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(54) Title: OXY-FUEL FIRED BOILER WITH SEPARATELY FIRED COMBUSTION CHAMBER FOR SUPERHEATER AND REHEATER DUTIES

(57) Abstract: Combustion apparatus useful for generating steam employs two combustion chambers that are connected in series to satisfy the overall heat duty.



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OXY-FUEL FIRED BOILER WITH SEPARATELY FIRED COMBUSTION
CHAMBER FOR SUPERHEATER AND REHEATER DUTIES

Field of the Invention

- 5 This invention relates to apparatus and methods for carrying out combustion to generate steam.

Background of the Invention

- 10 One of the promising approaches to develop technologies to capture and sequester CO₂ from utility boilers is to use oxy-fuel firing in boilers to produce flue gas with a very high concentration of CO₂ which can be subsequently separated, compressed and stored in appropriate underground storage sites. Most existing boilers, however, are designed to be fired with air, and need to be modified to be fired with oxygen instead of air. Over a hundred years of power
- 15 plant development has resulted in highly complex and optimized boiler designs for air firing to maximize the steam power cycle efficiency. In the standard steam power plant, steam expanded in the steam turbines is cooled and condensed in the main condenser and feedwater heaters to form most of the feedwater required for the boiler. Feedwater is pumped to high pressures in stages, fed to a series of
- 20 feedwater heaters and heated by steam streams extracted from intermediate pressure and low pressure steam turbines. The preheated feedwater is then introduced into the boiler to produce superheated steam while receiving heat from combustion of fuel with air in a series of indirect heat exchangers. The placement of water/steam heating tubes within the different sections of the boiler is designed
- 25 to maximize the overall flue gas to water/steam heat transfer efficiency and the boiler fuel thermal efficiency while minimizing the construction cost of the boiler. In essence a steam boiler for power generation comprises a complex series of indirect heat exchangers to convert feedwater to high temperature steam suitable for steam turbine operation and to cool the flue gas generated from combustion to
- 30 the lowest practical temperature. These designs require careful attention to the heat absorption pattern and the heat flux distributions. This is particularly true in

coal fired boilers where mineral matter in the coal can lead to extensive slagging, fouling, and submicron ash formation depending on the flame temperature.

One of the most important design parameters is the heat absorption pattern in the boiler. The proportion of heat absorbed to preheat the boiler feedwater to
5 the boiling temperature, evaporate the water, and superheat/reheat the steam must be carefully controlled to achieve the required steam characteristics. This heat absorption pattern, coupled with temperature and pressure limitations of tube materials, tend to define conventional boiler designs. For example, feedwater is heated first in the economizer which is an indirect heat exchanger placed in the
10 low temperature section of the convective passage of the boiler. High radiative heat flux from the flame zone to the ‘water walls’ formed by boiler tubes in the furnace section, i.e, the combustion chamber in the boiler, is used to evaporate boiler feedwater from the economizer. The relatively low temperature of the preheated feedwater and the high heat transfer coefficients under boiling
15 conditions for subcritical boilers keep the tube temperature within the allowable material limit. (A similar heat transfer arrangement is used in a supercritical steam boiler although the distinct phase change from liquid water to steam does not exist under the supercritical pressure of water, i.e., above 3208.2 psia.)

Steam generated in the water walls is then superheated in the superheater
20 tubes placed in the upper furnace section (“radiant superheater”) or in the high temperature section of the convective passage of the boiler. The high pressure superheated steam is fed into the high pressure steam turbine and expanded to an intermediate pressure at a reduced temperature while generating power. This steam is then re-introduced into the reheater section of the boiler to raise the steam
25 temperature again. Reheater tubes are also placed in the upper furnace section (“radiant reheater”) or in the high temperature section of the convective passage of the boiler. The reheated steam is then fed into the intermediate pressure turbine for expansion and power generation. The steam from the intermediate turbine is typically divided into three streams and fed to the low pressure turbine, to the
30 feedwater heater, and to the turbine to drive the feed water pump.

The flue gas temperature at the exit of the furnace (FEGT) is typically in a range between 1800 F and 2200 F and cool enough that heat flux to the superheat/reheat tubes is reduced. The lower heat flux in the convective section allows tube temperature limits to be avoided, even with high steam temperatures and relatively low steam side heat transfer coefficients.

Oxy-fuel combustion produces much higher adiabatic flame temperatures than air-fuel combustion. In order to convert an existing air-coal fired boiler to oxy-coal firing flue gas recirculation (FGR) is required to modulate the heat flux in the furnace section and to provide a sufficient volume of hot flue gas at proper temperature to satisfy the convective duties. A typical air fired boiler requires about 11 lb of air per 1 lb of coal. For a typical oxy-coal fired boiler about 2 lb of oxygen and about 7 lb of recycled flue gas per 1 lb of coal is required to match the original air fired boiler conditions. Many technical experts have stated that FGR is required even for newly designed oxy-fuel fired boilers due to the high adiabatic flame temperature and the resulting high heat flux of direct oxy-fuel combustion. In fact all of the proposed oxy-coal boiler demonstration projects for CO₂ capture are based on FGR to control the flame temperature and to maintain proper balancing of heat transfer to different parts of the steam cycle. FGR reduces boiler efficiency and increases the costs of boiler construction and operation.

For air-coal fired boilers typically 1 to 2 lb of heated "primary air" per lb of coal is required for grinding and transporting of coal to burners at a minimum velocity of 3000 ft/min. For oxy-coal fired boilers the coal transport gas to replace the primary air should be recycled flue gas with optional addition of some oxygen. High purity oxygen should not be used as the coal transport gas for safety reasons. "Recycled flue gas" (RFG) means a portion of the flue gas exited from the boiler that is re-introduced into the boiler with or without downstream treatment to remove some of the flue gas components such as water vapor, particulates, sulfur oxides and nitrogen oxides. "Recycled flue gas" (RFG) includes a purified carbon dioxide (CO₂) stream produced in a downstream CO₂ separation unit. In order to minimize nitrogen concentration in the flue gas stream the oxy-fuel fired boiler

and the down stream flue gas treatment units must be designed to prevent air leakage into the flue gas stream.

One way to balance the heat transfer distribution between boiling and superheating/reheating with oxy-coal combustion is to separately fire different water/steam circuits in two or more combustion chambers. This method guarantees that the appropriate amount of heat is transferred for each part of the water/steam circuit. The main chamber with water walls would be designed like a traditional furnace to take water to a specific temperature and pressure. For a subcritical boiler this would be the evaporative section where liquid water is evaporated to form saturated steam at design pressure. In a supercritical or ultrasupercritical boiler this would be a lower temperature supercritical water section. The average heat flux in the main chamber would be similar to that of the traditional boiler furnace and relatively high. The superheater and reheater combustion chambers would also be designed like the traditional radiant furnace with steam tubes placed on all walls. For example, US Patent No. 7,516,620 describes a boiler system with a main boiler, a superheat boiler and a reheat boiler where the water/steam circuits of the boiler system are connected in series between three independent and separately fired boilers. Flue gases from the three independent boiler furnaces are fed into a common economizer in a parallel fashion to heat the feedwater. According to the patent the water walls of each boiler are sufficiently exposed to the flame that the major portion of heat transfer takes place by a radiant heat transfer mechanism rather than a convective heat transfer mechanism.

A drawback of this concept, however, is the large size of the superheater and reheater (SH/RH) chamber volumes required to limit the heat flux to the SH/RH tubes placed in the combustion chamber walls. The maximum heat flux to SH/RH tubes has to be controlled in a range of 20,000 to 30,000 Btu/hr/ft² to prevent tube overheating or severe slagging and fouling in a typical coal fired boiler. By increasing the volume of the SH/RH chamber sufficiently large wall areas can be created to place SH/RH tubes, albeit at the expense of increasing the boiler size and cost. By comparison, the average heat flux to the water walls of a

conventional coal fired boiler may be in a range of 40,000 to 60,000 Btu/hr/ft² and the peak heat flux can be as high as 90,000 to 100,000 Btu/hr/ft² without exceeding the tube material temperature limit or the slagging temperature limit. The relatively low temperature of the feed water and the high heat transfer rate in the water side of the tube provides the necessary cooling in this case. For a given firing rate in a combustion chamber, if the average heat flux to the walls is reduced from 50,000 Btu/hr/ft² to 20,000 Btu/hr/ft², the total furnace wall area with water/steam tubes must be increased by about 2.5 times. As a result the volume of the combustion chamber would become very large and the cost increases for a separately fired SH/RH boiler without FGR.

Brief Summary of the Invention

One aspect of the present invention is a combustion system that comprises

(A) a first combustion unit that includes a first combustion chamber comprising heat exchanger tubes to heat H₂O having at least one inlet for H₂O to be heated and at least one outlet for a heated H₂O stream and that is capable of receiving fuel and gaseous oxidant having an average oxygen content of at least 50 vol.% into said first combustion chamber and that is capable of combusting said fuel and said oxidant in said first combustion chamber, and that further includes a first heat exchanger having at least one inlet for H₂O to be heated and at least one outlet for a heated H₂O stream and one or more passages between said inlet and said outlet in indirect heat exchange contact with flue gas and heat produced by combustion in said first combustion chamber, and a flue gas outlet from said first combustion chamber for gaseous products of combustion in said first combustion chamber,

(B) a second combustion unit that includes a second combustion chamber comprising heat exchanger tubes to heat H₂O having at least one inlet for H₂O to be heated and at least one outlet for heated H₂O and that is capable of receiving fuel and gaseous oxidant having an average oxygen content of at least 50 vol.% into said second combustion chamber and that is capable of combusting said fuel and said oxidant in said second combustion chamber, and that further includes a second heat exchanger having at least one inlet for H₂O to be heated

and at least one outlet for heated H₂O and one or more passages between said inlet and said outlet in indirect heat exchange contact with flue gas and heat produced by combustion in said second combustion chamber, and a flue gas outlet from said second combustion chamber for gaseous products of said combustion, and

- 5 (C) a passage operatively connected to said flue gas outlet from said first combustion chamber and to said second combustion chamber to convey gaseous combustion products from said first combustion chamber into said second combustion chamber.

 The passage (C) can contain an intermediate heat exchanger permitting
10 indirect heat exchange from said gaseous combustion products to H₂O.

 Another aspect of the present invention is a method of combustion comprising

- (A) combusting fuel and gaseous oxidant having an oxygen content of at least 50 vol.% in a first combustion chamber to generate heat and flue gas, and
15 heating H₂O with flue gas and heat generated by said combustion in said first combustion chamber;

- (B) combusting fuel and gaseous oxidant having an average oxygen content of at least 50 vol.% in a second combustion chamber, and heating H₂O with flue gas and heat generated by combustion in said second combustion
20 chamber, while feeding flue gas generated by combustion in said first combustion chamber into said second combustion chamber, to generate heat and flue gas, and

 (C) connecting said H₂O heated in said first combustion chamber and said H₂O heated in said second combustion chamber in series with steam turbines and feedwater heaters to operate a steam power cycle.

- 25 Preferably, said heated stream is also heated by indirect heat exchange with flue gas generated by combustion in said first combustion chamber, before said flue gas is fed into said second combustion chamber.

Brief Description of the Drawings

Figure 1 is a flowsheet depicting an embodiment of the present invention.

Figure 2 is another flowsheet of an embodiment of the present invention.

5 Detailed Description of the Invention

Referring to Figure 1, the boiler system comprises oxy-fuel fired main furnace (or first combustion chamber) 1 and superheat/reheat furnace (or second combustion chamber) 2 connected in series so that together they satisfy the overall steam generation duties with no or substantially reduced external flue gas recirculation. Main furnace 1 has conventional water walls to generate steam (or high temperature supercritical water for the case of a supercritical steam boiler) from feedwater heated in an economizer. Fuel 12 (preferably pulverized coal conveyed by a transport gas containing recycled flue gas with a low concentration of nitrogen) is fed into combustion chamber 11 through at least one burner 14. At least one stream of oxidant 13 is also fed to combustion chamber 11, preferably through at least one burner 14 in known manner. The oxidant 13 should have an average oxygen content of at least 50 vol.%, preferably greater than 90%. The fuel 12 and oxidant 13 are combusted in combustion chamber 11 to form flame 15 and to generate heat and flue gas. The fuel and oxidant should be fed into the first combustion chamber at an overall stoichiometric ratio (defined as oxygen fed divided by oxygen necessary for complete combustion) in the range of 1.0 to 3.0, preferably in the range of 1.0 to 1.5. Optionally, but preferably, main furnace 1 comprises radiant superheater/reheater 16 in a suitable furnace zone (often called the transition zone) less exposed to intense radiation from oxy-fuel flame 15. Hot flue gas from the flame zone typically passes through the upper transition zone with radiant superheater/reheater and then enters the convective section. It is not required for hot flue gas to pass through radiant superheater/reheater 16. Optionally radiant superheater/reheaters are also placed in the bottom hopper section of furnace 1.

30 The water/steam streams fed into or exit out of different sections of the boiler system are not shown as they follow any conventional sequence. Namely,

for example, preheated feedwater from feedwater heaters is heated first in the economizer which is an indirect heat exchanger placed in the low temperature section of the convective passage of a boiler. Heated feedwater from the economizer is then further heated in the “water walls” formed by boiler tubes in the furnace section of the boiler to produce “steam” (or supercritical hot water in a supercritical steam boiler). Steam/water mixture generated in the water walls is then superheated, after separating water, in the superheater tubes placed in the upper furnace section (“radiant superheater”) or in the high temperature section of the convective passage of the boiler. The high pressure superheated steam is fed into the high pressure steam turbine and expanded to an intermediate pressure at a reduced temperature condition while generating power. This steam is then re-introduced into the reheater section of the boiler to raise the steam temperature again. Reheater tubes are also placed in the upper furnace section (“radiant reheater”) or in the high temperature section of the convective passage of the boiler. The reheated steam is then fed into the intermediate pressure turbine for expansion and power generation. For the double reheat steam cycle the reheating step takes place twice. The steam from the intermediate turbine is typically divided into three streams and fed to the low pressure turbine, to the feedwater heater, and to the turbine to drive the feed water pump. Steam is then cooled and condensed in the main condenser and in the feedwater heater to form feedwater for the boiler. In view of the variety of possible pathways that may be utilized in combination with the present invention, and in view of the possible different states and mixtures of states of water in those pathways, the term “H₂O” is used to include liquid, steam, superheated steam, and supercritical steam including “supercritical pressure hot water”..

Flue gas 18 exits from main furnace 11 and enters into the so-called convective zone with heat exchanger 28. Typically heat exchanger 28 is directly connected to furnace 11, but a passageway connecting furnace 11 and heat exchanger 28 can be optionally provided to place heat exchanger 28 in a convenient location between furnace 11 and furnace 21. After being cooled in the heat exchanger 28, flue gas 19 passes into superheat/reheat furnace 21. Flue gas

19 may have an oxygen content of 0 vol. % to 5 vol. % or even up to 25 vol. %. The temperature of flue gas 19 is typically 700 to 1300F. Heat exchanger 28 is used primarily to superheat or reheat steam and optionally include the economizer function. The cooled flue gas 19 plays the same role as externally recirculated flue gas would, to control the flame temperature in superheat/reheat furnace 21.

Fuel 22 (preferably coal) is fed into superheat/reheat furnace 21, as is oxidant 23 which is preferably fed through at least one burner 24 in known manner. The primary function of superheat/reheat furnace 21 is to superheat/reheat steam. Flue gas 19 is fed into superheater/reheater furnace 21, preferably through burner 24 or through overfire air ports (not shown) if any, or through other suitable openings in boiler walls (not shown) to modulate the flame temperature of flame 25 formed by fuel 22 and oxidant 23. The walls of superheater/reheater superheat/reheat furnace 21 are covered or made of superheater/reheater tubes. Optionally some of the walls comprise boiler tubes to produce steam from feedwater. Optionally, but preferably, furnace 1 comprises radiant superheater/reheater 26 in a suitable furnace zone less exposed to intense radiation from oxy-fuel flame 15. Oxidant 23 should have an oxygen content of at least 50 vol. %, preferably at least 90 vol. %. Fuel 22 and oxidant 23, and combustible components (i.e., excess oxygen and unburned fuel) of flue gas 19, are combusted in superheat/reheat furnace 21 to generate heat and flue gas.

The ratio (based on BTU content) of the feed rates of fuel to the first and second combustion chambers depends on the SH/RH requirement of the steam cycle and can typically be 80:20 to 30:70, preferably 75:25 to 55:45. The fuels fed to the first and second combustion chambers can be the same or different. Preferred fuels include coal, including bituminous coal, anthracite, and lignite.

The overall stoichiometric ratio combining the first and the second combustion chambers should be in the range of 1.0 to 1.3. Preferably the overall stoichiometric ratio is close to 1.0 as long as the fuel combustion efficiency and the pollutants in the cooled flue gas 28 are within normally acceptable limits for fuel combustion.

The flame temperature in the second combustion chamber is reduced (compared to the temperature if it was being operated as the sole combustion chamber of a power plant) due to the dilution effects of flue gas from the first combustion chamber. The low peak flame temperature, coupled with careful
5 furnace design, enables proper control of heat flux to superheater/reheater (“SH/RH”) tubes placed around the walls of the second combustion chamber 21 and allows placement of more radiant superheater/preheater tubes in the optional heat exchanger 26. More than two combustion chambers can be connected in series, if desired, with flue gas from the second combustion chamber fed to a third
10 combustion chamber, as the flue gas from the first chamber was fed to the second, and so on.

Flue gas 28 exits from superheat/reheat furnace 21, is cooled in the heat exchanger 38, and passes into optional coal transport gas heater 39. Similar to heat exchanger 28, heat exchanger 38 is typically directly connected to furnace 21
15 in the convective section of furnace 2. Heat exchanger 38 is used to superheat or reheat steam and also contain the economizer function to cool down the flue gas in a range of 600 to 1000 F. Flue gas 29 preferably has an oxygen content of 0 vol.% to 5 vol.% . Flue gas 29 is cooled down further in optional coal transport gas heater 39 and/or auxiliary feedwater heater (not shown) to a typical range of
20 250 to 350 F. The cooled flue gas 30 may be treated further in down stream flue gas clean up devices (not shown) and then CO₂ is separated in a CO₂ separation unit (not shown) for CO₂ capture and storage.

An advantage of this design is a smaller superheat/reheat combustion
25 chamber volume as compared with the parallel configuration of the main boiler chamber and the SH/RH chamber described in US Patent No. 7,516,620. The fan power requirement, however, will increase somewhat as compared to the parallel configuration due to the increased flue gas volume in the superheater/reheater chamber. Another advantage is an optional high excess oxygen combustion in the
30 first combustion chamber which would facilitate more complete carbon burn out in ash. For example the excess oxygen level at the exit of the first chamber 11

could be set as high as 10 to 30% by volume to accelerate char combustion. In fact all of the oxidant required to burn both fuel 12 and 22 could be fed into main furnace 1 as oxidant 13 to achieve very high excess oxygen combustion in the first combustion chamber without any flow in oxidant 23 in superheat/reheat furnace 2.

5 Since the flue gas from the first chamber is used as a portion of oxidant in the second combustion chamber, the overall oxygen requirement remains the same and the excess oxygen in the flue gas from the second chamber is controlled to a normal level of 2 to 4 vol. %. Difficult to burn coals such as low volatile and high ash coals can be advantageously combusted under high excess oxygen combustion
10 conditions.

There are many different physical arrangements possible to place boiler tubes and SH/RH tubes as long as the second chamber is connected in the downstream of the first chamber. The distribution of the total firing rate between the two chambers can be varied as well. Preferably between 55 and 75% of the total
15 fuel is fired in the first chamber. The flue gas from the first furnace can be optionally ducted to the windbox (not shown) of the burners and over-fire air ports of the second furnace with an optional induced draft (ID) fan. A portion of oxidant 23 is preferably directly injected through the oxy-fuel (coal) burners to stabilize flame 25 and to complete the combustion in the second chamber.

20

Example

An example of the present invention is described in the following section and compared with a conventional subcritical 660 MW coal-air fired boiler with a heat rate of 9,500 Btu/kWh. and with a prior art oxy-fuel fired boiler.

25 An example of the boiler configuration with the present invention is shown in Figure 2. About 70% of the total fuel input is fired in the main furnace and heat from this combustion transfers to SH/RH tubes and boiler tubes located in zones 100 and 101 respectively. The flue gas from the main furnace is cooled by transferring heat to SH/RH tubes and economizer tubes located in convective
30 zone 102. The remaining 30% of fuel input is fired in the second furnace and heat from this combustion is transferred to SH/RH tubes located around furnace walls

in zone 103 as well as those located in zones 102 and 104. Flue gas from zone 104 cools down as it passes through the convective zones 105, 106, 107 and 108 by transferring heat to SH/RH tubes, economizer tubes, recirculated flue gas (RFG) heater, and feedwater heater tubes located, respectively, in zones 105 through 108.

5 Heat duties of the system of the present invention are compared in Table 1 with those of a conventional air-coal fired sub-critical boiler and a prior art oxy-fuel fired boiler. The prior art oxy-fuel boiler system consists of a main boiler furnace with a convective zone and a separate SH/RH furnace with a convective zone, but the two furnaces are connected in parallel as described in US Patent No.
10 7,516,620. About 70% of the total fuel input is fired in the main furnace and the remaining 30% of fuel input is fired in the second furnace. For the oxy-coal boiler systems, coal is pulverized and transported by preheated flue gas. A portion of the cooled flue gas after a SO_x scrubber is recirculated and heated in a recirculated flue gas (RFG) heater in the convective section. The water vapor content of RFG
15 is assumed to be saturated at 106 F. FEGTs for the air-fuel and oxy-fuel cases are assumed to be 2100 F and 1900 F respectively. The temperature of flue gas after the economizer is assumed to be 750 F. The temperature of the flue gas after the air heater for the air-fuel case is assumed to be 350 F. For oxy-coal fired cases the flue gas after the RFG heater is cooled further in an auxiliary feedwater heater to
20 350 F. Thus, a portion of the steam normally extracted from steam turbines for feedwater heaters is eliminated, which increases the overall steam turbine output. In order to normalize the boiler condition at the same net steam output the other boiler heat duties for oxy-fuel cases are reduced slightly to account for the auxiliary feedwater heating.

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As shown in Table 1, 56.7% and 82.4% of heat input is absorbed in the furnace/transition zones under the baseline air-coal firing and the prior art oxy-fuel firing respectively. With the present invention 71.6% of heat input is absorbed in the furnace/ transition zones. Thus the SH/RH tubes placed in the
30 furnace/transition zones are reduced substantially and the volume of the SH/RH furnace is reduced with the present invention. (SH+RH absorb 7.9+3.7=11.6%,

25.6+12.0=37.6% and 18.3+8.6=26.9% of heat input for air, prior art oxy and present invention oxy respectively.)

Table 1 Distribution of boiler duties in furnace and convective zones

Boiler Type		Air	Oxy	Oxy
			(prior art)	(this invention)
Boiler duties				
Boiling	(%)	46.0	44.7	44.7
Superheater	(%)	32.0	31.1	31.1
Reheater	(%)	15.0	14.6	14.6
Economizer	(%)	7.0	6.8	6.8
Feedwater heater	(%)	0.0	2.8	2.8
Total	(%)	100.0	100.0	100.0
Furnace / Transition zones				
(%)		57.6	82.4	71.6
Boiling	(%)	46.0	44.7	44.7
SH	(%)	7.9	25.6	18.3
RH	(%)	3.7	12.0	8.6
Convective zones (%)		42.4	14.8	25.6
SH	(%)	24.1	5.5	12.8
RH	(%)	11.3	2.6	6.0
Eco	(%)	7.0	6.8	6.8
FW	(%)	0.0	2.8	2.8

5

One of the most effective ways to minimize the furnace size is to make the heat flux distribution to the water walls very uniform throughout the furnace. In many furnaces the materials selection and furnace arrangement are based on the peak heat flux that creates the highest tube surface temperature. In typical air fired operation, the peak heat flux is about 30% higher than the average heat flux to the water walls. Only a small portion of the furnace near the burner zone actually sees that elevated heat flux and corresponding high tube surface temperature due to cooling of the furnace gasses as they rise in the furnace. The bottom hopper section receives a much lower average heat flux as the ratio of the total wall surface area to the total radiative heat flux from the burner zone is large. Therefore most of the tube surface temperature in the furnace is below the

10

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material limit and the surface area of much of the furnace is essentially being underutilized. To illustrate the benefit of distributed firing concept a hypothetical example of installing oxy-fuel burners along the entire furnace length was modeled. The firing rate was reduced to 70% of the original oxy-fuel case to
5 match the overall heat absorption to that of the baseline air case. The resulting heat flux distribution is very uniform and about 23% below the peak heat flux of the baseline air case in this example. Hence the overall firing rate for the distributed firing case with oxy-fuel burners can be increased by the same amount without exceeding the peak heat flux observed in the baseline air case. Conversely
10 a significant reduction in the furnace size without exceeding the temperature limit of tube material is feasible if the same oxy-coal firing rate, i.e., 70% of the air-coal firing rate, is maintained

In the conventional wall-fired fired boiler the location of the top row of burners is set, in part, by the requirements to provide a sufficient gas residence
15 time for char burnout and to provide the space for the introduction of overfire air for NO_x control. These requirements could be relaxed substantially for direct oxy-coal firing. The small physical size of oxy-coal burners makes it easier to place them in desired locations, including in the walls of the bottom hopper section of the furnace. Since the char burn out rate becomes faster and the average gas
20 residence time in the furnace is increased three-to-four fold under oxy-coal combustion, the top row oxy-fuel burners could be placed at a much higher elevation without increasing unburned carbon in char. Thus it is feasible to distribute oxy-fuel burners in the furnace walls so as to produce a uniform heat flux and make the furnace size smaller. Preferably the burners and oxy-fuel firing
25 rates are arranged so as to make the peak heat flux within 105 to 125% of the average heat flux to the water walls.

Besides the additional burners and their placement, the burner design and firing strategies could also be used to generate a more uniform heat flux. One such strategy is to drive internal flue gas recirculation by high momentum oxy-fuel
30 burners such as one described in US Patent No. 4,378,205. Furnace gases in cooler zones are pulled into high velocity oxygen jets by the turbulent jet

entrainment and reduce the flame temperature, and therefore the local heat flux. High internal furnace gas recirculation generates a more uniform temperature and heat flux distribution in the furnace. Another approach is to extend the heat release along the length of the furnace by deeply staging the burners in the burner zone. Under these fuel rich conditions only a portion of the heat is released in this zone. As supplemental overfire oxygen is fed at locations along the furnace more heat is released. This method can also control NO_x formation from fuel-bound nitrogen, but may increase the slagging and corrosion potential in the reducing atmosphere zone of the furnace.

10

WHAT IS CLAIMED IS:

1. A combustion system useful in generating steam that comprises
 - (A) a first combustion unit that includes a first combustion chamber
5 comprising heat exchanger tubes to heat H₂O having at least one inlet for H₂O to be heated and at least one outlet for a heated H₂O stream and that is capable of receiving fuel and gaseous oxidant having an average oxygen content of at least 50 vol.% into said first combustion chamber and that is capable of combusting said fuel and said oxidant in said first combustion chamber, and that further
10 includes a first heat exchanger having at least one inlet for H₂O to be heated and at least one outlet for a heated H₂O stream and one or more passages between said inlet and said outlet in indirect heat exchange contact with flue gas and heat produced by combustion in said first combustion chamber, and a flue gas outlet from said first combustion chamber for gaseous products of combustion in said
15 first combustion chamber,
 - (B) a second combustion unit that includes a second combustion chamber comprising heat exchanger tubes to heat H₂O having at least one inlet for H₂O to be heated and at least one outlet for heated H₂O and that is capable of receiving fuel and gaseous oxidant having an average oxygen content of at least
20 50 vol.% into said second combustion chamber and that is capable of combusting said fuel and said oxidant in said second combustion chamber, and that further includes a second heat exchanger having at least one inlet for H₂O to be heated and at least one outlet for heated H₂O and one or more passages between said inlet and said outlet in indirect heat exchange contact with flue gas and heat produced
25 by combustion in said second combustion chamber, and a flue gas outlet from said second combustion chamber for gaseous products of said combustion, and
 - (C) a passage operatively connected to said flue gas outlet from said first combustion chamber and to said second combustion chamber to convey gaseous combustion products from said first combustion chamber into said second
30 combustion chamber.

2. The apparatus of claim 1 wherein said passage (C) comprises an intermediate heat exchanger permitting indirect heat exchange from said gaseous combustion products to said heated H₂O stream.

5 3. The apparatus of claim 1 wherein said fuel which said first combustion unit is capable of receiving and combusting is coal.

4. The apparatus of claim 1 wherein said fuel which said second combustion unit is capable of receiving and combusting is coal.

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5. The apparatus of claim 1 wherein said flue gas from said second combustion chamber passes through an additional heat exchanger to heat recycled flue gas.

15 6. The apparatus of claim 1 wherein said flue gas from said second combustion chamber passes through a heat exchanger to heat feedwater.

7. A method of combustion comprising

(A) combusting fuel and gaseous oxidant having an oxygen content of
20 at least 50 vol.% in a first combustion chamber to generate heat and flue gas, and heating H₂O with flue gas and heat generated by said combustion in said first combustion chamber;

(B) combusting fuel and gaseous oxidant having an average oxygen
content of at least 50 vol.% in a second combustion chamber, and heating H₂O
25 with flue gas and heat generated by combustion in said second combustion chamber, while feeding flue gas generated by combustion in said first combustion chamber into said second combustion chamber, to generate heat and flue gas, and

(C) connecting said H₂O heated in said first combustion chamber and
said H₂O heated in said second combustion chamber in series with steam turbines
30 and feedwater heaters to operate a steam power cycle.

8. The method of claim 7 wherein said heated stream is also heated by indirect heat exchange with flue gas generated by combustion in said first combustion chamber, before said flue gas is fed into said second combustion chamber.

5

9. The method of claim 7 wherein said flue gas from said second combustion chamber passes through a heat exchanger to heat feedwater.

10. The method of claim 7 wherein said fuel which is combusted in said first combustion unit is coal.

11. The method of claim 7 wherein said fuel which is combusted in said second combustion unit is coal.

12. The method of claim 7 wherein said fuel of said first combustion unit is coal and is transported to said burner of said first combustion unit by a transport gas containing said flue gas of said first combustion unit or said flue gas of said second combustion unit.

13. The method of claim 7 wherein the oxygen content of said flue gas generated in said first combustion chamber is higher than the oxygen content of said flue gas generated in said second combustion chamber.

14. The method of claim 7 wherein said flue gas generated by said combustion in said first combustion chamber has an oxygen content of at least 5 vol.%.

15. The method of claim 7 wherein the peak heat flux to said first combustion chamber walls is less than 120% of the average heat flux to said first combustion chamber walls.

16. The method of claim 7 wherein the peak heat flux to said second combustion chamber walls is less than 120% of the average heat flux to said second combustion chamber walls.

- 5 17. The method of claim 7 wherein said gaseous oxidants in said first and said second combustion chambers have an average oxygen content of at least 90 vol. % .

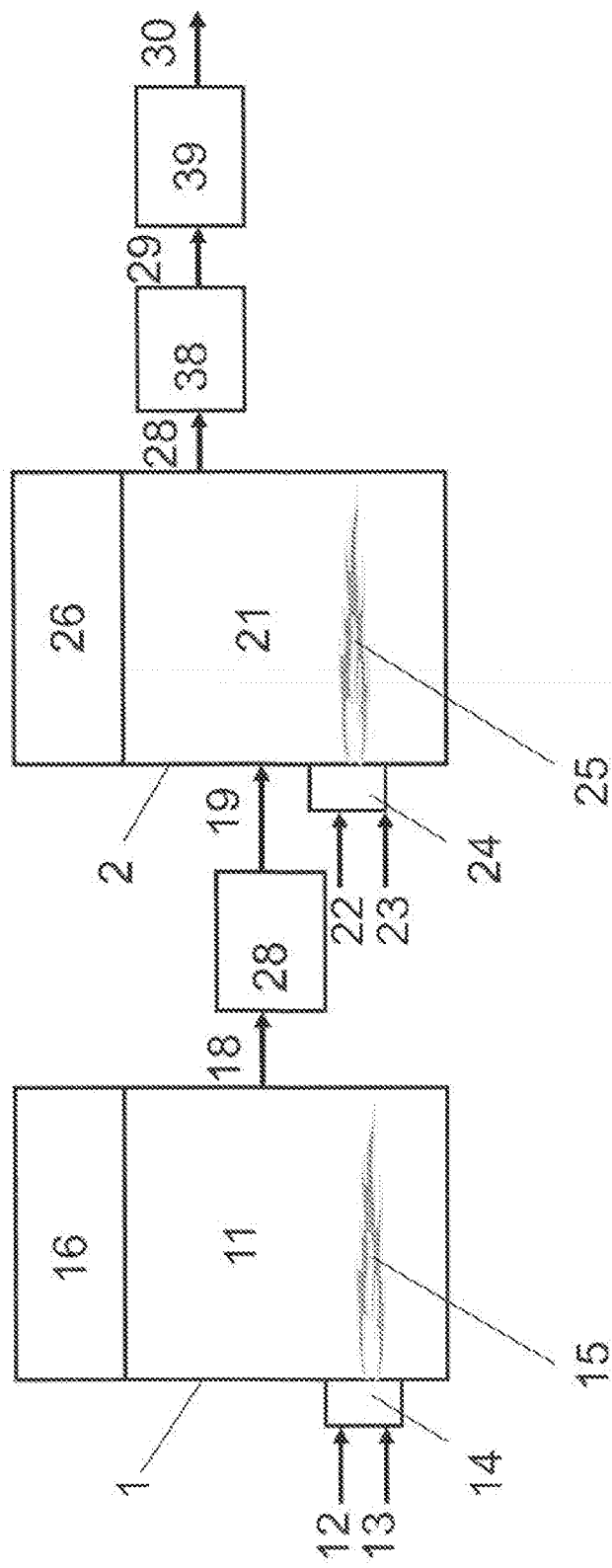


FIG. 1

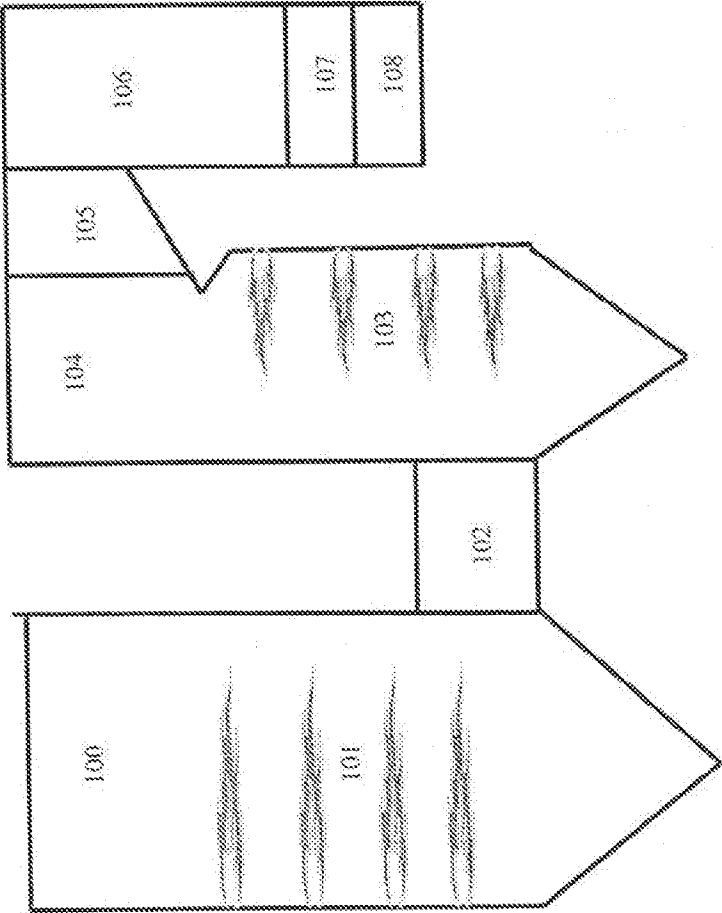


FIG. 2