A combustion control system allows the dramatic reduction of NOx emission levels from industrial combustion processes without having recourse to expensive flue gas clean up methods. The system combines the technique of oscillating combustion with an adapted system for post combustion burn out of the excess of CO resulting from the low-NOx combustion zone. A process for fuel combustion includes generating an oscillating combustion zone by oscillating at least one of the fuel flow and the oxidant flow to achieve a reduced nitrogen oxide emission, selecting oscillating parameters and furnace operating parameters to maximize nitrogen oxide reduction efficiency to the detriment of carbon monoxide production, and combusting carbon monoxide downstream of the oscillating combustion zone by injecting a post combustion oxidant.
PROCESS AND APPARATUS OF COMBUSTION FOR REDUCTION OF NITROGEN OXIDE EMISSIONS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application No. 60/348,661 filed Jan. 14, 2002, which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] The invention relates to a method and apparatus to reduce nitrogen oxide emissions from industrial combustion processes, and more particularly the invention relates to a method and apparatus to reduce nitrogen oxide emissions without affecting other emissions, such as carbon monoxide, by combining the technique of oscillating combustion with a system of post combustion removal of carbon monoxide.

DESCRIPTION OF THE RELATED ART

[0003] High-temperature, gas-fired furnaces, especially those fired with preheated air or industrial oxygen, produce significant quantities of nitrogen oxides (NOx) per unit of material processed. At the same time, regulations on emissions from industrial furnaces are becoming increasingly more stringent, especially in areas such as California.

[0004] Operators have been looking for improved combustion technologies allowing reduced NOx formation at a reasonably low cost. Different solutions have been developed, including low-NOx burners using staged combustion or Flue Gas Recirculation methods, with different levels of effectiveness.

[0005] One of these technologies, which has already proved to give good results, is Oscillating Combustion, where fuel-rich and fuel-lean zones are created within the flame, thus retarding NOx formation by avoiding stoichiometric combustion. However, if higher levels of NOx reduction are to be achieved while still maintaining carbon monoxide (CO) emissions at safe levels, a modified technique may be required.

[0006] Industrial Combustion processes, such as high-temperature, natural gas-fired furnaces, produce NOx emissions. These nitrogen oxides (primarily NO and NO2) being a major cause of air pollution as well as a significant health hazard in ambient air, they have been defined as a criteria pollutant by the Clean Air Act Amendment (CAA), which has established environmental limits in determined locations.

[0007] Because of the competition, operators of such processes are thus facing a difficult challenge: to increase their productivity under the more and more stringent constraints of higher efficiency and reduced NOx emissions. Lower-cost and more efficient compliance technology and combustion equipment is thus required by these industries in order to remain competitive.

[0008] In the combustion of natural gas, NOx are formed by oxidation of nitrogen in the combustion air under high temperatures. NOx emissions can be controlled by suppressing NOx formation or by reducing NOx to molecular nitrogen after they are generated. The most effective and most widely applied NOx control technologies so far are as follows.

- Combustion Control Techniques
  - Combustion control is a category of technologies which are intended to minimize NOx emissions by 1) lowering the temperature in the combustion zone to suppress NOx formation, 2) decreasing the oxygen concentration available for NOx formation in the high temperature zones, and/or 3) creating conditions under which NOx can be reduced to molecular nitrogen by reacting with hydrocarbon fragments. Technologies of this kind include the following four techniques.
    - Low excess air reduces the available oxygen to the point which is just sufficient to oxidize the fuel but not so much as to cause emissions such as NOx and CO.
    - Staged combustion involves combusting by arranging the inlets of fuel or air to achieve off-stoichiometric firing conditions in the different zones of combustion.
    - Flue gas recirculation (FGR) involves recirculation of the flue gas to the combustion zone as a diluent to reduce flame temperature and oxygen concentration.
    - Gas reburning involves introducing fuel gas to burn in the post combustion zone to generate various types of hydrocarbon fragments which reduce the NOx formed in the main combustion zone to molecular nitrogen.
- Flue Gas Clean Up Techniques
  - These technologies are the final alternatives when the previously described techniques fail to produce an acceptable NOx emission rate.

- Selective Non-Catalytic Reduction (SNCR) involves injecting reagents such as ammonia or urea in the furnace. In the temperature window between about 1800°F and 2000°F, the NOx formed during combustion can be reduced to molecular nitrogen by reacting with the reagent.
- Selective Catalytic Reduction (SCR) is a post combustion control technology. The reduction of NOx by the injected reagents such as ammonia or urea is enhanced by the presence of catalysts. The reaction requires a temperature window between 500°F and 750°F, which is suitable for flue gas scrubbing.
- Oscillating Combustion
  - An alternative method to the different techniques presented above is the technology of Oscillating Combustion. This process, which is already documented in U.S. Pat. Nos. 5,302,111; 5,522,721; and 4,846,665, has already been tested and its efficiency has been proved. In addition, European Patent No. 1139022, deals with methods to optimize the implementation of oscillating combustion in a furnace and to control its operation, and focuses mainly on multi-burner, side-fired furnaces.
- Oscillating Combustion involves the forced, out-of-phase oscillation of the fuel and/or oxidant flow rate(s) provided to a burner to create successive fuel-rich and fuel-lean zones within the flame, thus increasing heat transfer by enhancing flame luminosity and turbulence, and retarding NOx formation by avoiding stoichiometric combustion.
[0022] Oscillating combustion implemented alone has allowed up to approximately 60% NOx reduction on various industrial processes. However, this optimum reduction depends on the characteristics of the burner, process or combustion chamber under consideration, and the setting of parameters of oscillation.

[0023] In terms of NOx reduction, the SCR currently offers the best result (75-90%). Oscillating combustion, according to what has been demonstrated so far in both laboratory and field tests, provides the second best results (50-60%), as well as some other advanced combustion control techniques (optimized staged combustion and FGR methods). The reduction efficiency of both SNCR and less advanced combustion control techniques is low (30-50%).

[0024] In terms of cost-effectiveness, the SCR and SNCR systems tend to have extremely high capital and maintenance costs. On the contrary, oscillating combustion is a simple and low-cost technology that can be applied to a wide variety of combustion processes.

[0025] However, with the new stringent emissions standards to be met, most of the NOx generating facilities are currently forced to use the most effective, but also the most expensive NOx reduction technology, namely SCR.

SUMMARY OF THE INVENTION

[0026] The present invention relates to a low-cost technology of combustion control allowing the dramatic reduction of NOx emission levels from industrial combustion processes which is capable of achieving low NOx emissions without having recourse to expensive flue gas clean up methods. The present invention combines the technique of oscillating combustion with an adapted system for post combustion burn out of the excess of CO resulting from the low-NOx combustion zone.

[0027] According to one aspect of the present invention, a process for fuel combustion includes the steps of:

[0028] supplying a flow of fuel and a flow of oxidant to a burner;

[0029] generating an oscillating combustion zone by oscillating at least one of the fuel flow and the oxidant flow to achieve a reduced nitrogen oxide emission;

[0030] selecting oscillating parameters and furnace operating parameters to maximize nitrogen oxide reduction efficiency; and

[0031] combusting carbon monoxide downstream of the oscillating combustion zone by injecting a post combustion oxidant at a post combustion injection location to minimize carbon monoxide in an exhaust gas.

[0032] According to another aspect of the present invention, a combustor includes a combustion chamber, at least one burner positioned to direct a flame into the combustion chamber, the burner having at least a first channel for delivering fuel and at least a second channel for delivering an oxidant, a supply of fuel connected to the first channel, a supply of oxidant connected to the second channel, a pulsating mechanism arranged to pulse the flow of at least one of the fuel supply and the oxidant supply to the burner to create an oscillating combustion zone in the combustion chamber, a controller for controlling oscillating parameters of the burner to maximize nitrogen oxide reduction efficiency, and a post combustion oxidant injection system located downstream of the oscillating combustion zone and arranged to burn excess carbon monoxide.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

[0033] The invention will now be described in greater detail with reference to the preferred embodiments illustrated in the accompanying drawings, in which like elements bear like reference numerals, and wherein:

[0034] FIG. 1 is a graph of the NOx levels for stoichiometric, fuel-rich, and fuel-lean conditions.

[0035] FIG. 2 is a schematic diagram of a burner with oscillating combustion;

[0036] FIG. 3 is a graph of the oscillating fuel-oxidant ratio for oscillating combustion;

[0037] FIG. 4 is a graph of the NOx and Co emissions vs. oscillating flow frequency where only fuel flow rate is oscillated;

[0038] FIG. 5 is a graph of the NOx and CO emissions vs. oscillating flow frequency wherein both the fuel and oxidant flow rates are oscillated;

[0039] FIG. 6 is a schematic diagram of a single burner end fired furnace according to the present invention with an oscillating combustion burner and CO post combustion;

[0040] FIG. 7 is a schematic diagram of a cross fired furnace according to one embodiment of the invention operating in oscillating combustion and subsequent CO post combustion;

[0041] FIG. 8 is a schematic diagram of an industrial boiler according to one embodiment of the invention with an oscillating combustion burner and subsequent CO post combusion; and

[0042] FIG. 9 is a schematic diagram of a furnace with a control system according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0043] The present invention relates to a low-cost technology of combustion control allowing the dramatic reduction of NOx emission levels from industrial combustion processes. The present invention is capable of achieving NOx emissions which meet the most stringent NOx emission standards without having recourse to expensive flue gas clean up methods.

[0044] The furnace and the process of the present invention combine the technique of oscillating combustion with an adapted system for post combustion burn out of the excess of CO resulting from the low-NOx combustion zone.

[0045] The principles of the proposed system are to implement the already proven concept of oscillating combustion in an improved manner, so as to amplify its NOx reduction effect through an optimized fine-tuning of the oscillating parameters, even if it turns to be to the detriment of the CO production.
The possible detrimental effect of the NOx minimization is allowed by the presence before the exhaust of the combustion chamber of the post combustion device designed to reduce the effluent level of CO below environmentally regulated levels, without producing additional NOx.

A principle of the proposed process is to implement the proven concept of oscillating combustion (or "pulsed combustion") but, by amplifying its NOx reduction effect through an optimized fine-tuning of the oscillating parameters, namely the flow amplitude, the frequency and the duty cycle, as well as the oxygen to fuel ratio.

The achievement of additional NOx reduction compared to existing oscillating combustion systems is made possible by the fact that NOx performances of such processes have been limited by their CO emission levels. Actually, CO and unburned hydrocarbon emissions are dependent on the same three basic factors that influence NOx emissions: temperature, oxygen concentration, and residence time at elevated temperatures. Unfortunately, each of these must be controlled in the opposite direction from that of NOx reduction: if all three factors are increased, CO production can essentially be eliminated but NOx production is enhanced, and vice versa. As CO emissions can rarely be sacrificed for reduced NOx because a low emission system must keep both pollutants to a minimum, it is often impossible to fully minimize the NOx production of conventional oscillating combustion systems.

In the present invention, there is no limitation regarding the amount of CO produced by the oscillating combustion device because the process has the advantage of providing an effective system of post combustion, which allows the CO oxidation to take place in a location of the furnace where NOx concentrations are already frozen and where temperature is adapted to a reliable CO ignition.

The post combustion system includes a stream of oxidizing gas injected by one or several dedicated lance(s) toward the CO-rich stream resulting from the oscillating combustion zone. The post combustion injection system is designed to allow an enhanced mixing between the oxidant and the molecules of CO and unburned hydrocarbons. The location of the lance(s), even if it can vary from a process to another, is preferably chosen near the exhaust of the combustion chamber, where the CO concentration is supposed to be higher. Optional devices are also proposed so as to increase the efficiency of CO post combustion, such as means to adjust flue gas temperature in the zone of post combustion or means to reduce the additional formation of nitrogen oxides. Finally, the flow of oxidizing gas injected as well as the overall post combustion operation are controlled by a process control system based on the monitoring of process parameters, such as the composition of the flue gas, its temperature or oscillating combustion parameters.

Due to its concept, this innovative method of NOx reduction remains simple, low-cost and can be applied to a wide range of high-temperature air/gas- or oxygen/gas-fired industrial processes such as glass melters, steel reheat furnaces, aluminum melters, boilers, refinery and petrochemical combustors, etc.

Both single-burner and multiple-burner systems are addressed by this invention. However, the proposed technique is particularly adapted and effective for single burner processes, and more especially for industrial boilers (both firetube and watertube types), where unburned products of combustion can't be burned out by additional burners.

As already mentioned, it is an object of the invention to propose a customized version of the oscillating combustion process, enabling to minimize the generation of nitrogen oxides. The principle of the technique of pulsed combustion, already documented in patents previously cited, is summarized below.

Oscillating Combustion

FIG. 1 shows the NOx formation for fuel rich, fuel lean, and stoichiometric combustion. It has been shown that NOx formation is sensitive to temperature and oxygen concentration. An excess of either fuel or oxygen reduces the flame temperature. The maximum flame temperature is realized with excess air level close to stoichiometric concentrations of fuel and oxygen. At higher oxygen concentrations the dilution effect lowers the flame temperature sufficiently to reduce the NOx emissions. At lower oxygen concentrations, there is insufficient oxygen to achieve a high temperature flame. As a result of this sensitivity to temperature and fuel to oxidant proportions, both fuel-rich and fuel-lean flames can generate less NOx than a stoichiometric flame, as shown in FIG. 1.

The concept of oscillating combustion is thus to create successive, NOx retarding, fuel rich and fuel-lean zones within the flame. Oscillating combustion involves forced oscillation of the fuel and/or oxidant flow rates provided to the burner. FIG. 2 shows schematically a burner 100 in which the fuel flow rate is oscillated with the valve 110 to achieve a flame 120 with fuel rich zones 122 and fuel lean zones 124. FIG. 3 illustrates the fuel rich and fuel lean zones for the flame of FIG. 2. In the example of FIGS. 2 and 3, the level of NOx formed in each zone is significantly lower than that which would occur if the combustion took place without fuel oscillation but at the same overall average fuel flow rate. When the fuel-rich zone 122 and fuel-lean zone 124 eventually mix in the furnace, after heat has been transferred from the flame to the load and the flame temperature is lower, the resulting burnout of combustible gases occurs with little additional NOx formation. Additionally, the increased flame luminescence resulting from the fuel-rich combustion zones combined with the increased turbulence created by the flow oscillations provide increased heat transfer to the furnace load. To achieve these results, the technology only requires that an oscillating valve package be installed on the fuel and/or oxidant supply line ahead of each burner.

The oxidant fluid provided for the oscillating combustion process can be either air, oxygen-enriched air or substantially pure oxygen.

Optimized Oscillating Combustion

In order to optimize the performance of the oscillating combustion in the present invention, mainly three parameters must be adjusted to suit any particular application. The frequency of the oscillated flow corresponds to the number of oscillations cycles per unit of time. The amplitude of the oscillation is the relative change in gas flow rate during the oscillation cycle, above or below the average flow
rate. The amplitude is described as a percentage of the average flow rate. The duty cycle describes the fraction of time the gas flow rate is above the average flow rate during each oscillating cycle.

[0060] Oscillating combustion implemented alone has allowed up to approximately 60% NOx reduction on various industrial processes. The setting of parameters that allows such maximum NOx performances along with reasonably low CO emissions is usually about the following: around 70% flow amplitude, 0.5 Hz frequency, and 50% duty cycle. The NOx reduction also depends on the characteristics of the burner, process, and combustion chamber under consideration.

[0061] The present invention provides preferred settings of oscillating parameters and furnace operating parameters to be set allowing to further increase the NOx reduction efficiency of the pulsed combustion system, even if it turns to be to the detriment of the CO production. Indeed, one advantage of the proposed invention is that such a generation of CO in the combustion zone is made possible by the presence of a post combustion system, downstream, before the combustion chamber exhaust.

[0062] Optimization of the parameters also takes into account maintaining acceptable flame characteristics that offer stability and low maintenance operation of the process.

[0063] The following section will thus provide preferred trends for optimizing oscillating parameters so as to achieve additional NOx reductions. These trends are based on various test results obtained on different types of combustion processes. However, each process installation should be fine-tuned more precisely on case-by-case basis for meeting high emission performance and flame patterns, and this based on its own characteristics.

[0064] FIG. 4 displays experimental results collected during tests on an industrial side-fired oxyfired furnace, operating with several burners. The influence of frequency on NOx and CO is shown for a case where solely the fuel flow rate is oscillated and where the excess oxygen in the flue gas is kept constant (approx. 3% of oxygen in the flue gas). It is noted that the ratio of the emission rate of NOx to a reference system without pulsation (NOx(ref)) varies from 50% to 100% as pulsation frequency is increased from 0.2 to 10 Hz (10 Hz being fairly representative of a normal steady operation). In general, oscillations with lower frequencies produce greater NOx reductions and heat transfer increases, but at the same time, CO emissions are also higher. If the oscillation frequency is decreased beyond 0.5 Hz, particularly beyond 0.2 Hz and preferably around 0.1 Hz, NOx generation is further reduced but CO emissions then increase dramatically: in this case, the fuellean and the fuel-rich zones are too large to mix and burn out the CO within the furnace.

[0065] Accordingly, the frequency for the present invention is less than 3 Hz, preferably less than about 0.5 Hz, and more preferably between about 0.1 Hz and 0.5 Hz. This frequency has to be optimized case-by-case, according to the combustion chamber design and to the flue gas residence time in this chamber.

[0066] It is also clear from different tests of oscillating combustion conducted in the laboratory and in the field that higher amplitude gives higher NOx reduction. Actually, for a given stoichiometric ratio, higher amplitude provides better mixing and higher excess oxygen in the flue. An increase of the oscillating amplitude thus enables possible reduction in stoichiometric ratio, which increases the potential of NOx reduction. Beyond a certain amplitude (usually around 90%), and especially at low frequency, fuel-rich zones are no longer diluted enough by products from the preceding local combustion zones, which can produce high CO emissions. But in the context of the invention, this does not constitute any limitation since the produced CO can be burned out before the exhaust of the process. Thus, the higher the amplitude is, the lower the NOx production is. An amplitude of the present invention is about 50% or higher, and preferably about 80% or higher. However, this oscillating amplitude should still be optimized on case-by-case basis since a very high amplitude is sometimes not recommended for certain furnaces. For example, problems of flame length may occur at high flow rates and/or retraction within the burner block may occur at low flow rates.

[0067] The duty cycle can also play a significant role in the reduction of NOx generation. It has been proven that duty cycles slightly higher than 50%, preferably about 60% or greater, and more preferably between 60% and 70%, enable further NOx reduction. As described above, the duty cycle is the fraction of time during each cycle that the gas flow rate is above the average flow rate.

[0068] A purpose of the preferred configurations of oscillating parameters described above is to enhance the effects of local staged combustion naturally created by the pulsed combustion. By decreasing the frequency and increasing both the amplitude and the duty cycle (as close as possible to their technical limits), this invention allows increasing the duration and influence of fuel-rich zones, where little oxygen is available and where peak flame temperatures are avoided. In this manner, even if more CO is generated, very little NOx production occurs.

[0069] The setting of parameters of oscillation, as discussed above, allows efficient operation at lower stoichiometric ratio since the mixing between oxygen and fuel is further enhanced. Depending on the process, stoichiometric ratios below 2, and more likely around 1.95, are made possible by such a setting of oscillating parameters, allowing reduced oxygen consumption and thus operating costs.

[0070] In another embodiment of this invention, it is proposed to induce flow variations in both the streams of fuel and oxidant, at a frequency which is common to both flows and with a dephasing of at least π/2 between them. FIG. 5 represents the NOx and CO emissions observed during tests carried out on a single-burner pilot furnace where both the flows of natural gas and oxygen are oscillated at same frequency.

[0071] In this example, it must be noted that there is a very important reduction of the emissions of NOx for pulsation frequencies lower than 2 Hz, this reduction reaching 90% for frequencies below 0.3 Hz, with a dephasing of at least π/2 between the pulsations of the fuel and of the oxidant. However, below 0.3 Hz CO emissions are also increasing in dramatic proportions (up to 3% of the flue gas volume at 0.25 Hz), to the extent that the process may not be safely operated. The interest of the invention in this context is to provide an adapted post combustion system able to burn out such levels of CO in the flue gas, thus guaranteeing at the same time high NOx reductions and safe operation.
Post Combustion CO Removal

The present invention provides an optimized post combustion system downstream of the oscillating combustion zone to post-combust CO generated during this first phase of the process. The post combustion system may also remove other exhaust gas species if required.

The function of the post combustion system is to minimize the effluent level of CO below environmentally regulated levels without producing additional NOx so as not to affect the benefits achieved in the first zone of combustion.

The oxidizing gas used for this post combustion system should be air or more preferably oxygen enriched air or pure oxygen.

In order to efficiently burn the CO and unburned hydrocarbons resulting from the oscillating combustion, three parameters should be carefully addressed by the post combustion system:

1. The location of the post combustion oxidizing gas injection,
2. The quality of mixing between the post combustion oxidizing gas and CO, and
3. The temperature of the post combustion zone.

The location of the post combustion system including the post combustion oxidant injection locations should be decided according to a process which is described herein. This choice is driven by several criteria which are discussed hereafter. First, the oxidizing gas should be injected in or close to a zone where the CO concentration is high, and preferably locally in areas where the CO concentration is substantially higher than the average CO concentration in the furnace exhaust gases. Moreover, the oxidant injection should occur in a zone where the flue gas temperature will guarantee a reliable CO ignition and rapid burning. Finally, the stream of oxidizing gas should be blown into the combustion chamber in a location where it does not interact significantly with the oscillating combustion so as to allow this first stage of oscillating combustion to complete before additional oxidation. The oxidizing gas should consequently be injected in one or several local areas through at least one injector means, most likely close to the exhaust of the combustion chamber, and preferably in an area where temperature is suitable for CO post combustion. FIGS. 6-8 present some examples of possible locations for post combustion oxidant injection for different types of combustion processes, namely: a) end-fired furnaces, b) multiple-burner side-fired furnaces, and c) industrial boilers.

Examples

FIG. 6 illustrates schematically the implementation of a process for fuel combustion in a single burner end fired furnace 600. The oscillating flame 610 is illustrated with the low and high flames represented. The post combustion oxidant is injected at a one or more locations represented by the arrows 620. The post combustion oxidant injection locations are selected to be where the injected oxidant will not interact with the oscillating combustion and where the flue gas temperature is the lowest in the furnace. These locations in the furnace are generally along the back wall and along the exhaust gas path on the side of the furnace. The furnace 600 of FIG. 6 may be any known end fired furnace, such as a glass furnace or steel making furnace.

FIG. 7 illustrates schematically the implementation of a process for fuel combustion in a multiple burner, cross fired furnace 700. The plurality of oscillating flames 710 are illustrated on both sides of the furnace with the low flames shown on one side and the high flames represented. The post combustion oxidant is injected at one or more locations represented by the arrows 720. The post combustion oxidant injection locations are selected to be where the injected oxidant will not interact with the oscillating combustion and where the flue gas temperature is the lowest in the furnace, i.e. near the flue gas exhaust. The furnace 700 of FIG. 7 may be any known cross fired furnace, such as a glass furnace or steel making furnace.

FIG. 8 illustrates schematically the implementation of a process for fuel combustion in an industrial boiler 800. The boiler includes a single end fired burner 810 operated in oscillating combustion to create an oscillating flame 812. The oscillating flame 812 is illustrated with the low flame and high flames represented. The post combustion oxidant is injected into the boiler 800 at one or more locations represented by the arrows 820. The post combustion oxidant injection locations are selected to be where the injected oxidant will not interact with the oscillating combustion and where the flue gas temperature is the lowest in the furnace, i.e. near a location where the flue gas is exhausted around a plurality of boiler pipes 830.

Optimizing Post Combustion CO Removal

In single burner systems, products of combustion do not flow through a subsequent combustion zone, such as in side-fired furnaces, where unburned hydrocarbons can be burned out within the flames generated by facing burners. This is one reason why the present invention is particularly well adapted to single-burner processes and preferably to industrial boilers.

Another factor in achieving an effective oxidation of CO is the quality of the mixing between the injected oxidizing gas and the molecules of CO. For this purpose, the oxidant can be blown into the reactor space not only with high momentum but also with a swirl effect. The first condition for high momentum is to connect the injector means to a pressurized source of oxygen or oxygen containing gas, to enable injection of such gas through a lance. If air or enriched-air is used, a blower may be used to bring the gas to the required pressure. In case of pure oxygen, the post combustion oxidant injection nozzle(s) should be connected to a liquid oxygen tank; the liquid oxygen can thus be compressed to the required pressure and then be vaporized prior to injection.

In addition, the supply conduit used for injection of the oxidizing gas should have the outlet opening arranged as the converging/diverging profile of a Laval nozzle to provide for subsonic or supersonic velocity of injected gas. In any case, the purpose here is to create a high enough velocity to penetrate the incoming flow of flue gas and thus to enhance the mixing of these two streams. Additionally, within this outlet opening, there may be a helical swirler for imparting circumferential motion to oxidizing gas issuing therefrom. Different designs can be envisaged here, but the swirler can
include a helical baffle mounted on pipe, which decreases in pitch towards a tip of the nozzle. An alternative to the swirler could also be a multi-orifice injector, with various injection angles in order to spray the post combustion oxidant through the flue gas stream. The action of the swirler or of the multi-orifice injector, combined with the high gas velocity, results in a good distribution of the oxidizing gas within the flue gas stream and thus in an optimal mixing with the CO molecules. It should also be understood that, in these conditions, the injection of highly oxygen-enriched air is a favorable factor for an effective CO oxidation since it reduces the dilution of reactants within nitrogen molecules.

[0088] Once the oxidizing gas is injected in the preferred location, and optimized within the CO-rich flue gas, an adequate temperature is still required in order to induce the CO oxidation. The invention can provide methods for controlling this temperature.

[0089] If the temperature of the exhaust gases in the post combustion zone is below a predetermined temperature preset for reliable CO oxidation and rapid burning, the post combustion burner/injector means may supply the oxidizing gas along with fuel so as to generate a hot flame and to maintain the temperature within the required range. The predetermined temperature is above about 800º C. (1500º F.), preferably above about 930º C. (1700º F.) and even more preferably about 980º C. (1800º F.). This post combustion zone temperature is also a function of the dimensions of the combustion chamber. With smaller size chambers there is less retention time and a higher temperature may be needed. However, it is also noted that the temperature is preferably maintained below about 1100º C. (2000º F.).

[0090] High-temperature conditions provide for rapid NO generation when combustion products contain a substantial amount of nitrogen are inspired inside of the flame envelope containing highly concentrated oxygen. Thus, to minimize additional NOx generation under such conditions, a cooling agent such as sprayed water or steam may be introduced inside the flame. Moreover, the introduction of water also creates conditions to enhance CO post combustion in the exhaust gases passing through the combustion chamber. Actually, the kinetics of CO post combustion shows dependency of the rate of change of CO mole fraction on the H2O concentration, assuming that the injected water temperature is the same as the one of the flue gas. Thus, spraying water through the hottest zone of the hot oxygen rich flame will simultaneously accomplish two functions: first, it preheats the water entering the combustion chamber (which will speed CO post combustion reactions) and, second, it cools the flame hot zone by using the heat released in this zone for heating, volatilizing, and superheating of the injected water (which will inhibit NOx formation).

[0091] The CO emissions from the process and apparatus of the present invention are preferably about 3,000 ppm or less, and more preferably about 400 ppm or less.

[0092] One example of the invention is illustrated in FIG. 9 in which a furnace 900 includes a burner 910 for creation of an oscillating combustion zone in the furnace. A fuel supply 912 and an oxidant supply 914 are connected to a the burner via one or more valves 916, 918 for oscillating the fuel and oxidant to create the pulsed combustion. The furnace also includes a post combustion zone 920 into which an oxidant is supplied from a post combustion oxidant supply 924 through nozzles 922. As discussed above, the post combustion oxidant nozzles 922 may include swirlers for imparting a swirling motion to the flow and/or a valve 926 for pulsatile delivery of the oxidant.

[0093] The invention also can include a post combustion control system 930 which insures not only an effective post combustion by ensuring complete oxidation of CO without additional generation of NOx, but also an efficient operation by injection of the minimum amount of oxygen.

[0094] The flows of oxidizing gas, extra fuel, and water injected by the post combustion means are controlled by the post combustion control system 930 and are based on the combination of process parameters actively measured and/or controlled by this system.

[0095] The method of controlling the post combustion system includes the steps of measuring the content of oxygen in the exhaust gases, the content of CO, and/or alternative process parameters influencing CO emissions by one or more sensors 932 within the furnace during the oscillating combustion. The results of these measurements are communicated to the post combustion control system 930, then compared with a control model to predict the deficiency of oxygen in the flue gas as well as the necessary amount of extra oxidant which should be added to minimize the effluent level of CO below environmentally regulated levels. A controlled flow of post combustion oxidizing gas is thus injected accordingly in the post combustion zone in order to reduce and/or eliminate the deficiency of oxygen and preferably to insures the presence of excessive oxygen in hot exhaust gases traveling through and leaving the combustion chamber. The prediction of the deficiency can be performed by using a computer model based on furnace inputs developed from empirical data.

[0096] Similarly, the flows of extra fuel and water injected in order to adjust the reaction temperature and to inhibit NOx formation are also controlled by the post combustion control system through monitoring of the temperature of the hot flue gas in the combustion chamber.

[0097] The use of an oxygen-rich oxidizing gas for the post combustion CO removal stage provides advantages in the present invention. Specifically, the use of oxidizing gas with an oxygen content higher than air increases the amount of heat being released per standard cubic feet of the newly formed combustion products and at the same time increases the temperature of the flame introduced in the combustion chamber. This way, when the post combustion of CO and unburned hydrocarbons occurs under conditions permitting the heat released to be efficiently transferred to the load, the process throughput capacity and thermal efficiency can even be increased.

[0098] This can be particularly valuable in certain operating configurations described before where high NOx reductions are accompanied by significant CO generation as a counterpart (as high as a few percents of the flue gas volume). It can even be more valuable in the case of combustion staging, as also mentioned above, where fuel combustion needs to complete in the post combustion zones.

[0099] According to an additional embodiment of the invention, the post combustion oxidant flow provided for post combustion of unburned hydrocarbons can be oscillated.
by a valve 926 as shown in FIG. 9. The purpose of oscillating the post combustion oxidant is to further limit any additional formation of NOx (through a phenomenon based on the same principle as mentioned before), while still post-combusting the products resulting from the first stage of combustion.

[0100] The present method of NOx reduction is applicable to any industrial combustion process, as well as the described apparatus.

[0101] The promoted configuration of oscillating combustion allowing high NOx performances generally aims at enhancing the effects of local staged combustion naturally created by pulsed combustion in the fuel-rich and fuel-lean zones. The present invention can achieve NOx reduction levels as high as 90%, but with dramatic increase of the CO formation as a counterpart. This excess of CO is oxidized before the combustion chamber exhaust through the post combustion CO removal apparatus positioned in a thermally adapted location and controlled by an optimized system, thus guaranteeing both an effective and efficient operation.

[0102] Through this innovative concept, the invention thus proposes a low-cost and effective compliance technology providing operators of industrial combustion processes with a competitive alternative to the expensive flue gas clean up techniques such as SCR. Being preferably suited for single-burner systems, the promoted technique will be of particular interest for industrial boiler processes, both firetube and watertube types.

[0103] A further embodiment of the invention promotes a large-scale staged combustion in this process. The local phenomenon of combustion staging induced in fuel-rich and fuel-lean combustion zones is further increased. It is thus proposed to decrease the stoichiometric ratio at the oscillating combustion level, by decreasing the oxidant flow rate. The post combustion system located near the exhaust of the combustion chamber then provides the balance of oxidant so as to complete combustion. By this way, NOx reductions achieved through oscillating combustion can be further enhanced, while still controlling CO emissions. Moreover the effectiveness of this staged combustion system is guaranteed by the location of the post combustion system far from the primary combustion zone, thus allowing the primary reaction to be completed before secondary injection of oxidant.

[0104] While the invention has been described in detail with reference to the preferred embodiments thereof, it will be apparent to one skilled in the art that various changes and modifications can be made and equivalents employed, without departing from the present invention.

What is claimed is:

1. A process for fuel combustion, comprising:
   - supplying a flow of fuel and a flow of oxidant to a burner;
   - generating an oscillating combustion zone by oscillating at least one of the fuel flow and the oxidant flow to achieve a reduced nitrogen oxide emission;
   - selecting oscillating parameters and furnace operating parameters to maximize nitrogen oxide reduction efficiency; and
   - combusting carbon monoxide downstream of the oscillating combustion zone by injecting a post combustion oxidant at a post combustion injection location to minimize carbon monoxide in an exhaust gas.

2. The process of claim 1, wherein the supplied fuel is a gaseous fuel.

3. The process of claim 1, wherein the supplied oxidant is air, oxygen-enriched air, or substantially pure oxygen.

4. The process of claim 1, wherein the post combustion oxidant is injected at a sufficient velocity to penetrate flue gas and to allow mixing of flue gas and post combustion oxidant.

5. The process of claim 1, wherein the post combustion oxidant is injected through a swirler or through a multi-orifice injector with various injection angles in order to distribute as evenly as possible the oxidant in the post-combustion zone and thus to improve mixing.

6. The process of claim 1, wherein the step of combusting carbon monoxide also combusts unburned hydrocarbons.

7. The process of claim 1, comprising controlling a temperature of the post combustion injection location to a temperature of about 800° C. to about 1100° C.

8. The process of claim 7, wherein the temperature is controlled by injecting a cooling agent comprising water inside the flame to cool a flame hot zone and to inhibit nitrogen oxide formation.

9. The process of claim 7, wherein the temperature is controlled by the injection of additional fuel to the post combustion injection location.

10. The process of claim 1, wherein the post combustion oxidant is injected in an oscillating pattern to improve mixing and inhibit nitrogen oxide formation.

11. The process of claim 1, wherein the post combustion oxidant is air, oxygen-enriched air, or substantially pure oxygen.

12. The process of claim 1, wherein the selected oscillating parameters include the flow amplitude, the frequency, and the duty cycle which are selected to maximize nitrogen oxide reduction efficiency to the detriment of carbon monoxide production.

13. The process of claim 1, wherein an air/fuel ratio of the supplied fuel and oxidant is selected to be approximately stoichiometric or lower to reduce nitrogen oxide formation.

14. The process of claim 1, wherein an air/fuel ratio of the supplied fuel and oxidant is selected to be below stoichiometric by reduction of the oxidant flow rate supplied to the burner, and wherein the balance of oxidant is supplied at the post-combustion injection location in order to complete the combustion and reduce nitrogen oxide formation.

15. The process of claim 12, wherein the flow amplitude is about 30% or higher.

16. The process of claim 12, wherein the flow amplitude is about 70% or higher.

17. The process of claim 12, wherein the duty cycle is about 50% to about 70%.

18. The process of claim 12, wherein the frequency is about 3 Hz or less.

19. The process of claim 12, wherein the frequency is about 0.5 Hz or less.

20. The process of claim 1, wherein the post combustion injection is located where the oxidant will not interact significantly with the oscillating combustion.
21. A combustor having an emissions control system, comprising:

a combustion chamber;

at least one burner positioned to direct a flame into the combustion chamber, the burner having at least a first channel for delivering fuel and at least a second channel for delivering an oxidant;

a supply of fuel connected to the first channel;

a supply of oxidant connected to the second channel;

a pulsating mechanism arranged to pulse the flow of at least one of the fuel supply and the oxidant supply to the burner to create an oscillating combustion zone in the combustion chamber;

a controller for controlling oscillating parameters of the burner to maximize nitrogen oxide reduction efficiency; and

a post combustion oxidant injection system located downstream of the oscillating combustion zone and arranged to burn excess carbon monoxide.

22. The combustor of claim 21, wherein the post combustion oxidant injection system includes at least one oxidant injection nozzle having a swirler or multi-orifice injector with various injection angles.

23. The combustor of claim 21, wherein the post combustion oxidant injection system includes a post combustion nozzle positioned between the oscillating combustion zone and an exhaust of the furnace.

24. The combustor of claim 23, wherein the combustor is an industrial boiler, of either firetube or watertube type.

25. The combustor of claim 23, wherein the furnace is an end fired, single burner furnace, and the post combustion nozzle is positioned at an opposite end or side of the furnace from the burner.

26. The combustor of claim 21, wherein the post combustion oxidant injection system includes an oscillating device for oscillating a post combustion oxidant flow.

27. The combustor of claim 21, wherein the controller monitors flue gas composition and temperature and commands post combustion parameters according to an operator-defined model.