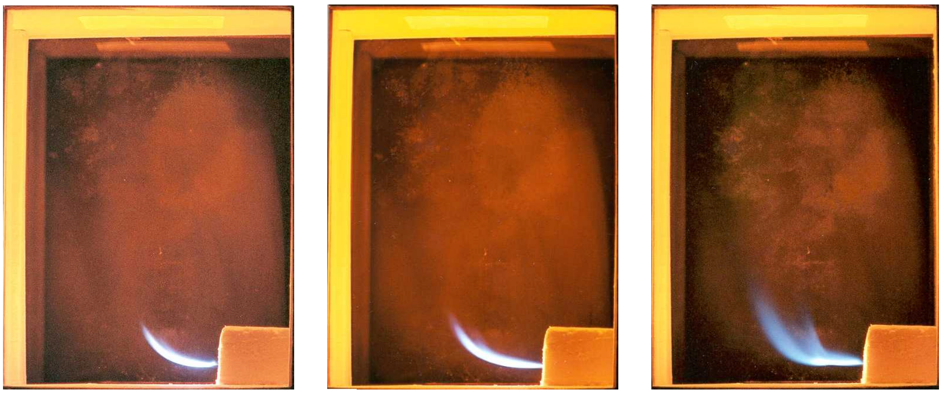

Fig 13. Carbon monoxide flame photographs with combustion air temperature of 1000°C and oxygen concentration of 21%, 8% and 2%, respectively (dilution gas: Nitrogen).

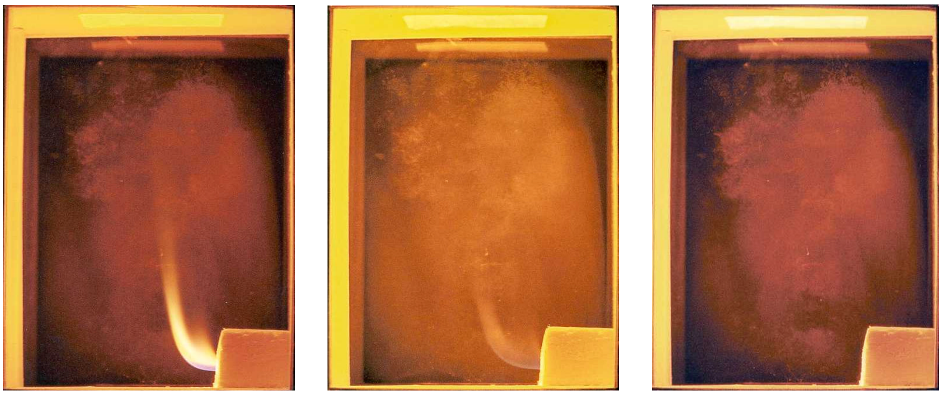

Fig 14. Hydrogen flame photographs with combustion air temperature of 1000°C and oxygen concentrations of 21%, 8% and 2%, respectively (dilution gas: Nitrogen).