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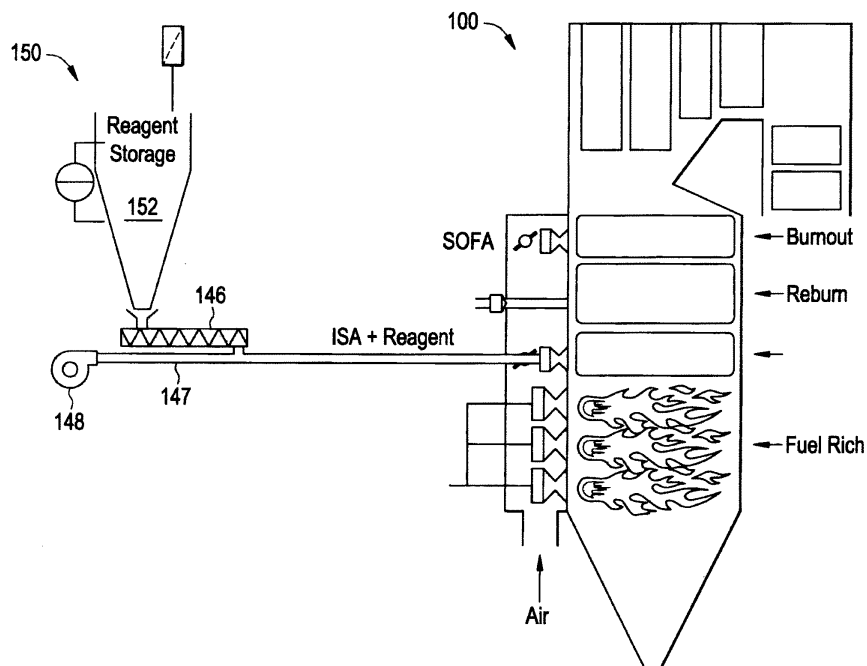
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(54) **Combustion systems and processes for burning fossil fuel with reduced emissions**

(57) A combustion system (100) comprising a combustion zone comprising a burner for converting a fuel, under fuel rich conditions, to a flue gas; an intermediate staged air zone (ISA) downstream from the combustion zone for supplying intermediate staged air to the flue gas and producing fuel lean conditions; a reburn zone down-

stream from the intermediate staged air zone for receiving the flue gas; and an inlet downstream from the combustion zone for supplying a mixture of air and a reduction reagent to the flue gas, wherein the reduction reagent is configured to reduce an amount of pollutant species in the flue gas.

**FIG. 2**



## Description

**[0001]** This disclosure relates generally to combustion systems for power plants, and more particularly to combustions systems having reduced emissions.

**[0002]** During a typical combustion process within a furnace or boiler, for example, a flow of combustion gas, or flue gas, is produced. Known combustion gases contain combustion products including, but not limited to, carbon, carbon dioxide, carbon monoxide, water, hydrogen, nitrogen oxides (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), chlorine, and/or mercury generated as a result of combusting fuels. Various technologies have been applied to combustion systems to reduce the emissions of pollutant species, however, further improvements are needed.

**[0003]** At least some known furnaces use air/fuel staged combustion, such as a multi-stage combustion, to facilitate reducing the production of at least some of the combustion products, such as NO<sub>x</sub>. For example, a three-stage combustion process includes combusting fuel and air in a first stage, introducing fuel into the combustion gases in a second stage, and then introducing air into the combustion gases in a third stage. In the second stage, fuel is injected, without combustion air, to form a substoichiometric, or fuel-rich, zone. During the second stage, at least some of the fuels combust to produce hydrocarbon fragments that react with NO<sub>x</sub> that may have been produced in the first stage. As such, the NO<sub>x</sub> may be reduced to atmospheric nitrogen in the second stage. In the third stage, air is injected to consume the carbon monoxide and unburnt hydrocarbons exiting the second stage. Although such air/fuel staging may achieve relatively high NO<sub>x</sub> reduction, combustion products such as SO<sub>x</sub> and mercury continue to exist in the flue gas.

**[0004]** One strategy for reducing or eliminating SO<sub>x</sub> and mercury emissions in flue gas is to install wet scrubbers, selective catalytic reduction, or activated carbon systems to capture the sulfur and mercury before they are emitted into the atmosphere. These technologies, however, can have their disadvantages. For example, it can be cost prohibitive to install wet scrubbers to an existing plant, and the energy required to run the scrubbers can affect the efficiency and environmental impact of the plant. The use of activated carbon systems can lead to carbon contamination of the fly ash collected in exhaust-air treatments, such as the bag house and electrostatic precipitators.

**[0005]** An alternative method for the removal of sulfur and mercury is the application of sulfur sorbing and stabilizing materials to the fuel itself (e.g., the coal), or injection of the materials into the combustion process. The sorbent material particles adsorb sulfur from the coal, or SO<sub>x</sub>, mercury, and other contaminants from the flue gas, and the particles are captured in the solids collection system of the combustion process.

**[0006]** According to one aspect of the invention, a combustion system includes a combustion zone comprising a burner for converting a fuel, under fuel rich conditions,

to a flue gas; an intermediate staged air zone downstream from the combustion zone for supplying intermediate staged air to the flue gas and producing fuel lean conditions; a reburn zone downstream from the intermediate staged air zone for receiving the flue gas; and an inlet downstream from the combustion zone for supplying a mixture of air and a reduction reagent to the flue gas, wherein the reduction reagent is configured to reduce an amount of a pollutant species in the flue gas.

**[0007]** According to another aspect of the invention, a process for using a combustion system includes supplying a fuel and air under fuel rich conditions to a combustion zone comprising a burner to form a flue gas; supplying intermediate staged air to the flue gas through an intermediate staged air inlet downstream of the combustion zone to produce fuel lean conditions; channeling the flue gas to pass to a reburn zone downstream from the intermediate staged air inlet; and supplying a reduction reagent to the flue gas, wherein the reduction reagent is configured to reduce an amount of a pollutant species in the flue gas.

**[0008]** According to yet another aspect of the invention, a method of reducing at least sulfur oxides and/or mercury in a flue gas of a combustion system includes supplying a fuel and air under fuel rich conditions to a combustion zone comprising a burner to form a flue gas; supplying intermediate staged air to the flue gas through an intermediate staged air inlet downstream of the combustion zone to produce fuel lean conditions; channeling the flue gas to pass to a reburn zone downstream from the intermediate staged air inlet; supplying overfire air to a burnout zone downstream from the reburn zone through an overfire air inlet; and mixing a sorbent composition with the overfire air and/or the intermediate staged air before supplying the air to the flue gas.

**[0009]** These and other advantages and features will become more apparent from the following description taken in conjunction with the drawings.

**[0010]** The subject matter, which is regarded as the invention, is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. 1 is a schematic diagram showing a side, cross-sectional embodiment of a multi-stage reburn combustion system.

FIG. 2 is a schematic diagram showing a side, cross-sectional embodiment of the multi-stage reburn combustion system of FIG. 1 having a reduction reagent storage and delivery system.

FIG. 3 is a schematic view of an exemplary multifunctional burner that may be used with the multi-stage reburn combustion system shown in FIG. 1.

FIG. 4 is a schematic diagram showing a side, cross-sectional embodiment of the multi-stage reburn combustion system having hybrid boosted overfire air.

FIG. 5 is a schematic diagram showing a side, cross-sectional embodiment of the multi-stage reburn combustion system having boiler nose overfire air.

**[0011]** The following description explains embodiments of the invention, together with advantages and features, by way of example with reference to the drawings.

**[0012]** Disclosed herein are multi-stage reburn combustion systems utilizing reduction reagents to aid in reducing pollutant emissions caused by fossil fuel combustion. As will be described in greater detail below, multi-stage reburn combustion systems apply intermediate staged air (ISA) between combustion and reburn zones to help reduce the initial NO<sub>x</sub> formation entering the reburn zone. The ISA stream is a high-energy stream that mixes the air rapidly into the flue gas of the combustion system. Other optional air streams such as overfire air, including boosted overfire air, hybrid boosted overfire air, and nose overfire air, as well as burner air injection can also be used to mix air into the flue gas. These air streams can be used to introduce reduction reagents into the combustion system in order to further reduce pollutant emissions in the flue gas beyond the NO<sub>x</sub> reduction already inherent to the multi-stage reburn system. Integrating reduction reagent injection with one or more of the system air streams provides a means of utilizing the energy of the air stream or streams to rapidly and thoroughly mix reagents within the flue gas, thereby providing simultaneous control of NO<sub>x</sub> and other pollutant species.

**[0013]** Examples of pollutant species to be reduced and/or removed from the flue gas can include, without limitation, carbon, carbon dioxide, carbon monoxide, hydrogen, NO<sub>x</sub>, SO<sub>x</sub>, chlorine, metals such as mercury, arsenic, and nickel, and other like pollutant species generated as a result of combusting fuels. As used herein, reduction reagents are intended to generally include any compound configured to reduce the amount of pollutant species in a furnace flue gas. Exemplary reduction reagents can include, without limitation, sorbent species for reduction of SO<sub>x</sub>, hydrochloric acid (HCl), metals, and other like emissions; NO<sub>x</sub> reduction agents such as, ammonia, urea, cyanuric acid, and the like; and oxidizing species such as halogen-based compounds.

**[0014]** FIG. 1 illustrates an exemplary embodiment of a multi-stage reburn combustion system 100, which incorporates reduction reagent injection. In this particular embodiment, the reduction reagent is injected as a mixture with the ISA into the flue gas. Other embodiments discussed below illustrate different reduction reagent-air stream mixtures and injection points. The combustion system 100 can be used for various applications such as in a fossil-fuel fired boiler, furnace, engine, incinerator, etc. One exemplary application of combustion system 100 is as the source of power generation in a power plant.

The flue gas can enter the system at 110 and travels to the main combustion zone 120. The main combustion zone 120 is equipped with one or more main burners (not shown) such as specially designed burners for producing low levels of NO<sub>x</sub>. In one embodiment, the main combustion zone 120 includes two or more burners arranged in two or more rows. Fuel and primary air are supplied together to the main combustion zone 120 through one or more inlets 128. Secondary air is also generally supplied to the main combustion zone 120 through inlets 128. The amounts of fuel and air supplied to the main combustion zone 120 are selected to achieve fuel rich conditions therein. The exact stoichiometric ratio (SR) in the main combustion zone 120 will vary depending on the fuel type and furnace design, but will be less than about 1.0. In one embodiment, the SR in the main combustion zone 120 is about 0.90 to about 0.95. Examples of suitable fuels for use in the main combustion zone 120 include, but are not limited to, fossil fuels, such as lignite coal, bituminous coal, sub-bituminous coal, anthracite coal, oil, or gas, such as natural gas or gasified coal, various types of biomass, and combinations including at least one of the foregoing fuels. Any suitable form of fuel can be supplied to the main combustion zone 120, including pulverized coal that is ground using a coal mill. Within the main combustion zone 120, the fuel undergoes combustion and forms a flue gas that flows upwardly toward the intermediate staged air zone 122.

**[0015]** The flue gas produced in the main combustion zone 120 flows to the ISA zone 122. Air is added to the flue gas in this zone through one or more intermediate staged air inlets 132. The amount of ISA supplied to zone 122 is effective to produce fuel lean conditions, i.e., SR of greater than about 1.0. In one embodiment, sufficient ISA is supplied to zone 122 to produce an SR of about 1.05 to about 1.10. Flow into the ISA inlet 132 may be regulated by an ISA damper 131.

**[0016]** The reduction reagent can be mixed with the ISA at any point prior to the air entering the ISA zone 122. Mixing the reduction reagent with the air at some distance prior to entry into the ISA zone 122 will provide residence time for the reduction reagent to substantially disperse throughout the ISA. FIG. 2 illustrates a reduction reagent system 150, which includes a reduction reagent storage system 152, such as a hopper, in operative communication with a reduction reagent metering system 146. The metering system 146 is configured to control the amount of reduction reagent being fed into an ISA stream 147. For example, the metering system 146 could be a screw feeder configured to feed the reduction reagent into an inlet in the ISA stream 147. The reduction reagent is introduced to the ISA stream 147 prior to the ISA inlet 132, and in this way, the ISA acts as a carrier fluid for the reduction reagent. As show in FIG. 2, a booster fan 148 can be configured to increase the pressure of the ISA feedstream 147. The ISA is an advantageous means for effectively mixing and dispersing the reduction reagent into the flue gas of the combustion system, be-

cause of the energy with which the ISA stream flows and is injected into the flue gas.

**[0017]** After the ISA zone 122, the fuel-lean flue gas then enters the reburn zone 124 and fuel is added to the flue gas through one or more reburn inlets 134. The fuel is typically accompanied by carrier gas. The carrier gas may be carrier air, boosted flue gas recirculation (FGR), or any other appropriate gas for the specific fuel and furnace design. The amount of fuel added through the reburn inlets 134 is effective to produce fuel rich conditions in the reburn zone 124. The exact SR in the reburn zone 124 of the combustion system 100 varies depending on the fuel type and combustion system design but generally ranges from about 0.85 to about 0.95.

**[0018]** The flue gas formed in the reburn zone 124 then proceeds through the combustion system 100 and is subjected to optional operations and treatments. In one embodiment the flue gas formed in the reburn zone 124 flows upwardly to the burnout zone 126, which is downstream from the reburn zone 124. Overfire air (OFA), also known as separated overfire air (SOFA), is supplied to the burnout zone 126 through inlet 136. OFA flow through inlet 136 may be regulated by an OFA damper 135. The OFA restores the system to overall fuel lean conditions, i.e., SR of greater than about 1.0. The exact SR varies depending on the fuel type and furnace design. In one embodiment, the SR in the burnout zone 126 is about 1.15 to about 1.3. The OFA can be added to the burnout zone 126 at a relatively higher pressure through inlet 136, such as with boosted overfire air (BOFA). This may be accomplished using one or more rotating booster fans. The BOFA can be in the form of cool ambient air, heated air, or both cool ambient air and heated air, with heated air being preferred. The introduction of the BOFA can achieve desired levels of air jet penetration and mixing in the burnout zone 126.

**[0019]** The flue gas in the burnout zone 126 passes downstream to an outlet 144, where the flue gas exits the combustion system 100. As the flue gas passes to outlet 144, the flue gas flows past the tip of the boiler nose 140 and can flow through one or more heat exchangers 142 to serve as a heat source.

**[0020]** The residence time of the substances flowing through various regions of the combustion system 100 varies depending on fuel and air flow rates. As used herein, the term "residence time" refers to the average time the flue gas spends in a defined region of the furnace. Operation of the exemplary furnace is conducted such that there is sufficient residence time to enable conversion of the NO<sub>x</sub> to take place, as well as sufficient time for the reduction reagents to absorb, reduce, or the like the remaining pollutant species in the flue gas. The exact residence time required depends on the furnace design, primary fuel type, reburn fuel type, and/or reduction reagent injection location. In one embodiment, a residence time of flue gas in a region of the combustion system 100 between a centerline of the intermediate staged air inlet 132 and a centerline of the reburn inlet 134 is about 100

to about 400 milliseconds. In an alternative embodiment, a residence time of flue gas in a region of the combustion system 100 between the centerline of the reburn inlet 134 and a centerline of the overfire air inlet 136 is about 300 to about 1000 milliseconds. In general, fuels that devolatilize and mix quickly require relatively low average residence times. In another alternative embodiment, a residence time of the flue gas in a region of the combustion system 100 between the centerline of the OFA inlet 136 and the tip of the boiler nose 140 is greater than about 300 milliseconds. In still another alternative embodiment, a residence time of the flue gas in a region of the combustion system 100 between a centerline of a top burner row and the centerline of the tip of the boiler nose 140 (i.e., the total residence time of the combustion system) is greater than about 1,300 milliseconds. As used herein, the term "centerline" refers to an imaginary line running through the middle of an object.

**[0021]** The use of intermediate staged air in the exemplary combustion system 100 enables the main combustion zone 120 to operate at fuel rich conditions. This reduces the initial NO<sub>x</sub> flowing into the reburn zone 124 to improve overall NO<sub>x</sub> emissions by, for example, about 10% to about 25%, as compared to reburn without intermediate staged air. In at least some known combustion system, both air and fuel staging usually have the unwanted side effect of increasing the emissions of CO and unburned carbon in fly ash as measured by loss-on-ignition (LOI). In the exemplary embodiment, the use of ISA and air-carried reduction reagent injection provides additional flexibility and control of CO and LOI, while maintaining low NO<sub>x</sub>, SO<sub>x</sub>, and metal levels. The use of ISA combined with BOFA can also help restore the CO and unburned carbon emissions to more acceptable levels by improving the penetration of air into, and mixing with, the combustion gas. This type of integrated technology can reduce NO<sub>x</sub> emissions to less than or equal to about 100 milligram/normal meters cubed (mg/Nm<sup>3</sup>) at about 6% O<sub>2</sub> dry, or about 0.163 pound/million Btu (lb/MMBtu), thus meeting the NO<sub>x</sub> emissions requirement of the European Union Large Combustion Plant Directive (LCPD), Phase 2. The combustion system 100 also can maintain the LOI at a sufficiently low level, such as levels that permit the fly ash waste to be sold in Europe for example.

**[0022]** In one embodiment, the ISA inlet 132 is a burner out of service (BOOS) through which cooling air is injected. In this way, an existing furnace may be adapted to incorporate ISA by running cooling air through the existing top row of burners, making them the ISA inlets 132. This has a minimal cost impact and avoids additional wall penetrations in the furnace of the combustion system 100.

**[0023]** In another embodiment, the existing burners in the top row of the main combustion zone 120 are replaced with injectors specifically designed to inject ISA. In this way the velocity and mixing of the ISA in the ISA zone 122 may be better configured for the system, but new

furnace wall penetrations are not required. Alternatively, the existing burners in the top row of the main combustion zone 120 are blocked off and new injectors specifically designed to inject ISA and reduction reagent are placed at an elevation below, equal to, or above the top burner row. This does require additional wall penetrations for the ISA inlets 132. In another embodiment, the ISA inlet 132 is above (downstream) of the upper burner row of the main combustion zone 120. This enables the use of all of the existing burners in the main combustion zone 120, but does require additional wall penetrations for the ISA inlets 132.

**[0024]** In an exemplary embodiment, at least one burner in the combustion zone 120 is a multi-function burner. Alternatively, combustion zone 120 can include a row and/or array (not shown) of multi-function burners. The multi-function burner either burns the fuel/air mixture or injects air into the combustion zone 120. In this particular embodiment, the multi-function burner either burns the fuel/air mixture or injects a mixture of ISA and reduction reagent into the combustion zone 120 of the combustion system 100. The multi-function burner can occupy the top row of the combustion burner, or it can be included anywhere within the combustion zone 120 that enables the system to function as described herein. FIG. 3 is a schematic view of an exemplary multi-function burner 200 that may be used to combust the fuel/air mixture in the combustion zone 120 or inject the ISA-reduction reagent mixture into the flue gas. In this embodiment, burner 200 has a substantially cross-sectional shape that enables burner 200 to function as described herein.

**[0025]** The multi-function burner 200 includes a first duct 206, a second duct 208, a third duct 210, and a fourth duct 212 that are each substantially concentrically aligned with a centerline 214 of the burner 200. More specifically, first duct 206 is the radially outermost of the ducts 206, 208, 210, and 212 such that a radially outer surface 216 of first duct 206 defines the outer surface of burner 200. Furthermore, in the exemplary embodiment, first duct 206 includes a convergent and substantially conical section 218, a substantially cylindrical section 220, and a divergent and substantially conical section 222. Second duct 208, in the exemplary embodiment, is spaced radially inward from first duct 206 such that a first passageway 224 is defined between first and second ducts 206 and 208. Moreover, second duct 208 includes a substantially cylindrical section 226 and a divergent and substantially conical section 228.

**[0026]** In the exemplary embodiment, third duct 210 is spaced radially inward from second duct 208 such that a second passageway 230 is defined between second and third ducts 208 and 210. Furthermore, in the exemplary embodiment, third duct 210 is substantially cylindrical and includes an annular flame regulation device 232, such as a flame holder, that creates a recirculation zone 234. Fourth duct 212, in the exemplary embodiment, defines a center passageway 236 that has a diameter D1 and that is radially spaced inward from third duct

210 such that a third passageway 238 is defined between third and fourth ducts 210 and 212. In the exemplary embodiment, fourth duct 212 is substantially cylindrical including having conical and/or cylindrical shapes, ducts 206, 208, 210, and 212 may each have any suitable configuration or shape that enables burner 200 to function as described herein.

**[0027]** First and second ducts 206 and 208, in the exemplary embodiment, are each coupled in flow communication with a common plenum 240, which is coupled in flow communication with air source 32 via main air regulation device 62. Alternatively, first and second ducts 206 and 208 are each coupled separately in flow communication independently with air source 32 such that first and second ducts 206 and 208 do not share a common plenum 240. In the exemplary embodiment, first and second ducts 206 and 208 are oriented such that ISA-reduction reagent mixture 30 may be injected into common plenum 240, through first passageway 224 and/or second passageway 230, and into primary combustion zone 120 (shown in FIG. 1) and/or ISA zone 122 (shown in FIG. 1). In one embodiment, first passageway 224 and/or second passageway 230 may induce a swirl flow pattern (not shown) to ISA-reduction reagent mixture 30 injected through first passageway 224 and/or second passageway 230.

**[0028]** Furthermore, third duct 210, in the exemplary embodiment, is coupled in flow communication with fuel source 14 via fuel flow regulation device 40. In the exemplary embodiment, third duct 210 is oriented such that fuel 12 may be injected through third passageway 238 and into primary combustion zone 120, when burner 200 is used to combust fuel 12 and air. Moreover, fourth duct 212, in the exemplary embodiment, is coupled in flow communication with air source 32 via air flow regulation device 42 and air velocity control device 44. In the exemplary embodiment, fourth duct 212 is oriented such that ISA-reduction reagent mixture 30 may be injected through center passageway 236 and into intermediate air zone 46 at a predetermined velocity, when burner 200 is used to inject ISA-reduction reagent mixture 30.

**[0029]** During a first operation of multi-function burner 200, burner 200 is used to burn fuel 12 and air. Control system 60 controls fuel flow regulation device 40 to enable fuel 12 to enter combustion zone 120 through third passageway 238, controls main air regulation device 62 to inject ISA-reduction reagent mixture 30 into combustion zone 120 or ISA zone 122 through first passageway 224 and/or second passageway 230, and controls air flow regulation device 42 to prevent air ISA-reduction reagent mixture 30 from being injected into combustion zone 120 through center passageway 236.

**[0030]** During a second operation of multi-function burner 200, burner 200 is used to inject ISA-reduction reagent mixture 30. Control system 60 controls fuel flow regulation device 40 to prevent fuel 12 from entering combustion zone 120 through third passageway 238, controls main air flow regulation device to inject air 30 into com-

bustion zone 18 through first passageway 224 and/or second passageway 230 at first velocity  $V_1$ , and controls air flow regulation device 42 and air velocity control device 44 to inject ISA-reduction reagent mixture 30 into combustion zone 18 through center passageway 236 at second velocity  $V_2$ , which is higher than velocity  $V_1$ . As such, the first portion 202 of ISA-reduction reagent mixture 30 is injected at velocity  $V_1$  and the second portion 204 of ISA-reduction reagent mixture 30 is injected at velocity  $V_2$ . In another embodiment, ISA-reduction reagent mixture 30 entering through center passageway 236 does not experience a velocity change through air velocity control device 44, and ISA-reduction reagent mixture 30 entering combustion zone 18 through center, first, and/or second passageways 236, 224, and/or 230, respectively, enters from air flow regulation device 42 and main air regulation device 62 at substantially the same velocity.

**[0031]** The ISA supplied through the ISA inlet 132 or through the multi-function burner 200 may be in the form of cool ambient air, heated air, or both cool ambient air and heated air. In one embodiment, the ISA is boosted such that the ISA is supplied at a relatively higher pressure. This may be accomplished using one or more rotating booster fans. For example, a booster fan 148 is configured to increase the pressure of the ISA feedstream 147 and can be disposed upstream of the reduction reagent metering system 152 (as shown in FIG. 1) or it can boost the pressure of the feedstream after the reduction reagent has been added thereto. The boosting of the ISA can achieve improved levels of air jet penetration and mixing in the ISA zone 122, thereby providing improved dispersion of the reduction reagent into the flue gas.

**[0032]** Air may be fed to the various stages in the combustion system 100 from a variety of sources. In one embodiment, a windbox supplies secondary air to the main combustion zone inlets 128, ISA to the ISA inlets 132, and/or OFA to the OFA inlets 136 through ducting 138. In another embodiment, air is delivered to one or more inlets 128, 132, and 136 through separate ducting (not shown). Control of the flow to the various inlets may be linked, or may be independent. The source of the air and the configuration of the ducting is not critical to the combustion system 100 and may be tailored to suit the particular furnace design.

**[0033]** Overfire air is a well-known technology that is used to reduce NOx emissions in utility and industrial furnaces. The OFA system of the combustion system 100 diverts secondary combustion air from a burner windbox ducting 138 to the OFA injectors at the inlets 136. The OFA supply pressure in the burner windbox ducting, determines the maximum dynamic pressure that will be available at the OFA injector outlet. Sufficient OFA dynamic pressure ensures effective penetration and mixing of overfire air with combustion flue gas. In some cases, the available dynamic pressure to the OFA injector is not high enough to achieve the required penetration and mix-

ing of the air and combustion gas. If this happens, boosting the OFA can assist in reducing NOx emissions.

**[0034]** The multi-stage reburn combustion system can further include an optional hybrid boosted overfire air system to supplement the OFA. FIG. 4 illustrates an exemplary embodiment of a combustion system 300 comprising hybrid boosted overfire air (HBOFA). In this embodiment, the HBOFA is configured to deliver the reduction reagent to the combustion flue gas in the system 300. The combustion system 300 functions in the same manner as the combustion system 100 of FIG. 1, with the only difference being that hybrid boosted overfire air is used to combine two discrete air supply systems, boosted air and secondary combustion air, to achieve effective penetration and mixing of overfire air and reduction reagent with combustion flue gas in the burnout zone 324. In another embodiment, the HBOFA can also supply air to the multifunction burner of FIG. 3 when the burner is in the desired operational mode. A portion of the OFA is delivered to the OFA injectors 336 as either "cold" or "hot" high-pressure air from booster fans (not shown). The remaining OFA is delivered to the OFA injectors 336 from the existing "hot" secondary combustion air (HOFA) system (e.g., burner windbox ducting 338). This approach is a low-cost alternative to a traditional stand-alone boosted overfire air system. A feature of HBOFA is that both the boosted high-pressure air (BOFA) and low-pressure secondary combustion air, such as OFA, achieve air jet penetration and mixing in an overfire air system.

**[0035]** The BOFA can also be injected into the ISA zone 322 through ISA inlets 332. As such, the BOFA and ISA can be mixed in the ISA zone to further improve NOx reduction and help lower CO emissions. As mentioned, in this embodiment the HBOFA is used as a carrier medium for injection of the reduction reagent into the ISA zone 322 and/or the burnout zone 324 of the combustion system 300. Again, the penetration and mixing achieved by the HBOFA streams into the flue gas makes the HBOFA system an excellent carrier fluid for the reduction reagent into the combustion system 300. The reduction reagent, therefore, can be introduced into the OFA, the BOFA, the ISA (as discussed above), or some combination of all three. Because the HBOFA can be supplied at a higher than normal boost pressure, it provides a desired level of penetration into, and mixing of the reduction reagents with the boiler gases. Similar to ISA injection of the reduction reagents, the desired reducing compounds can be mixed with the HBOFA at any point prior to the OFA or ISA injectors. The greater the mixing distance before the injectors, the greater the time for the reduction reagent to substantially disperse throughout the HBOFA. For example, the reduction reagent system 150 of FIG. 2, can also be in operative communication with the HBOFA streams, wherein the system controls the amount of reduction reagent being fed into the HBOFA.

**[0036]** To reiterate, for several reasons HBOFA can be a useful addition to a multi-stage reburn combustion system having reduction reagent injection. For example,

cold ambient or hot preheated overfire air can be supplied at a higher than normal boost pressure, to induce the high temperature, low pressure air, and provide a desired level of penetration into and mixing of the air and reduction reagent with the boiler gases.

**[0037]** Moreover, boosting a portion of the OFA lends to smaller fans (for OFA and/or BOFA) with a reduced weight, reduced power requirements, and lower capital cost.

**[0038]** In another exemplary embodiment, the upper furnace arch, i.e., the boiler nose, is employed as a plenum from which overfire air is injected into the combustion gases. This can be in addition to or instead of the BOFA and HBOFA systems described above. Moreover, if necessary the nose overfire air itself can be either BOFA or HBOFA. With this configuration, the overfire air need penetrate only a short distance into the flue gas to provide optimum mixing performance without the need for higher pressure boost air fans or higher pressure overfire air. As such, the nose overfire air (NOFA) provides another means with which to inject the reduction reagent into the combustion system so that the reagent is able to penetrate and thoroughly mix with the flue gas for optimum effect in reducing pollutants in the gas. Particularly, the boiler nose itself may serve as a plenum in which an overfire air-reduction reagent mixture is received, preferably through openings in one or both of the side walls for flow through ports in the boiler nose and consequent injection into the combustion gases. The overfire air-reduction reagent mixture can be supplied to ducts extending from one or both of the side walls of the furnace into the boiler nose. A plurality of port ducts communicate between the laterally extending duct(s) in the boiler nose and ports formed along the one or more inclined surfaces of the boiler nose for injection into the combustion gases. That is, the boiler nose is generally comprised of a vertically upwardly inclined lower surface directed toward the restriction in the flue gas passage formed by the nose and the opposite boiler wall and an upper inclined surface directed away from the restriction in the flue gas passage. The overfire air-reduction reagent mix injection ports may be provided in the lower or upper or both inclined surfaces of the boiler nose. In a further embodiment, the overfire air-reduction reagent mixture may be supplied to the boiler nose in a pair of discrete ducts respectively extending into the boiler nose from opposite side walls of the furnace.

**[0039]** Referring now to FIG. 5, there is illustrated a multi-stage reburn combustion system generally designated 400, which is similar in construction to the combustion system 100 of FIG. 1 with the exception of the nose overfire air injection as set forth below. Thus, the combustion system 400 includes a combustion zone 420, a ISA zone 422, a reburn zone 424, and a burnout zone 426. Fuel and primary and/or secondary air are supplied through the inlets 428. The flue gas from the burnout zone 426 passes downstream to an outlet 444 where the flue gas exits the combustion system 400. As the flue

gas passes to outlet 444, it flows past the tip of the boiler nose 440.

**[0040]** In an exemplary embodiment, the boiler nose 440 is used as a plenum for receiving overfire air mixed with the reduction reagent and injecting the mixture directly into the flue gases passing through the flue gas passage restriction 443. For example, the overfire air-reduction reagent mixture may be supplied directly into the cavity or plenum 441 within the boiler nose 440 for flow through injection ports 445 directly into the flue gas passage. The ports 445 can be arrayed in the inclined wall portion of the boiler nose 440. While the injection ports 445 are illustrated in the lower wall surface of the boiler nose inclined upwardly toward the restriction in the passage, it will be appreciated that the injection ports 445 may be disposed in the upper inclined surface of the boiler nose extending in a direction away from the restricted passage 443. The location of the NOFA provides another exemplary point of injection for the reduction reagent. The flue gas passage restriction 443 permits the reduction reagent to substantially penetrate the flue gas in this location and improve the mixture of the reagent with the flue gas.

**[0041]** A control system may control reduction reagent application to any of the system air streams described above, i.e., the ISA, OFA, BOFA, HBOFA, NOFA, or any combination of the foregoing air streams. The control system may also manage application of the air-reagent mixture by the injectors into the combustion system. The control system may be configured to independently control each of the injectors. The control system may further be configured to control reduction reagent application based on at least one input parameter.

**[0042]** The control system can be in operative communication, for example, with the main feed line for the reduction reagent into an air stream. As mentioned previously, the main feed line is also in operative communication with a storage system, such as a silo or hopper (as shown in FIG. 2).

**[0043]** The control system may automatically control quantity and frequency of reduction reagent injection as a function of combustion system operating parameters. For example, reduction reagent injection may be adjusted by increasing or decreasing the rate of feed from a blower in communication with the reduction reagent supply and/or the rotational speed of a star feeder. Input parameters to control system may include sulfur content in the flue gas, mercury content in the flue gas, the air flow rate to combustion system, and the like. Reduction reagent injectors may be operated independently of one another or as a group to each or all of the air streams to the combustion system.

**[0044]** In one embodiment, the measured sulfur content of the flue gases can be compared to a target sulfur content that is desired to be achieved for environmental, regulatory, or other reasons. If the measured sulfur content in the flue gases is above the target, the rate of addition of the reduction reagent into the combustion sys-

tem via one of the available air streams is adjusted accordingly. If the measured sulfur content is at or below target, the method includes the step of leaving the addition rate of the reduction reagent into the system unchanged or reducing it.

**[0045]** The combustion gases contain carbon dioxide, various undesirable gases containing sulfur, and mercury species. The convective pathways of the combustion system are also filled with a variety of ash which is swept along with the high temperature flue gases. To remove the ash before emission into the atmosphere, particulate removal systems are used. A variety of such removal systems, such as electrostatic precipitators and a bag house, can be disposed in the convective pathway. In addition, chemical scrubbers can be positioned in the convective pathway. Additionally, there may be provided various instruments to monitor components of the gas, such as sulfur oxides, metals, and the like. The reduction reagents can be effective in absorbing some of the components, such that the reduction agents can be removed from the gas by the particulate removal systems, thereby removing the pollutant from the flue gas stream.

**[0046]** In each of the multi-stage reburn combustion system embodiments described above any suitable reduction reagent can be injected into the combustion gases by utilizing one or more of the system air streams. The reduction reagents described herein will reduce pollutant emissions in the multi-stage reburn combustion system, such as, without limitation, carbon, carbon dioxide, carbon monoxide, hydrogen, NO<sub>x</sub>, SO<sub>x</sub>, chlorine, metals such as mercury, arsenic, and nickel, and other like pollutant species generated as a result of combusting fuels. For example, mercury is at least partially volatilized upon combustion of coal. When present during coal combustion, the mercury tends not to stay with the ash, but rather becomes a component of the flue gases. If remediation is not undertaken, the mercury tends to escape from the coal-burning facility into the surrounding atmosphere.

**[0047]** Exemplary reduction reagents are able to be injected in locations within the combustion system that may experience temperatures greater than or equal to 2000° F. during operation of the furnace. Further, the location may be at a temperature greater than or equal to 2300° F. Exemplary reduction reagents can include, without limitation, sorbent species for reduction of SO<sub>x</sub>, hydrochloric acid (HCl), metals, and other like emissions; NO<sub>x</sub> reduction agents such as, ammonia, urea, cyanuric acid, and the like; and oxidizing species such as halogen-based compounds. The reduction reagent composition may be in the form of a powder, fluid, or any other like form suitable for being mixed in an air stream as a carrier fluid.

**[0048]** In one embodiment, the reduction reagent comprises a powder sorbent composition. The components of the sorbent composition may be provided as alkaline powders. Without being limited by theory, it is believed that the alkaline nature of the sorbent components leads at least in part to the desirable properties that aid in re-

ducing pollutants in the flue gas as described above. Sources of calcium for the sorbent compositions can include calcium powders such as calcium carbonate, limestone, calcium oxide, calcium hydroxide, calcium phosphate, and other calcium salts. An alkaline powder sorbent composition may contain one or more calcium-containing powder such as cement (e.g., Portland cement), cement kiln dust, lime kiln dust, various slags, sugar beet lime, and the like, along with an aluminosilicate clay such as, without limitation, montmorillonite, kaolin, and the like. The sorbent composition may contain sufficient SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> to form a refractory-like mixture with calcium sulfate produced by combustion and with mercury and other heavy metals such that the calcium sulfate is handled by the particulate removal system of the combustion system, and mercury and heavy metals are not leached from the fly ash under acidic conditions. The calcium containing powder sorbent composition may contain by weight a minimum of 2% silica and 2% alumina, more specifically a minimum of 5% silica and 5% alumina. Thus, the sorbent compositions may include from about 2 to 50%, more specifically 2 to 20%, and more specifically yet about 2 to 10% by weight aluminosilicate material such as the exemplary clays.

**[0049]** Suitable aluminosilicate materials include a wide variety of inorganic minerals and materials. For example, a number of minerals, natural materials, and synthetic materials contain silicon and aluminum associated with an oxy environment along with optional other cations such as, without limitation, Na, K, Be, Mg, Ca, Zr, V, Zn, Fe, Mn, and/or other anions, such as hydroxide, sulfate, chloride, carbonate, along with optional waters of hydration. Such natural and synthetic materials are referred to herein as aluminosilicate materials and are exemplified in a non-limiting way by the clays noted above.

**[0050]** In aluminosilicate materials, the silicon tends to be present as tetrahedra, while the aluminum is present as tetrahedra, octahedra, or a combination of both. Chains or networks of aluminosilicate are built up in such materials by the sharing of 1, 2, or 3 oxygen atoms between silicon and aluminum tetrahedra or octahedra. Such minerals go by a variety of names, such as silica, alumina, aluminosilicates, geopolymer, silicates, and aluminates. However presented, compounds containing aluminum and/or silicon tend to produce silica and alumina upon exposure to high temperatures of combustion in the presence of oxygen.

**[0051]** Aluminosilicate materials may include polymorphs of SiO<sub>2</sub>.Al<sub>2</sub>O<sub>3</sub>. For example, sillimanite contains silica octahedra and alumina evenly divided between tetrahedra and octahedra. Kyanite is based on silica tetrahedra and alumina octahedra. Andalusite is another polymorph of SiO<sub>2</sub>.Al<sub>2</sub>O<sub>3</sub>.

**[0052]** Chain silicates may contribute silicon (as silica) and/or aluminum (as alumina) to the sorbent compositions. Chain silicates can include, without limitation, pyroxene and pyroxenoid silicates made of infinite chains of SiO<sub>4</sub> tetrahedra linked by sharing oxygen atoms.



**[0053]** Other suitable aluminosilicate materials include sheet materials such as, without limitation, micas, clays, chrysotiles (such as asbestos), talc, soapstone, pyrophyllite, and kaolinite. Such materials are characterized by having layer structures wherein silica and alumina octahedra and tetrahedra share two oxygen atoms. Layered aluminosilicates include clays such as chlorites, glauconite, illite, polygorskite, pyrophyllite, sauconite, vermiculite, kaolinite, calcium montmorillonite, sodium montmorillonite, and bentonite. Other examples include micas and talc.

**[0054]** Suitable aluminosilicate materials also include synthetic and natural zeolites, such as without limitation the analcime, sodalite, chabazite, natrolite, phillipsite, and mordenite groups. Other zeolite minerals include heulandite, brewsterite, epistilbite, stilbite, yagawaralite, laumontite, ferrierite, paulingite, and clinoptilolite. The zeolites are minerals or synthetic materials characterized by an aluminosilicate tetrahedral framework, ion exchangeable "large cations" (such as Na, K, Ca, Ba, and Sr) and loosely held water molecules.

**[0055]** In various embodiments, the alkaline powder sorbent compositions that form the reduction reagent can further comprise an optional halogen (such as bromine) compound or compounds to capture chloride as well as mercury, lead, arsenic, and other heavy metals in the ash, thereby rendering the heavy metals non-leaching under acidic conditions, and improving the cementitious nature of the ash produced. As a result, emissions of pollutants are mitigated, reduced, or eliminated, and a valuable cementitious material is produced as a by-product of the fuel combustion.

**[0056]** Sorbent compositions comprising a halogen compound contain one or more organic or inorganic compounds that contain a halogen. Halogens include chlorine, bromine, and iodine. The halogen compounds are sources of the halogens, especially of bromine and iodine. For bromine, sources of the halogen include various inorganic salts of bromine including bromides, bromates, and hypobromites. In various embodiments, organic bromine compounds are less preferred because of their cost or availability. However, organic sources of bromine containing a suitably high level of bromine are considered within the scope of the invention. Non-limiting examples of organic bromine compounds include methylene bromide, ethyl bromide, bromoform, and carbon tetrabromide. Non-limiting inorganic sources of iodine include hypoiodites, iodates, and iodides, with iodides being preferred. Organic iodine compounds can also be used.

**[0057]** The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. Ranges disclosed herein are inclusive and combinable (e.g., ranges of "up to about 25 wt%, or, more specifically, about 5 wt% to about 20 wt%", is inclusive of the endpoints and all intermediate values of the ranges of "about 5 wt% to about 25 wt%," etc.). "Combination" is inclusive of blends, mixtures, alloys, reaction products, and the like. Further-

more, the terms "first," "second," and the like, herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another, and the terms "a" and "an" herein do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item. The modifier "about" used in connection with a quantity is inclusive of the stated value and has the meaning dictated by context, (e.g., includes the degree of error associated with measurement of the particular quantity). The suffix "(s)" as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including one or more of that term (e.g., the colorant(s) includes one or more colorants). Reference throughout the specification to "one embodiment", "another embodiment", "an embodiment", and so forth, means that a particular element (e.g., feature, structure, and/or characteristic) described in connection with the embodiment is included in at least one embodiment described herein, and may or may not be present in other embodiments. In addition, it is to be understood that the described elements may be combined in any suitable manner in the various embodiments.

**[0058]** Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the embodiments of the invention belong. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and the present disclosure, and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

**[0059]** While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

**[0060]** Various aspects and embodiments of the present invention are defined by the following numbered clauses:

1. A combustion system, comprising:

- a combustion zone comprising a burner for converting a fuel, under fuel rich conditions, to a flue gas;
- an intermediate staged air zone downstream from the combustion zone for supplying inter-

- mediate staged air to the flue gas and producing fuel lean conditions;  
 a reburn zone downstream from the intermediate staged air zone for receiving the flue gas; and  
 an inlet downstream from the combustion zone for supplying a mixture of air and a reduction reagent to the flue gas, wherein the reduction reagent is configured to reduce an amount of pollutant species in the flue gas.
2. The combustion system of clause 1, wherein the inlet is disposed in the intermediate staged air zone and configured to supply a mixture of the intermediate staged air and the reduction reagent into the flue gas.
3. The combustion system of any preceding clause, wherein the intermediate staged air comprises boosted air.
4. The combustion system of any preceding clause, further comprising an overfire air inlet configured to supply overfire air to a burnout zone downstream from the reburn zone and a boosted overfire air inlet configured to supply boosted overfire air at a pressure higher than a pressure of the overfire air.
5. The combustion system of any preceding clause, wherein the overfire air inlet is configured to supply a mixture of the overfire air and the reduction reagent into the flue gas.
6. The combustion system of any preceding clause, wherein the boosted overfire air inlet is configured to supply a mixture of the boosted overfire air and the reduction reagent into the flue gas.
7. The combustion system of any preceding clause, wherein the boosted overfire air inlet is disposed in the intermediate staged air zone.
8. The combustion system of any preceding clause, further comprising a boiler nose downstream from the reburn zone, wherein the boiler nose comprises a plurality of ports disposed therein configured to supply a mixture of overfire air and the reduction reagent into the flue gas.
9. The combustion system of any preceding clause, further comprising a burner disposed in the combustion zone, wherein the burner comprises a first duct configured to channel a fuel flow into the combustion zone; and a second duct substantially concentrically-aligned with and extending through the first duct, wherein the second duct is configured to channel a mixture of air and the reduction reagent into the combustion zone.
10. The combustion system of any preceding clause, wherein the air comprises intermediate staged air.
11. The combustion system of any preceding clause, wherein the reduction reagent comprises a sorbent composition, a nitrogen oxides reduction agent, an oxidizing composition, or a combination comprising at least one of the foregoing.
12. The combustion system of any preceding clause, wherein the sorbent composition comprises calcium carbonate, limestone, calcium oxide, calcium hydroxide, calcium phosphate, cement, cement kiln dust, lime kiln dust, sugar beet lime, clay, talc, or a combination comprising at least one of the foregoing.
13. A process for using a combustion system, said process comprising:
- supplying a fuel and air under fuel rich conditions to a combustion zone comprising a burner to form a flue gas;
  - supplying intermediate staged air to the flue gas through an intermediate staged air inlet downstream of the combustion zone in an amount effective to produce fuel lean conditions;
  - channeling the flue gas to pass to a reburn zone downstream from the intermediate staged air inlet; and
  - supplying a reduction reagent to the flue gas, wherein the reduction reagent is configured to reduce an amount of pollutant species in the flue gas.
14. The process of clause 13, wherein supplying the reduction reagent further comprises mixing the reduction reagent with the intermediate staged air.
15. The process of clause 13 or 14, wherein supplying intermediate staged air to the flue gas further comprises supplying intermediate staged air to the flue gas as boosted air.
16. The process of any of clauses 13 to 15, further comprising:
- supplying fuel to the reburn zone through a reburn inlet; and
  - supplying overfire air to a burnout zone downstream from the reburn zone through an overfire air inlet.
17. The process of any of clauses 13 to 16, wherein supplying the reduction reagent further comprises mixing the reduction reagent with the overfire air.
18. The process of any of clauses 13 to 17, further comprising supplying overfire air through a port in a

boiler nose downstream from the reburn zone.

19. The process of any of clauses 13 to 18, wherein supplying the reduction reagent further comprises mixing the reduction reagent with the overfire air from the boiler nose.

20. A process for reducing at least sulfur oxides and/or mercury in a flue gas of a combustion system, the method comprising:

supplying a fuel and air under fuel rich conditions to a combustion zone comprising a burner to form a flue gas;

supplying intermediate staged air to the flue gas through an intermediate staged air inlet downstream of the combustion zone to produce fuel lean conditions;

channeling the flue gas to pass to a reburn zone downstream from the intermediate staged air inlet;

supplying overfire air to a burnout zone downstream from the reburn zone through an overfire air inlet; and

mixing a sorbent composition with the overfire air and/or the intermediate staged air before supplying the air to the flue gas.

## Claims

1. A combustion system (100, 300, 400), comprising:

a combustion zone (120, 420) comprising a burner for converting a fuel, under fuel rich conditions, to a flue gas;

an intermediate staged air zone (122, 322, 422) downstream from the combustion zone for supplying intermediate staged air to the flue gas and producing fuel lean conditions;

a reburn zone (124, 424) downstream from the intermediate staged air zone for receiving the flue gas; and

an inlet (128, 132, 134, 136, 200, 332, 336, 338, 428, 445) downstream from the combustion zone for supplying a mixture of air and a reduction reagent to the flue gas, wherein the reduction reagent is configured to reduce an amount of pollutant species in the flue gas.

2. The combustion system (100, 300) of claim 1, wherein the inlet (132, 332) is disposed in the intermediate staged air zone (122, 322) and configured to supply a mixture of the intermediate staged air and the reduction reagent into the flue gas.

3. The combustion system (100, 300) of any preceding claim, further comprising an overfire air inlet (136,

336) configured to supply overfire air to a burnout zone (126, 324) downstream from the reburn zone (124) and a boosted overfire air inlet (132, 332) configured to supply boosted overfire air at a pressure higher than a pressure of the overfire air.

4. The combustion system (100, 300) of claim 3, wherein the overfire air inlet (136, 336) is configured to supply a mixture of the overfire air and the reduction reagent into the flue gas.

5. The combustion system of claim 3 or claim 4, wherein the boosted overfire air inlet (132, 332) is configured to supply a mixture of the boosted overfire air and the reduction reagent into the flue gas.

6. The combustion system (400) of any preceding claim, further comprising a boiler nose (440) downstream from the reburn zone (424), wherein the boiler nose comprises a plurality of ports (445) disposed therein configured to supply a mixture of overfire air and the reduction reagent into the flue gas.

7. The combustion system (100, 300, 400) of any preceding claim, further comprising a burner (200) disposed in the combustion zone (120, 420), wherein the burner comprises a first duct (206) configured to channel a fuel flow into the combustion zone; and a second duct (208) substantially concentrically-aligned with and extending through the first duct, wherein the second duct is configured to channel a mixture of air and the reduction reagent into the combustion zone.

8. A process for using a combustion system (100, 300, 400), said process comprising:

supplying a fuel and air under fuel rich conditions to a combustion zone (120, 420) comprising a burner (200) to form a flue gas;

supplying intermediate staged air to the flue gas through an intermediate staged air inlet (132, 332) downstream of the combustion zone in an amount effective to produce fuel lean conditions; channeling the flue gas to pass to a reburn zone (124, 424) downstream from the intermediate staged air inlet; and

supplying a reduction reagent to the flue gas, wherein the reduction reagent is configured to reduce an amount of pollutant species in the flue gas.

9. The process of claim 8, wherein supplying the reduction reagent further comprises mixing the reduction reagent with the intermediate staged air.

10. The process of claim 8 or claim 9, further comprising:

supplying fuel to the reburn zone (124, 424) through a reburn inlet (134); and supplying overfire air to a burnout zone (126, 324, 426) downstream from the reburn zone (124, 424) through an overfire air inlet (136, 336). 5

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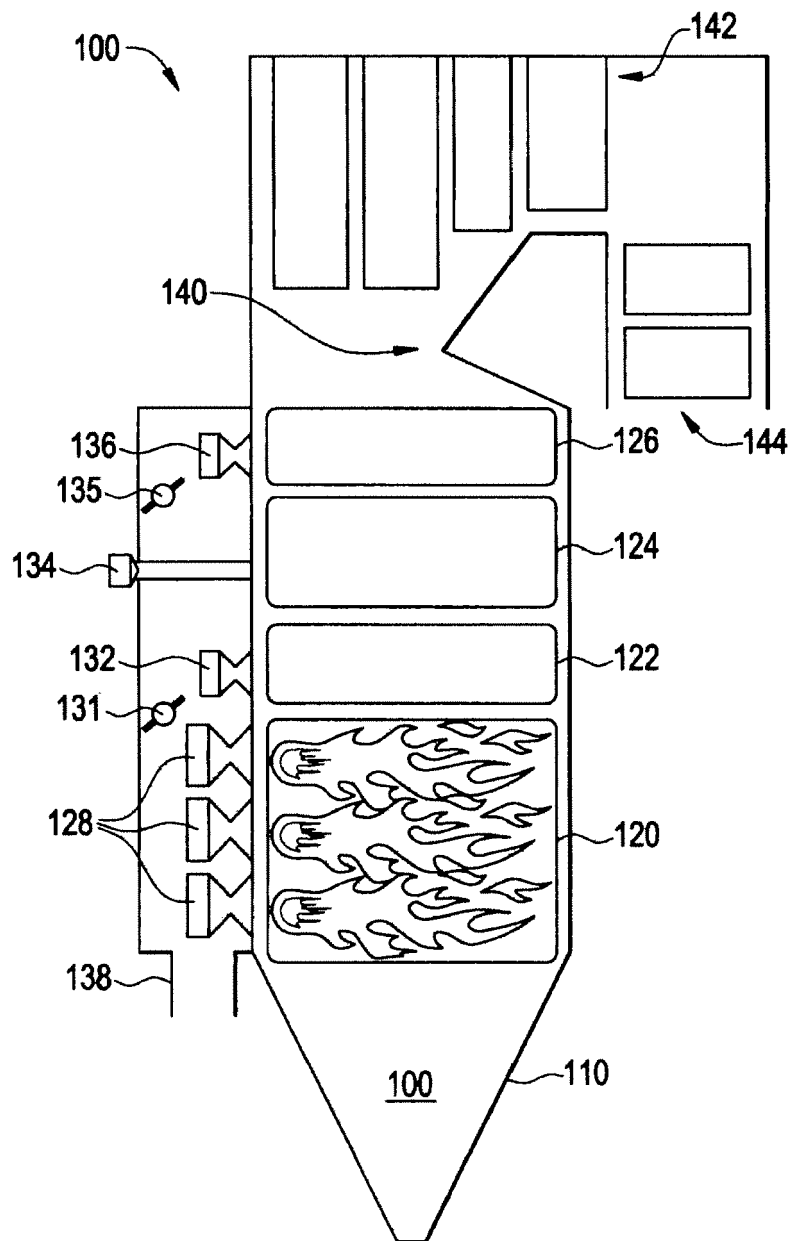
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FIG. 1



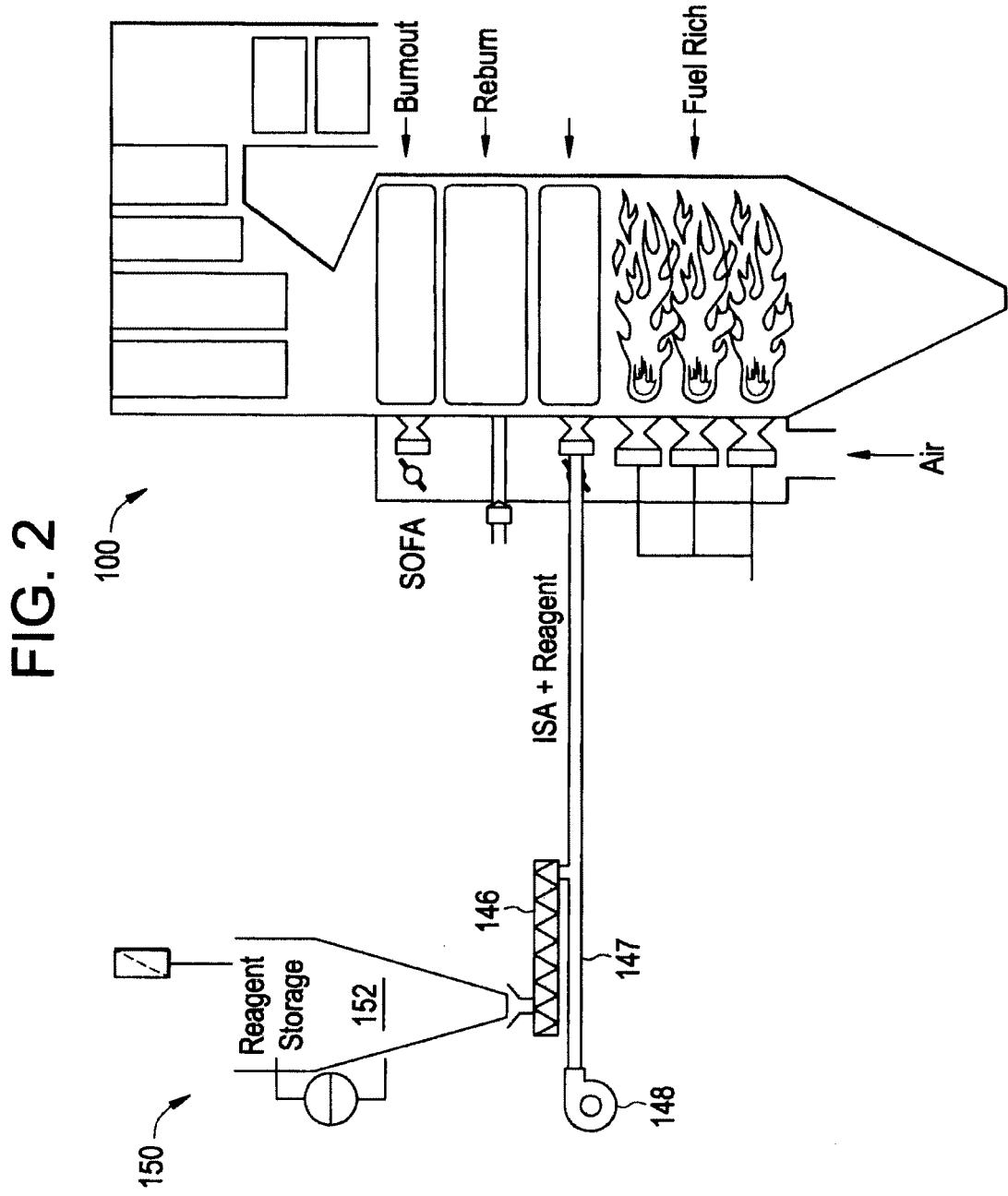


FIG. 3

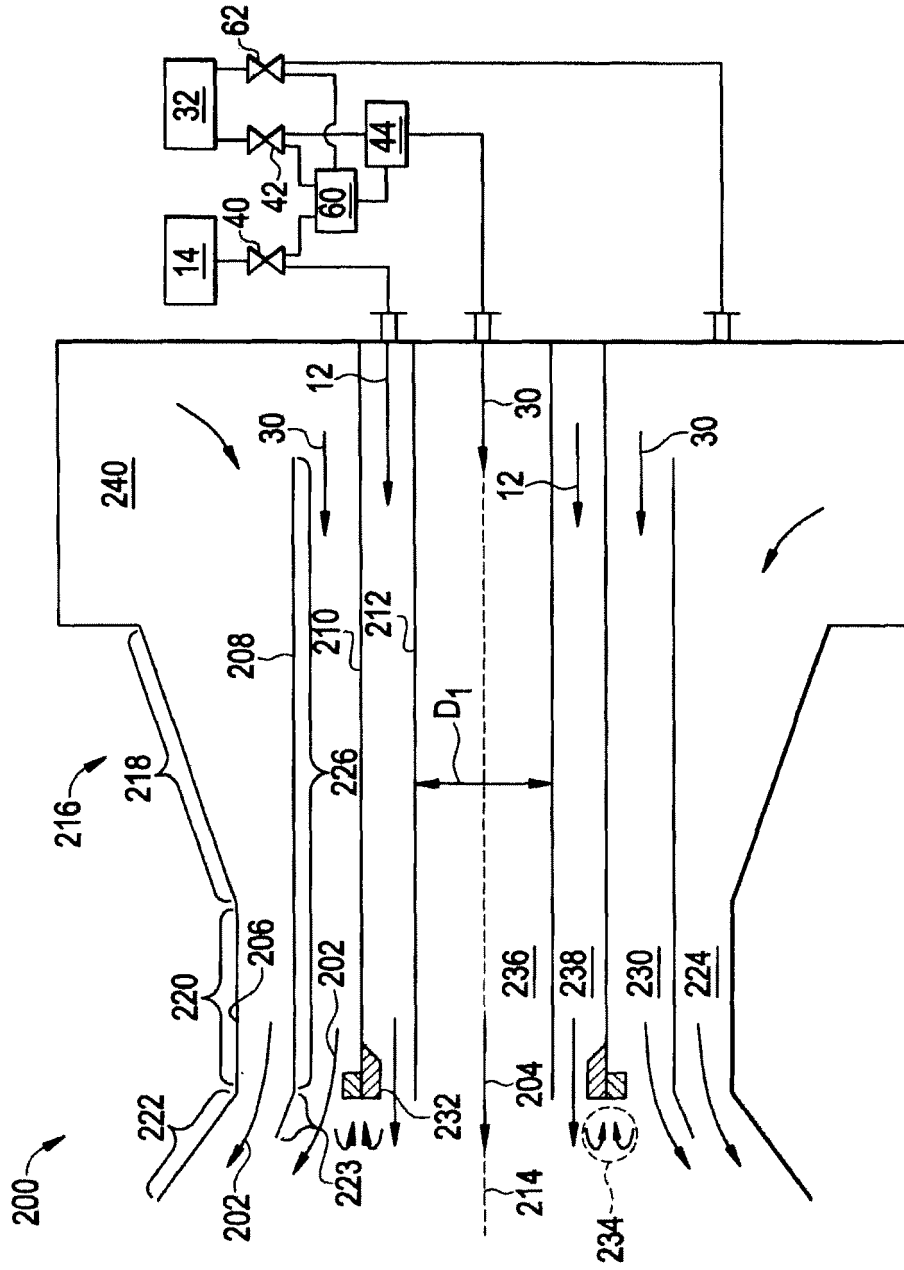


FIG. 4

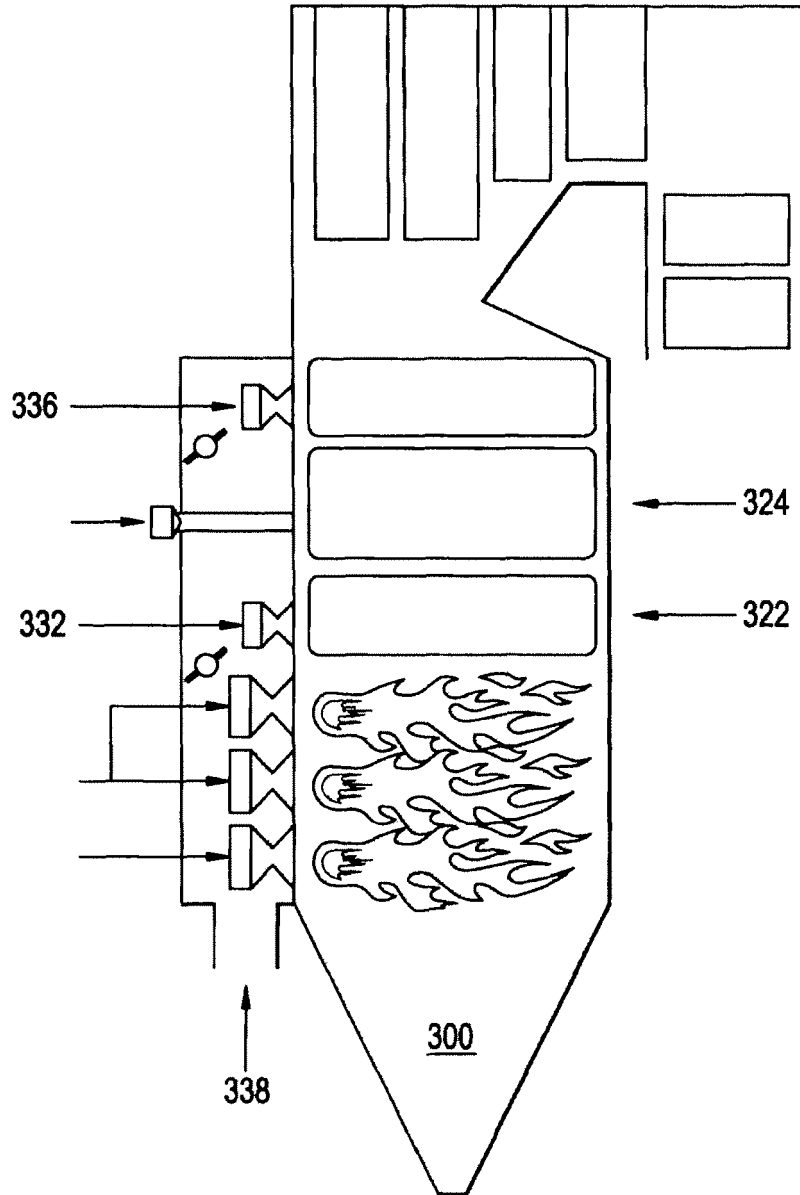




FIG. 5

