Highly Preheated Combustion Air Furnace with Oxygen Enrichment for Metal Processing to Significantly Improve Energy Efficiency and Reduce Emissions

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ABSTRACT

Improving furnace efficiency is a high priority need for aluminum, glass, steel and other metal casting industries. This paper attempts to address these needs. It describes furnace technology to reduce energy usage and emissions while improving productivity. Estimates based on data compiled by DOE indicate that about 40% of the energy used in these industries is lost. We hope to reduce this significant amount of energy loss and the corresponding CO_2 emissions.

In this work, wasted flue gas enthalpy is used to highly preheat the incoming oxygen-enriched air and fuel. However, this is often not done because it increases the NOx production rates and contributes to heat flux non-uniformities within the furnace. A novel solution to this problem is proposed where exhaust gas recirculation and intense flame radiation are employed to reduce the flame temperatures and thus thermal NO. Nearly homogeneous burning occurs in distributed reaction zones under slightly rich conditions that enable increasing the flame radiation and also promote NO reburn. A second-stage air injection completes the combustion and efficiently transfers the heat to the incoming fresh fuel and air. Near unity flame emissivities are obtained at a temperature not exceeding 1900K. The furnace provides nearly uniform radiation heat flux to the objects at a magnitude exceeding 400 kW/m^2, while maintaining strict constraints on NOx, CO, unburned hydrocarbons (UHC) and particulate emissions. This level of heat flux enables an increase in the furnace productivity or a decrease in size and cost.

Introduction

The Michigan IOF Program "Metal Casting Initiative" has identified improving furnace efficiency and overall plant energy efficiency as high priority needs in its "roadmap" for Michigan metal casters. These needs were established by industry representatives and energy audits conducted by MI-IAC of several metal casting facilities (Everest & Atreya 2001). Also, according to a recent Interlaboratory Working Group Report (DOE 2000), in 1997, the U.S. industrial sector consumed 35 quads of primary energy resulting in about 494 MtC [million metric tons of carbon] of carbon emissions. More than half of this energy was used as production process heat by energy-intensive industries like Steel, Metal Casting, Aluminum, Chemicals, Paper and Glass. However, the useful portion was less than 60% and over 40% was lost. This significant amount of lost energy (~7 quads costing about $21 billion) and the corresponding CO_2 emissions need to be reduced.

To reduce fuel expenses and CO_2 emissions, it is important to drastically increase furnace efficiencies. Such efficiency improvements can be achieved by better insulation (reducing conductive, convective and radiative losses) and by reducing stack losses. This work focuses on reducing the stack losses that are a major part of the total and for which appropriate technology is not readily available. The furnace technology described here not only reduces energy usage, but also reduces emissions, improves productivity and reduces capital and operational costs. It is applicable to melting furnaces used in industries such as aluminum, glass, and steel.

Background

Scientific solution for increasing energy efficiency and reducing pollutant formation in furnaces requires an understanding of the physical energy-transfer and mixing mechanisms along with the chemical reaction pathways for pollutant formation in various fuel/oxidizer/inert mixtures. Further, of the numerous possible operating conditions, there exists an acceptable parameter range. Thus, from a practical point-of-view; appropriate sensors are needed to enable active feedback control of the furnace. To fix ideas, consider hydrocarbon combustion in air that may be represented by the following chemical reaction:

$$Hydrocarbon\,(HC)\,Fuel + O_2 + 3.76N_2 \longrightarrow$$

$$\underbrace{\boxed{CO_2 + H_2O}}_{\textbf{unavoidable}} + \underbrace{\boxed{3.76N_2}}_{\textbf{unnecessary}} + \underbrace{\boxed{(CO, unburned\ HC, soot, NO_X)}}_{\textbf{undesirable}} + \underbrace{\boxed{Heat}}_{\textbf{needed}}$$

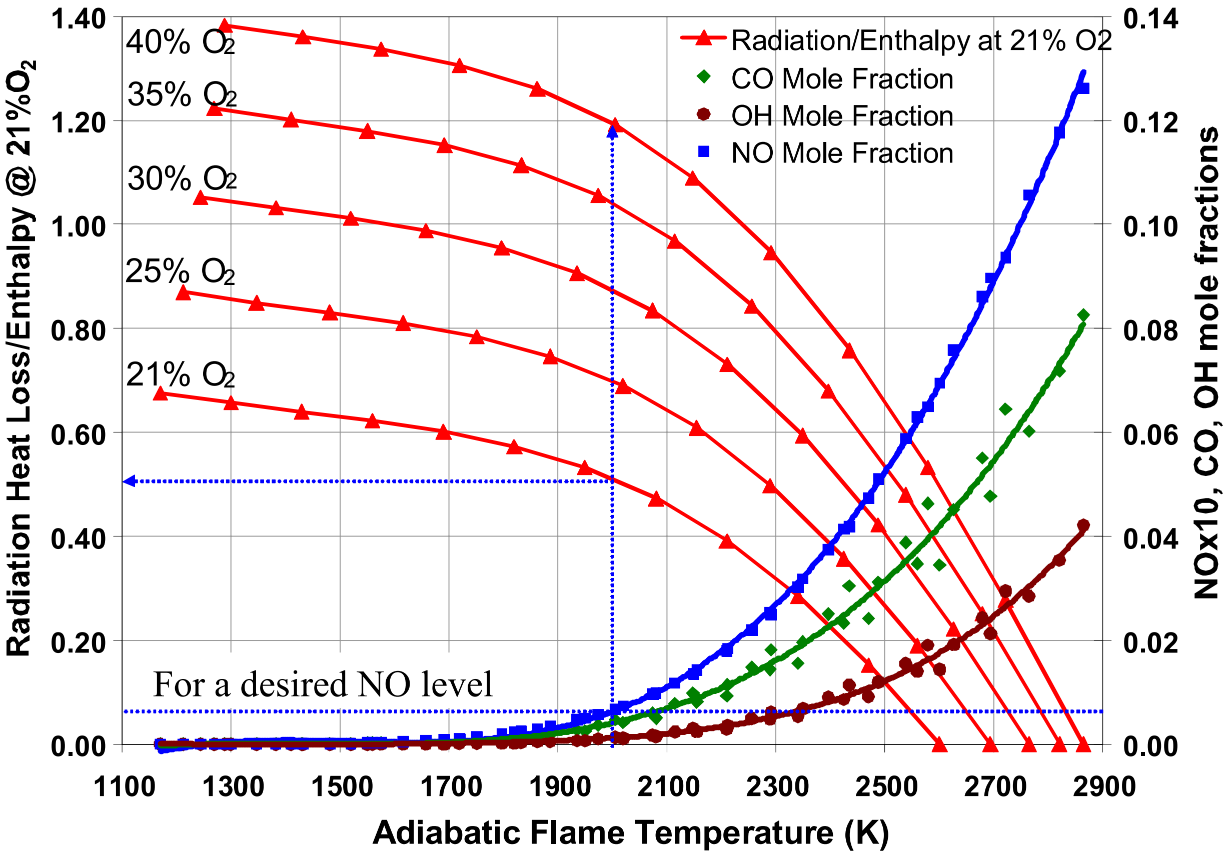
Here, as indicated, it is not possible to avoid CO_2 production except through energy efficiency. N_2 present in air is not needed for the combustion process, but it is not economical to get rid of it. Recent developments in membrane separation technology can economically provide up to 45% oxygen-enriched air. However, this has not been practically utilized because 45% O_2 considerably increases the flame temperature and the remaining N_2 is sufficient to produce copious amounts of NO. All the other combustion products, marked undesirable, are pollutants that we wish not to produce but may be inevitable unless the operating conditions are carefully controlled. Clearly, reducing or eliminating the exhaust of hot N_2 by using oxygen-enriched air will significantly increase the energy utilization efficiency. However, it will also create significant temperature nonuniformities (or hot spots) and increase NO production if N_2 is present – unless uniform burning is accomplished via distributed reaction zones and energy is transferred at a very high rate from these reaction zones via radiation. Since radiation is the primary mode of heat transfer in the furnace, intensely and spatially uniformly radiating flames is a desirable attribute.

Oxygen-Enriched, Highly Radiating Flame Calculations

To obtain an upper bound on temperature, radiation and pollutant formation, equilibrium calculations were done using the NASA equilibrium code for fuel/air mixtures ranging from 21% to 40 % O_2 in air and with various amounts of heat loss per unit flame volume. Figure 1 below shows the results plotted against the adiabatic temperature which corresponds to zero heat loss. The heat loss per unit volume is normalized by the sensible enthalpy at 21% O_2 (i.e. $C_P(T_{ad}$ - $298.15)$ for normal air). Equilibrium concentrations of

NO, CO & OH are also plotted. At 21% O_2, the desired NO level (say corresponding to 2000K, as shown in the figure) can be obtained by radiating about 50% of the enthalpy. However, at 40% O_2, 120% of the energy available per unit volume with 21% O_2 can be radiated without NO penalty.

Figure 1. NASA Equilibrium Calculations



The benefits of oxygen-enriched or pure oxygen combustion in conjunction with high flame radiation are further demonstrated by in Figure 2. In these equilibrium calculations the production of CO_2 and NO was determined <u>for the same amount of CH_4 burning in "air" with different oxygen concentrations</u>. Different amount of radiative heat transfer per unit flame volume was used to determine its effect on pollutant formation. Clearly as the radiative heat transfer from the flame increases, productivity (a measure of the rate at which objects are heated in a furnace) increases proportionally without an increase in the fuel consumption. Furthermore, the CO_2 and NO production rate decrease substantially (CO_2 by a factor of six and NO by five orders of magnitude) for the same productivity and the same fuel consumption. The normal flame condition for CH_4 combustion is shown in this figure by the shaded circle marked '(1)' and the desired flame condition is marked by '(2)'. Our goal is to obtain condition '(2)' or better. This can be accomplished by burning in oxygen enriched "air" and enhancing the flame radiation. At 45% O_2, a radiative fraction (energy lost by flame radiation/energy released by combustion) of 0.72 is required which can only be accomplished by configuring flames that simultaneously produce and oxidize soot and have a high concentration of radiative gases (such as CO_2 & H_2O) in the reaction zone. Calculations in Figure 3 show that the amount of soot required is quite small (~0.05ppm), hence slightly rich conditions at a temperatures about 1900K are needed. While we do not have experimental results for furnace flames, experiments conducted on flamelets ("elements" of turbulent non-premixed flames used in furnaces) show that the presence of even small amounts of soot in the high temperature reaction zone significantly increases the flame emissivity (Atreya et al. 1997; Mungekar & Atreya 2000, 2001a, 2001b). Thus, oxygen-enriched conditions can be beneficial as long as they are accompanied by high flame radiation.

Figure 2. NASA Equilibrium Calculations for the Same Amount of CH_4 Burning in 21% to 45% O_2 "Air" with Different Amounts of Flame Radiation.

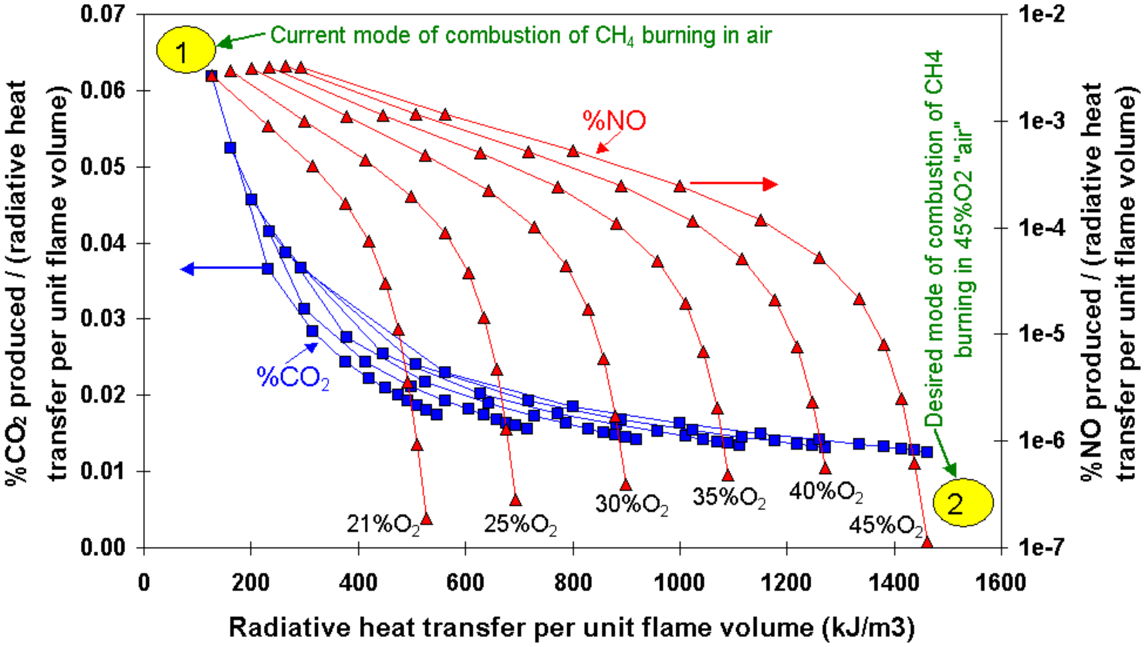
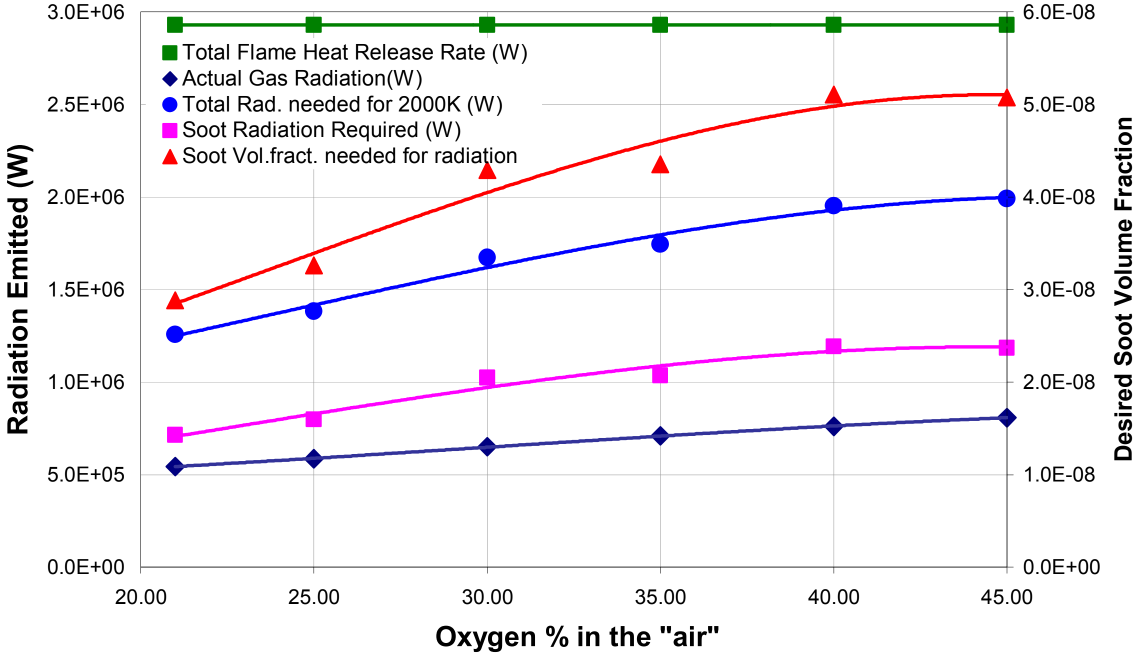


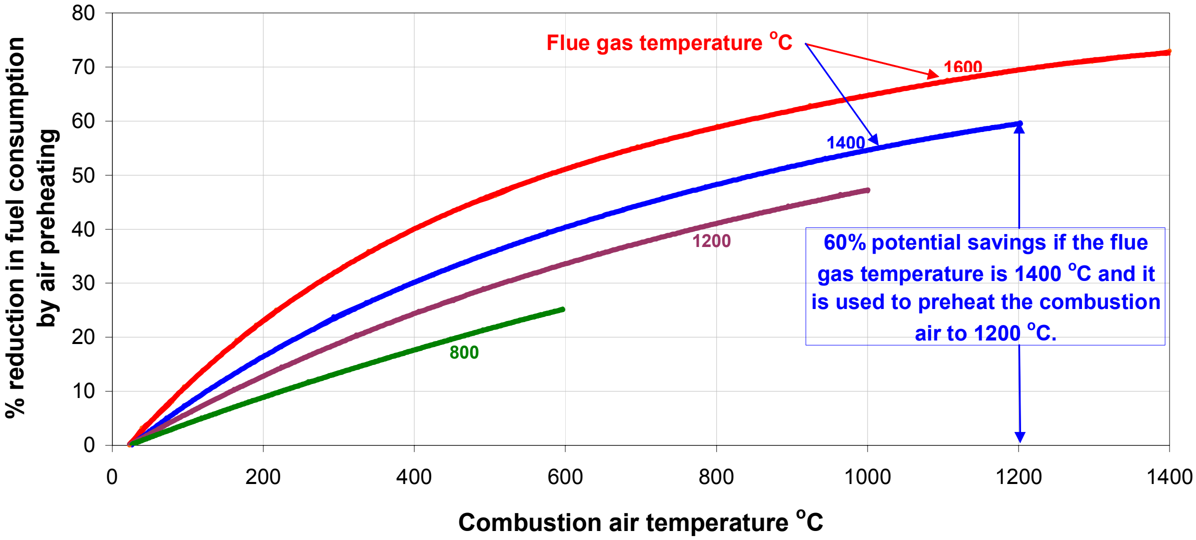
Figure 3. Calculations of Soot Volume Fraction Required for Radiation



Benefits of Preheating and Exhaust Gas Recirculation

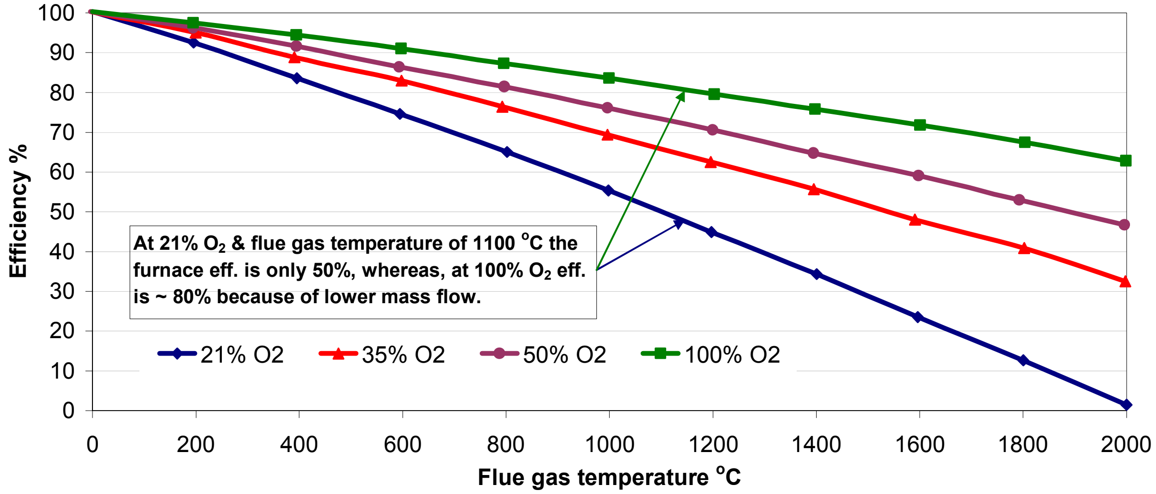
Recently, there has been a great deal of activity in designing efficient burners and furnaces motivated by pollutant prevention and global warming concerns. Most of these new combustion techniques, such as flameless oxidation (FLOX) to increase furnace efficiency, are being developed in Europe and Japan (Wlodzimierz & Simon 2000; Katsuki & Hasegawa 1998; Wunning & Wunning 1997). The FLOX concept, while actively under development, has shown considerable promise in reducing pollutant emissions, increasing furnace efficiency and providing a more uniform heat flux to the objects in the furnace. However, this concept is diametrically opposite to the one proposed above. In the FLOX concept, high regenerative preheating (above the auto ignition temperature) of combustion air along with excessive dilution by exhaust gas recirculation is utilized to enable burning in a very low oxygen concentration atmosphere. This produces a nearly uniform distributed reaction zone with low peak flame temperatures to reduce thermal NO formation. In the previous discussion, oxygen-enriched air was used and flame temperatures were reduced by intense flame radiation. As we will see later, both these concepts can be profitably combined to yield additional advantages.

Figure 4. Reduction in Fuel Consumption by Air Preheating



Clearly, recapturing wasted flue gas enthalpy to preheat the combustion air and/or reducing the total amount of exhaust by using oxygen-enriched air is necessary for significantly improving the furnace efficiency. Simple calculations to quantitatively evaluate the savings (Everest & Atreya 2001) are presented in Figures 4 and 5. Either one or both these techniques can be simultaneously employed. For example, if 50% O_2 is used and the flue gas temperature is 1200 ^oC and if the incoming "air" is heated to 1000 ^oC with the flue gas the overall furnace efficiency becomes 85%. This is a substantial improvement if 21% O_2 air was used and no preheating was employed. Thus, one way to advance the state-of-the-art is to use the salient features of both research in References (Everest & Atreya 2001; Atreya et al. 1997; Mungekar & Atreya 2000, 2001a, 2001b) and research in References (Wlodzimierz & Simon 2000; Katsuki & Hasegawa 1998; Wunning & Wunning 1997) for designing an efficient furnace. In addition, an understanding of pollutant formation during combustion, particularly soot and NOx, would be helpful (Miller & Bowman 1989). The furnace design

Figure 5. Effect of Flue Gas Temperature on Furnace Efficiency for Various O_2% without Air Preheating



presented here aims not only to reduce energy usage, but also to reduce emissions, improve productivity and reduce capital and operational costs (Everest & Atreya 2001). The technical hurdle to overcome is how to combine the available understanding into a single furnace design. This is discussed below.

Furnace Design

Summary of Salient Features

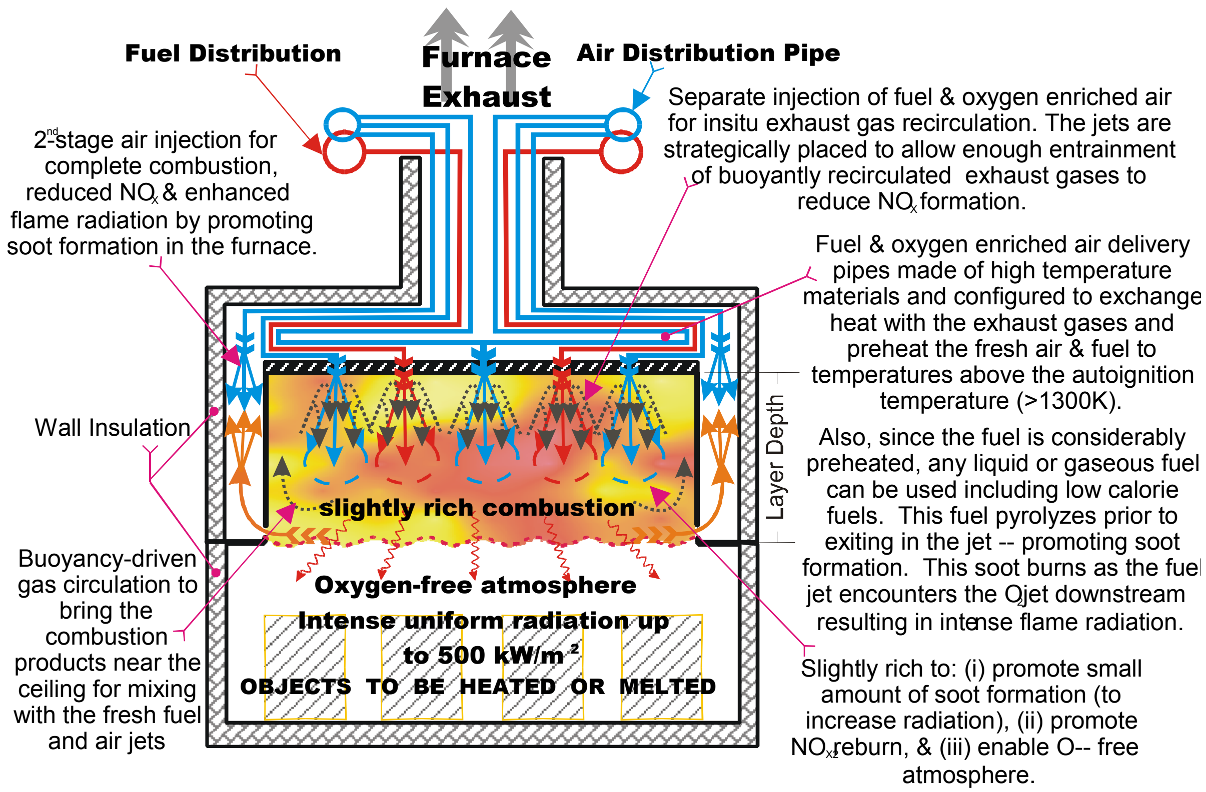
1. Capturing the exhaust gas enthalpy to preheat the incoming combustion air and fuel to the maximum possible level is essential for increasing the furnace efficiency. Two methods, regenerative and recuperative, have been used in the past for this purpose. Previous work shows that a more uniform distributed reaction zone is possible if combustion air and fuel are highly preheated to above the auto ignition temperature (>1300K).
2. Oxygen-enriched combustion reduces the total mass of the exhaust gases and hence further increases the furnace efficiency by reducing the exhaust gas enthalpy.
3. Very high preheating allows substantial dilution by combustion products (exhaust gas recirculation) which can be utilized to burn with low oxygen concentration to reduce peak flame temperatures and hence thermal NO.
4. Enhancing flame radiation is another method of reducing the peak flame temperatures with an added advantage that it substantially increases the furnace productivity. To enhance flame radiation a high concentration of combustion products (primarily CO_2 & H_2O) and some soot is required to be present in the high temperature reaction zone. Thus, slightly rich combustion is desirable (alternatively, some pulverized coal dust may be added to the reaction zone). Further, the use of oxygen-enriched air increases the CO_2 & H_2O concentrations and reduces the N_2 concentration. Substantial dilution by combustion products (exhaust gas recirculation) is also essential to increase radiation and homogeneity.

5. Slightly rich combustion would also enable reburn reactions to further reduce the NO production. However, it will require a second stage air injection for complete combustion.
6. To fully utilize the benefits of flame radiation, it is essential to have a substantial volume of hot combustion products because radiation is proportional to the flame volume. Furthermore, it is advantageous to have a distributed reaction zone throughout this volume to provide uniform radiation. Thus, excessive mixing of the exhaust gases with the incoming air and fuel prior to reacting is essential.

Summary of Furnace Design

Based on these guiding principles, a furnace is designed to drastically increase the efficiency within the strict constraints on NOx, CO, total unburned hydrocarbons (THC) and particulate emissions. This is schematically shown in Figure 6. Here nearly homogeneous burning (distributed reaction zone) occurs under slightly rich conditions in the ceiling configuration forming a hot layer of intensely radiating combustion products. These combustion products eventually spill out into the concentric annular exhaust where a second-stage air injection completes the combustion and efficiently transfers the heat to the incoming fresh fuel and air. The highly preheated oxygen-enriched air and fuel are injected separately into the hot ceiling layer to enable mixing with the existing combustion products prior to burning. This dilution by combustion products ensures homogeneous burning with low peak flame temperatures and produces a distributed reaction zone. The arrangement provides nearly uniform radiation heat transfer at a magnitude exceeding 400kW/m^2. This enables an

Figure 6. A Schematic Diagram of the Furnace



increase in the furnace productivity or a decrease in size and cost. NO produced in the hot layer is reduced by slightly rich conditions in the hot layer that promotes NO reburn. Hence, very low NO concentrations exist in the exhaust. Due to increased residence time of the hot gases in the upper layer CO & unburned hydrocarbons are also oxidized & any remaining are oxidized in the second stage.

Additional advantages of this furnace design are: (i) An oxygen-free atmosphere is maintained within the furnace which prevents scale formation and subsequent material loss. (ii) Low heating value gases can be burned in the hot layer due to high temperatures. (iii) Volatile organic compounds (VOCs), can be directly burned in the hot layer – thus avoiding the use of auxiliary incinerators. (iv) The hot layer temperature and hence the furnace heat flux is limited only by NOx formation and the furnace construction materials. Thus very high temperatures can be easily obtained by using pure oxygen and appropriate construction materials.

It is also important to emphasize that while the guiding calculations presented in Figures 1 & 2 are obtained from equilibrium considerations, these calculations are expected to hold for the furnace design because the residence time of the products of combustion is much larger than chemical reaction time and turbulent mixing time (long reactant residence times are also needed to effectively cool the combustion products via radiative heat transfer). Experiments, as well as numerical calculations with detailed chemistry are currently underway to enable choosing the dimensions of the furnace to enable long reactant residence times.

Finally, it is necessary to have feedback controls on the furnace to ensure pollutant-free, efficient and safe operation. This is an extensive subject and cannot be discussed within the confines of this paper. However, guidance may be obtained from references (Berhan, Atreya, & Everest 2001; Kelly, Wooldridge & Atreya 2001).

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