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(54) **COMBUSTION SYSTEM COMPRISING AN ANNULAR SHROUD BURNER**

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(71) Applicant: **Jupiter Oxygen Corporation**, Des Plaines, IL (US)

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(72) Inventors: **Brydger Van Otten**, Herriman, UT (US); **Steven Harold Krimsky**, Spring, TX (US); **Kevin Davis**, Salt Lake City, UT (US); **Andrew Paul Chiodo**, Sandy, UT (US)

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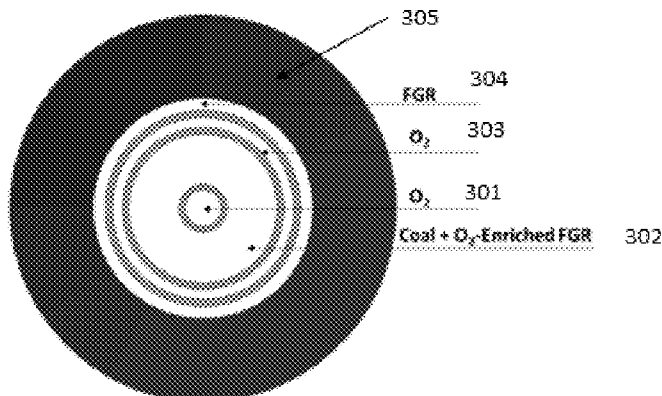
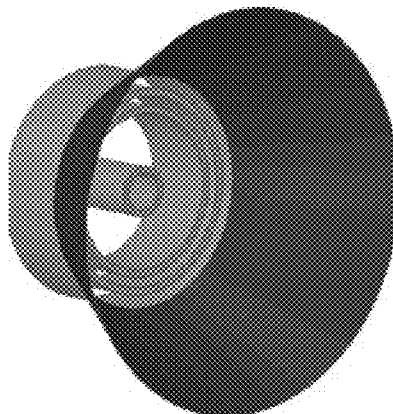
(57) **ABSTRACT**

(22) Filed: **Jun. 22, 2022**

A carbon sequestration system includes a furnace having an oxy-combustion burner, a mill configured to receive a fuel and to provide the fuel to the oxy-combustion burner, a waste heat recovery exchanger configured to receive a flue gas from the furnace, the flue gas ultimately supplied to one or more of an overfire air port of the furnace, the oxy-combustion burner, the mill, and a CO₂ purification unit, the CO₂ purification unit configured to produce a purified CO₂ stream.

Related U.S. Application Data

(63) Continuation-in-part of application No. 16/952,737, filed on Nov. 19, 2020, which is a continuation of application No. 16/722,010, filed on Dec. 20, 2019, now Pat. No. 10,845,052.



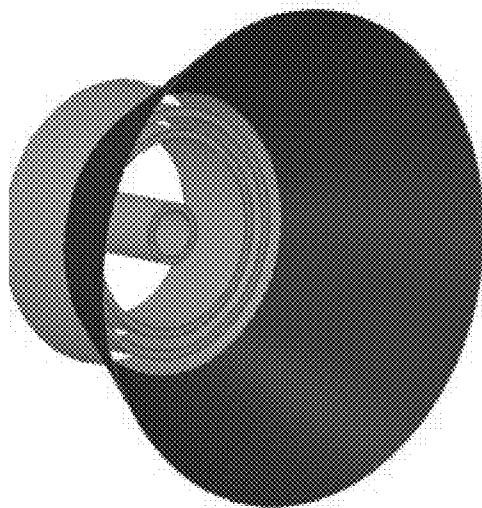


FIG. 1A

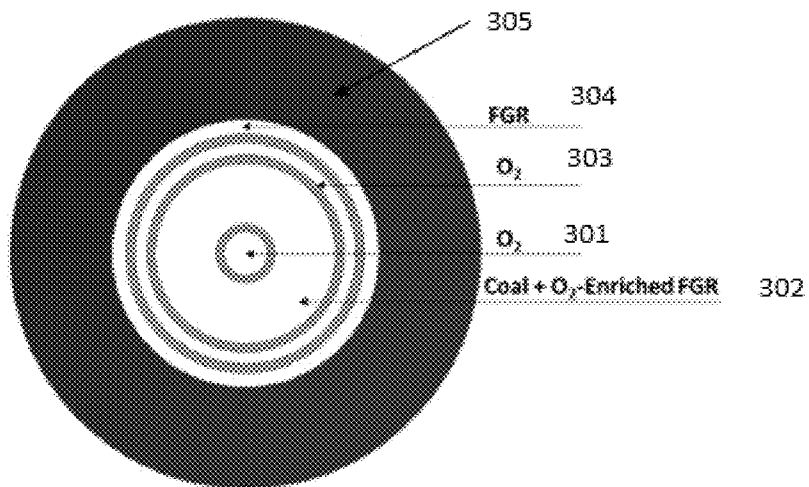


FIG. 1B

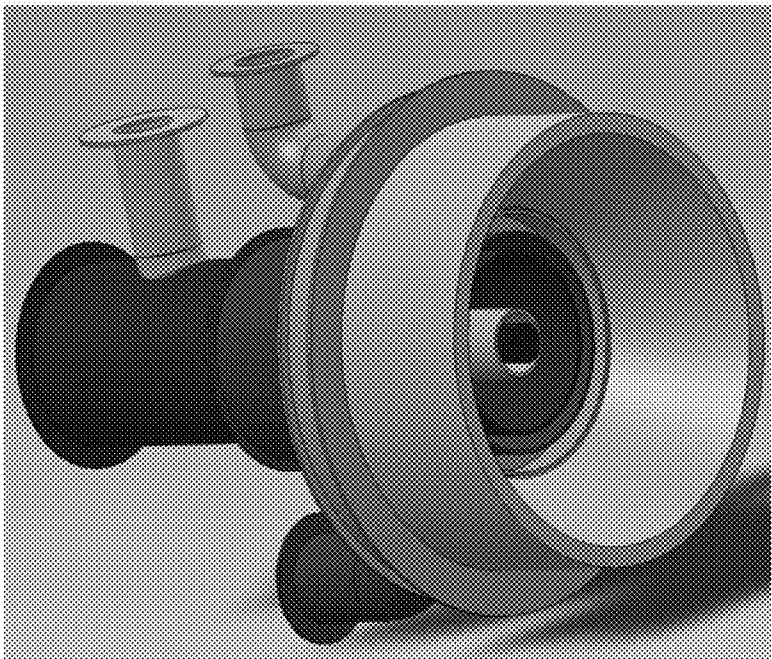


FIG. 2A

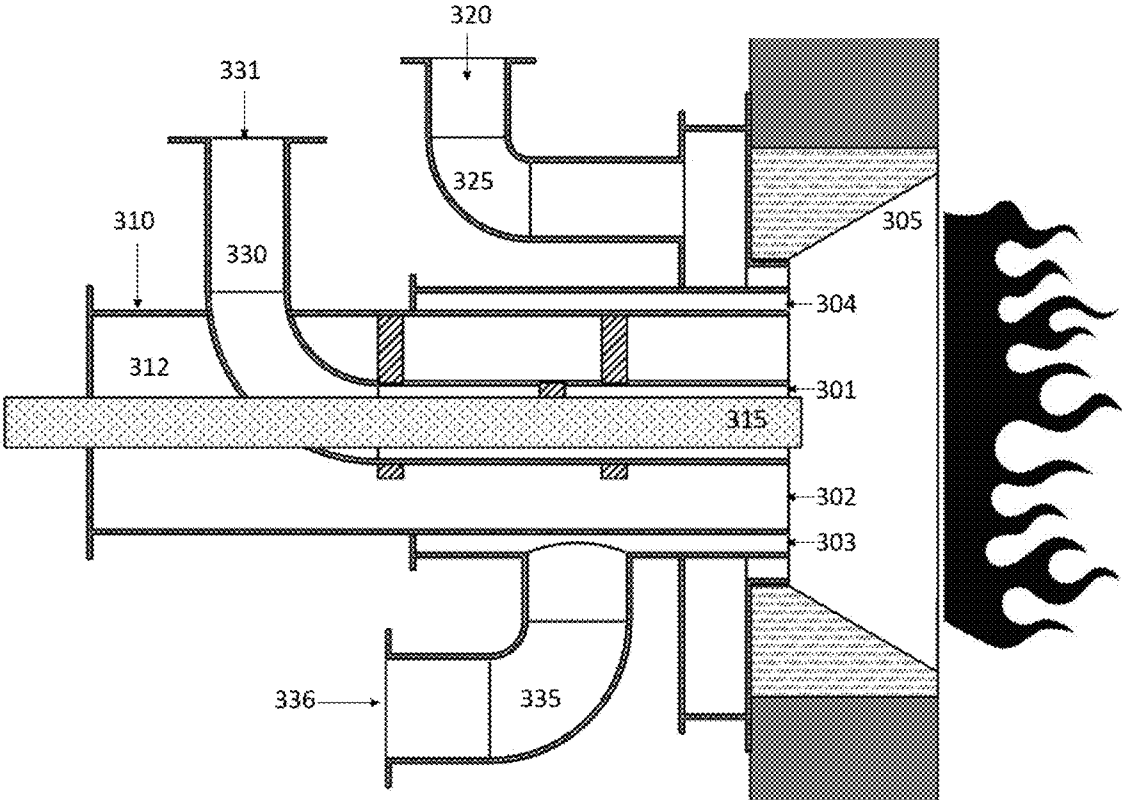


FIG. 2B

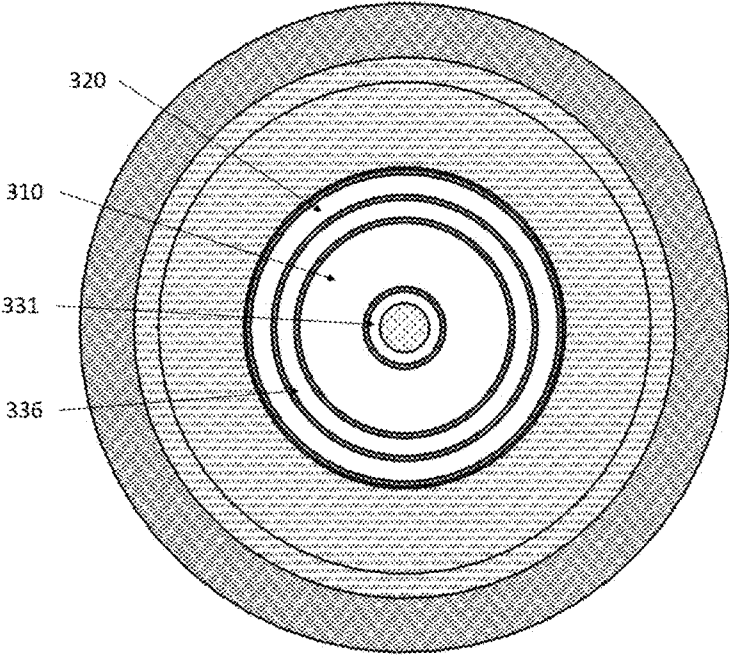


FIG. 2C

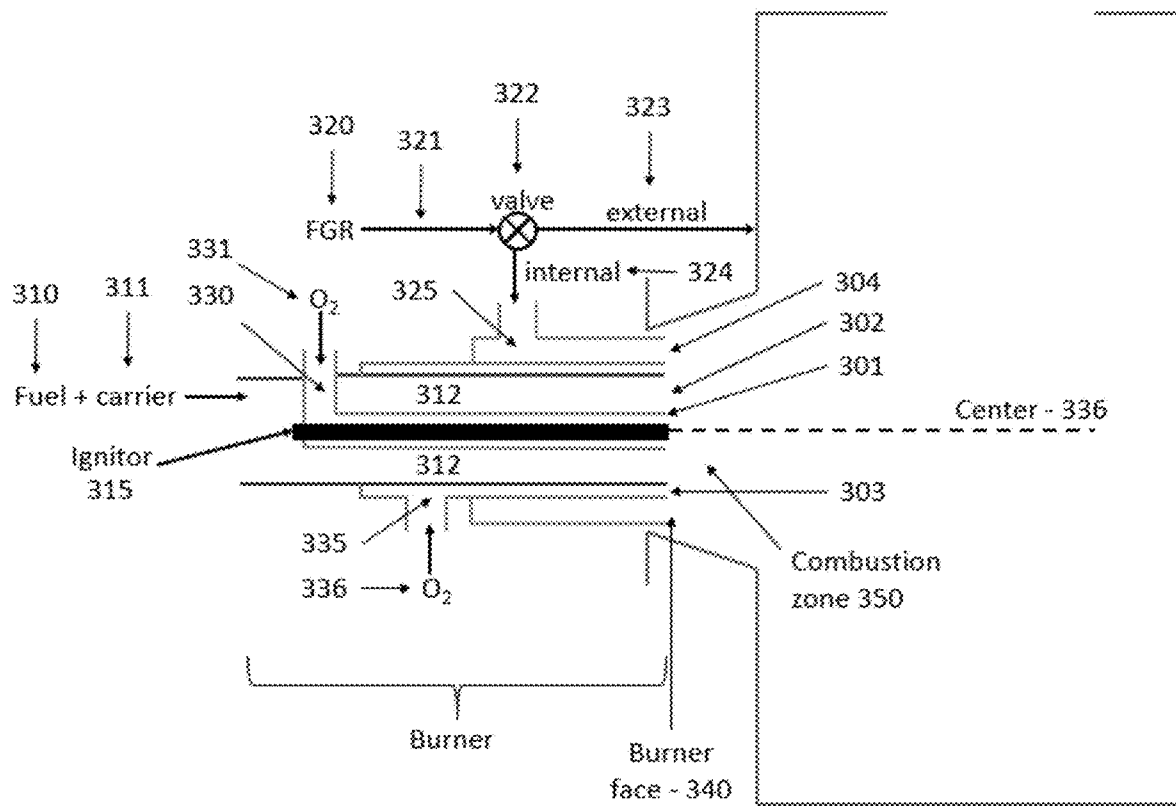
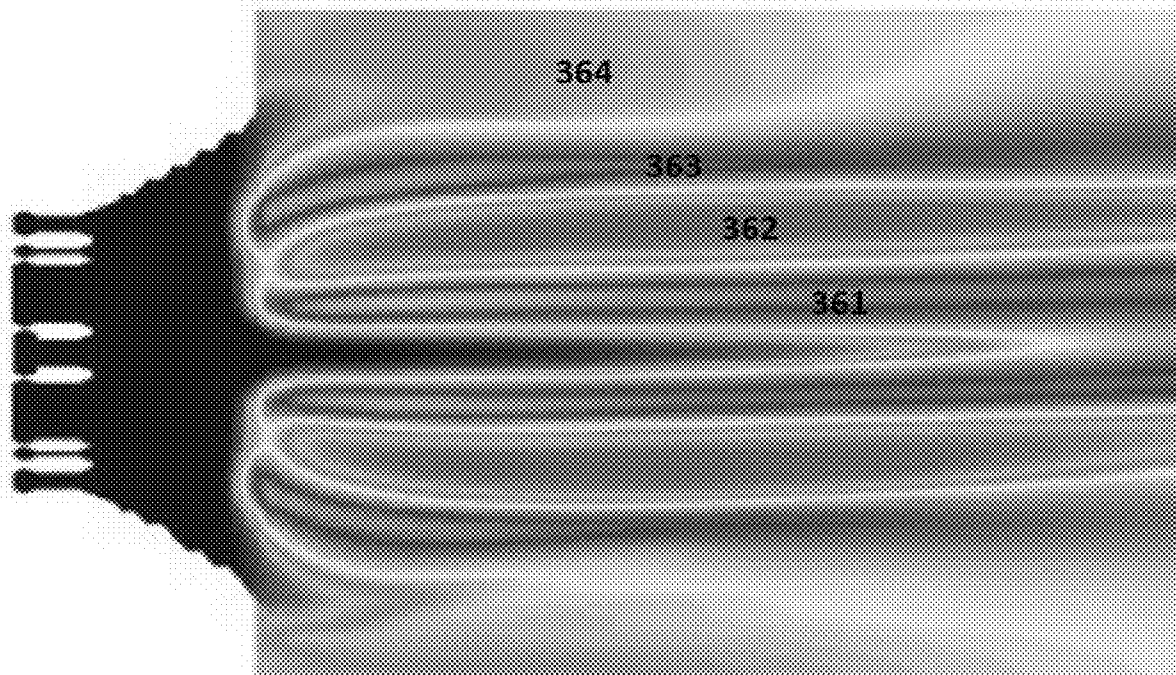


FIG. 3



Gas Temperature (°F)

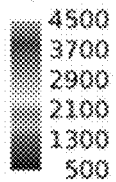
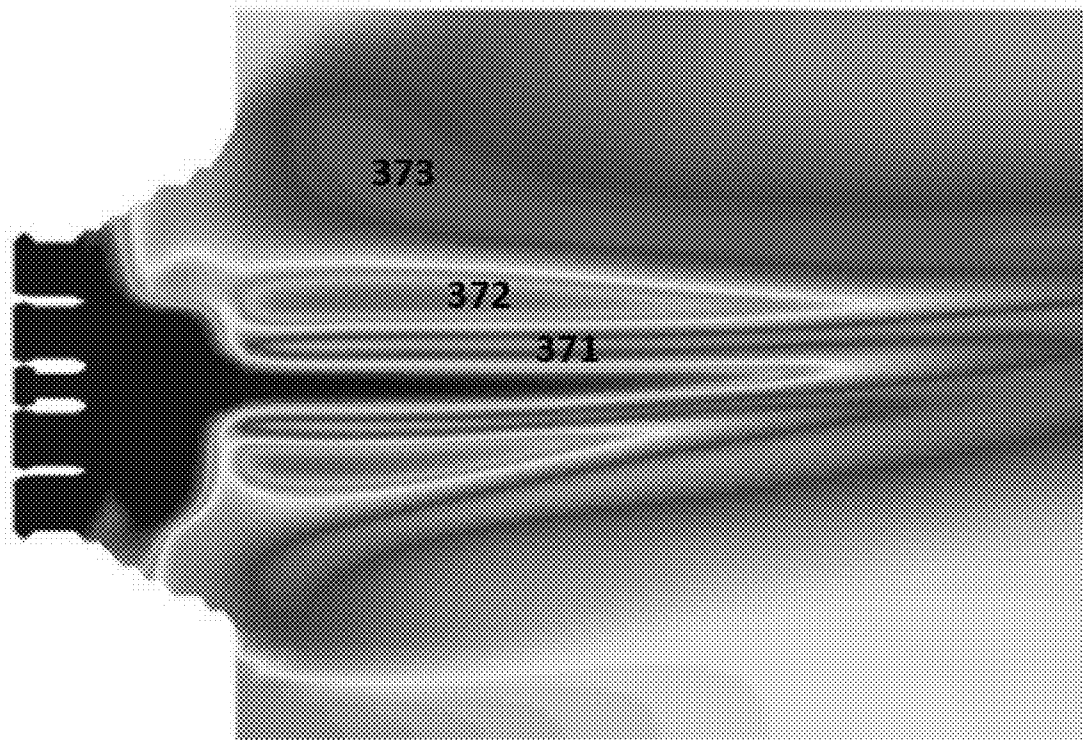


FIG. 4



Gas Temperature (°F)

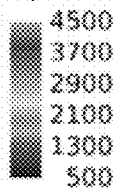


FIG. 5

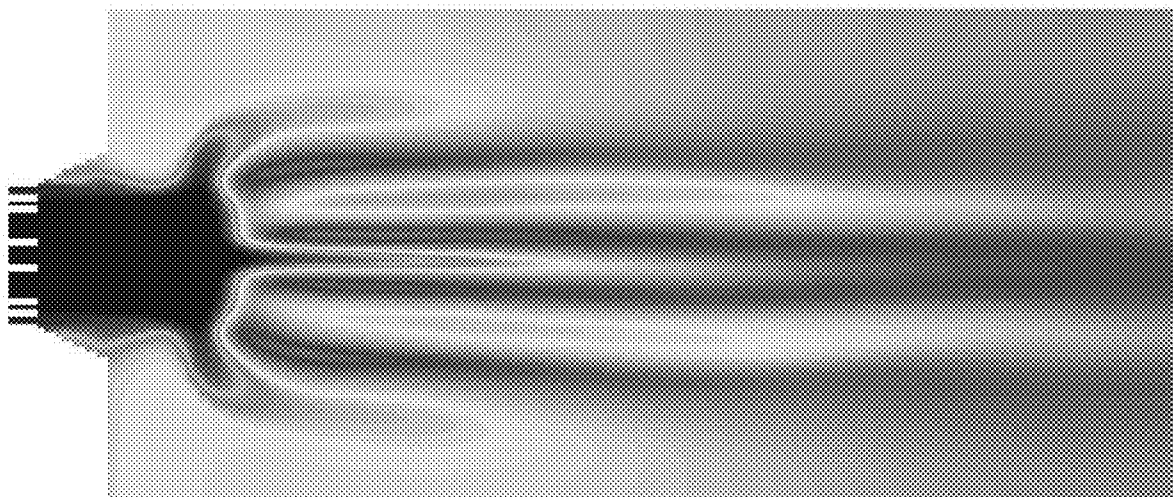


FIG. 6

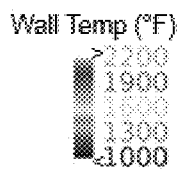


FIG. 7

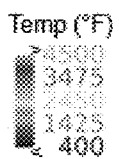
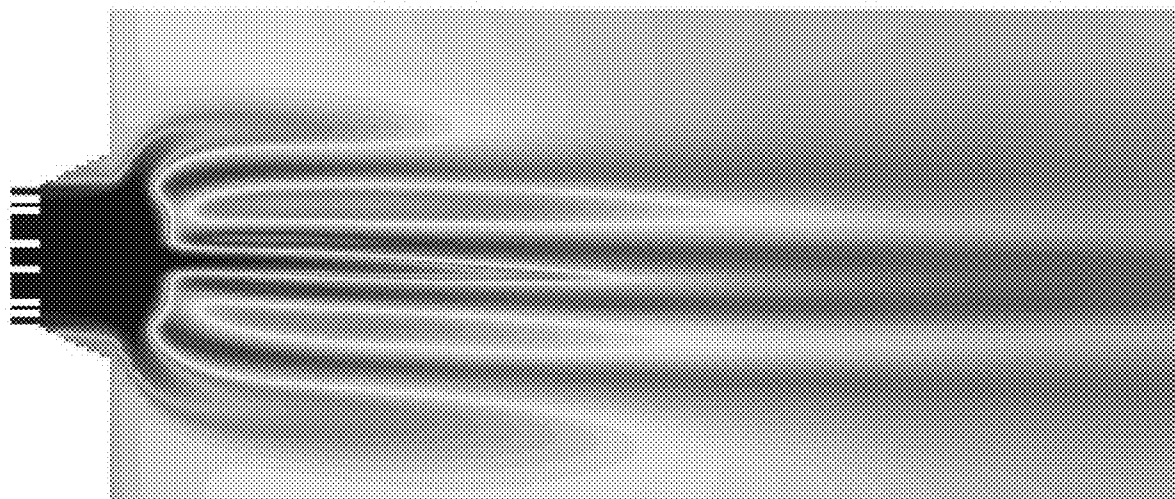


FIG. 8

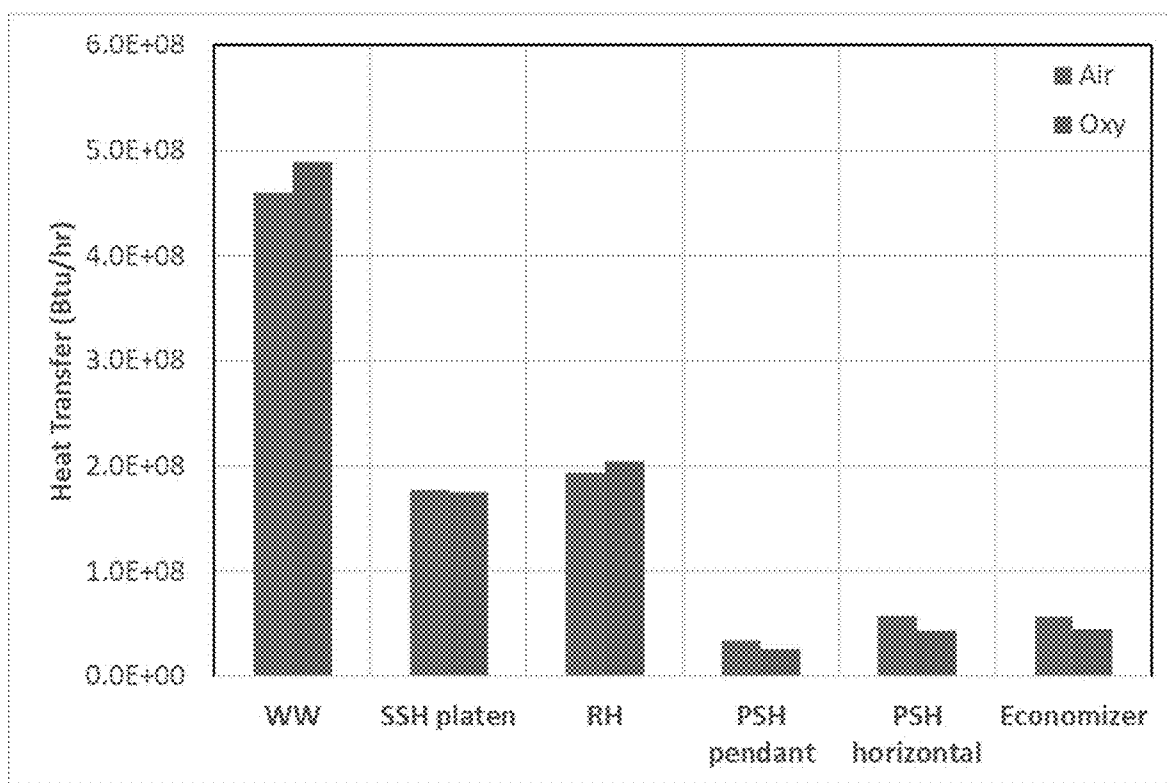


FIG. 9

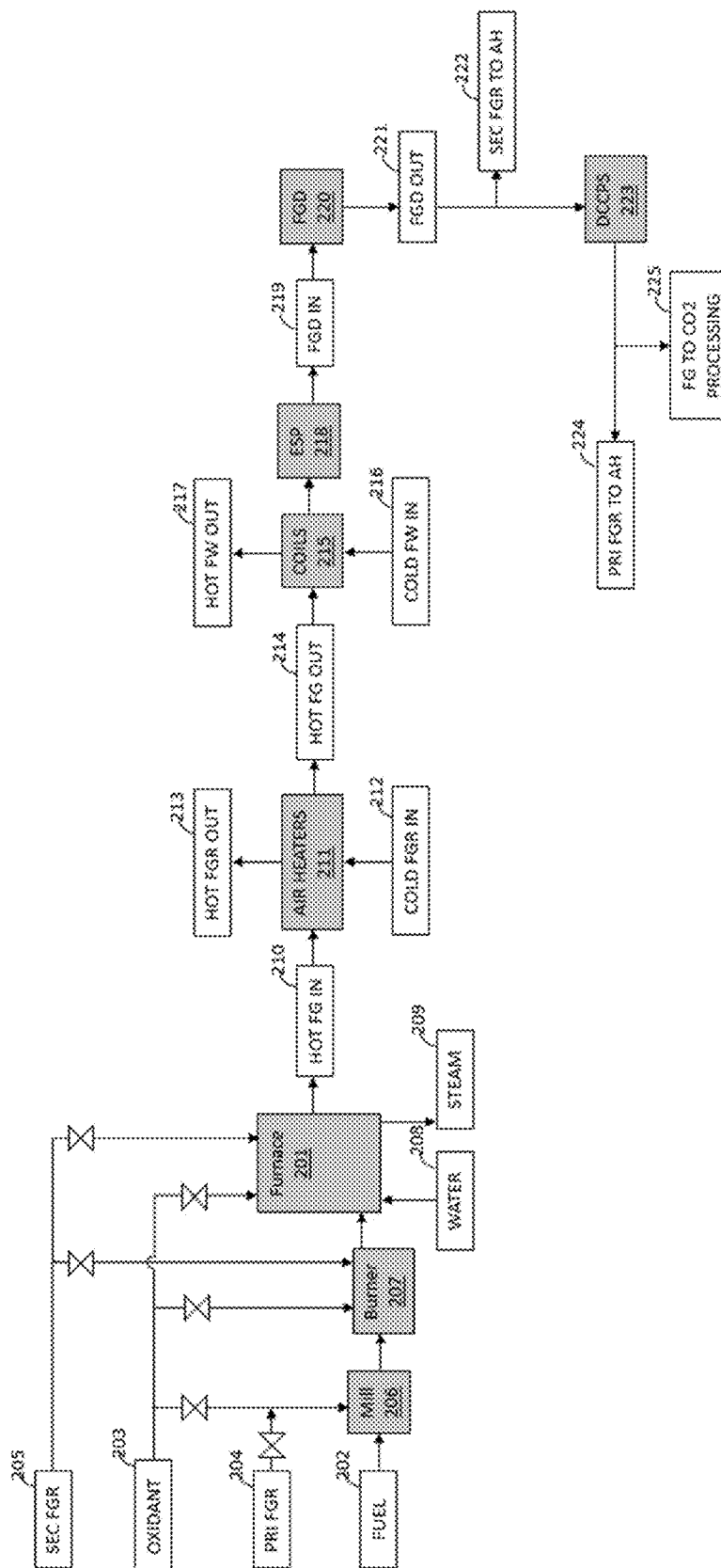


FIG. 10

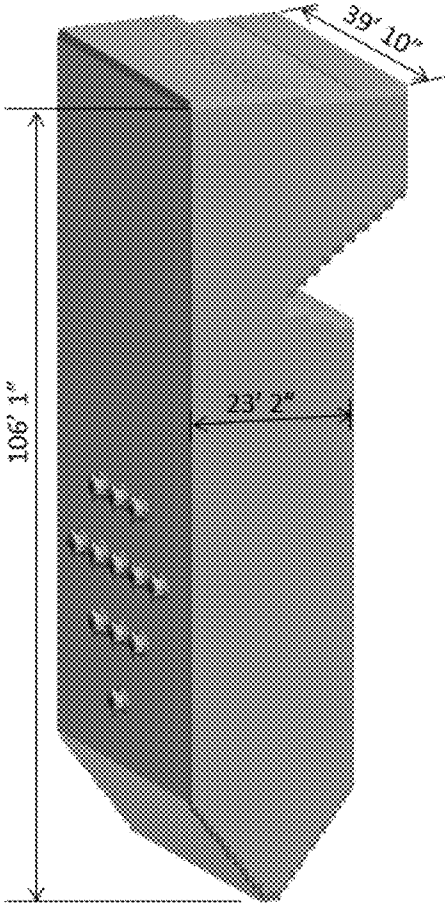


FIG. 11

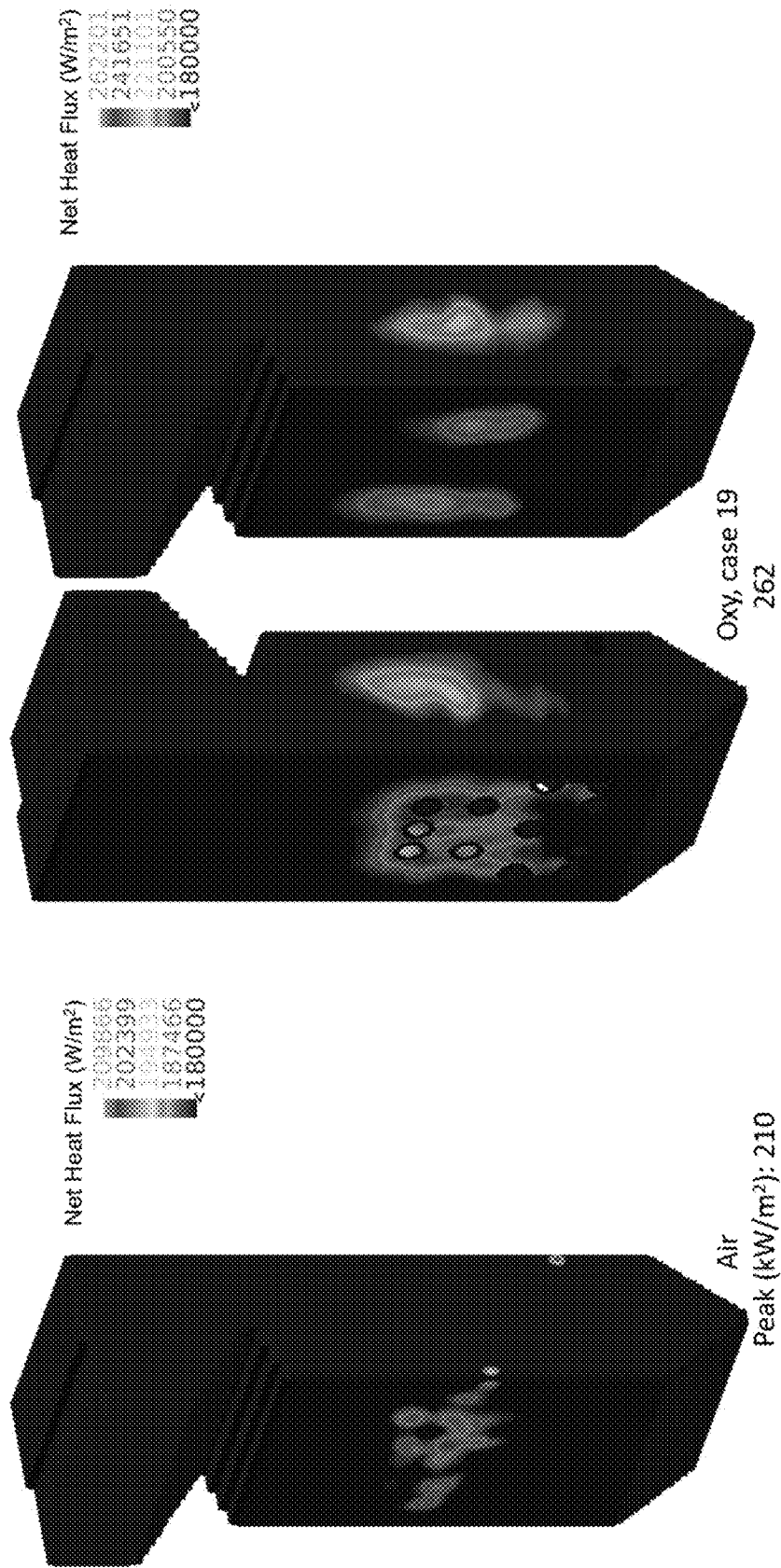


FIG. 12

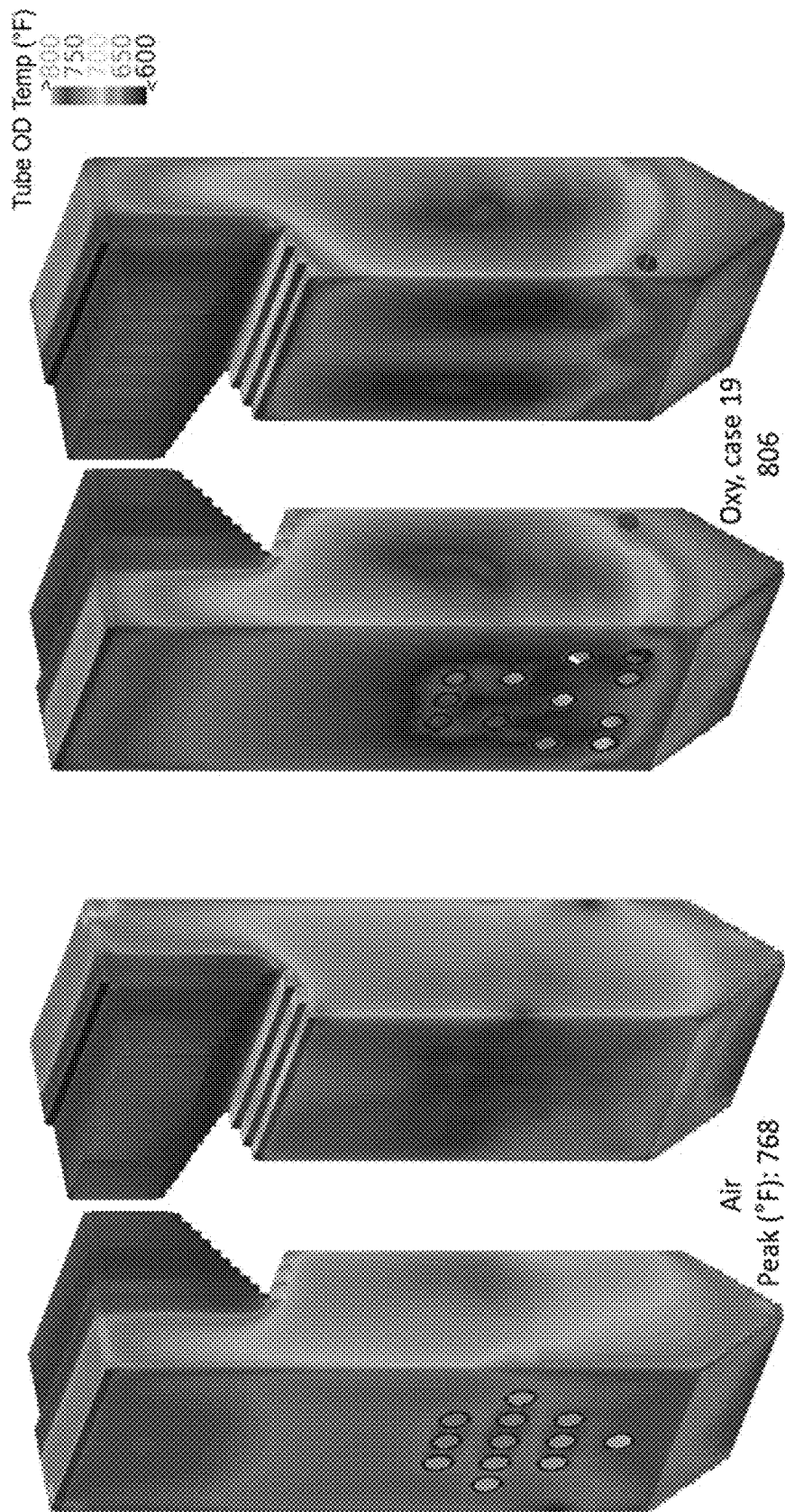


FIG. 13

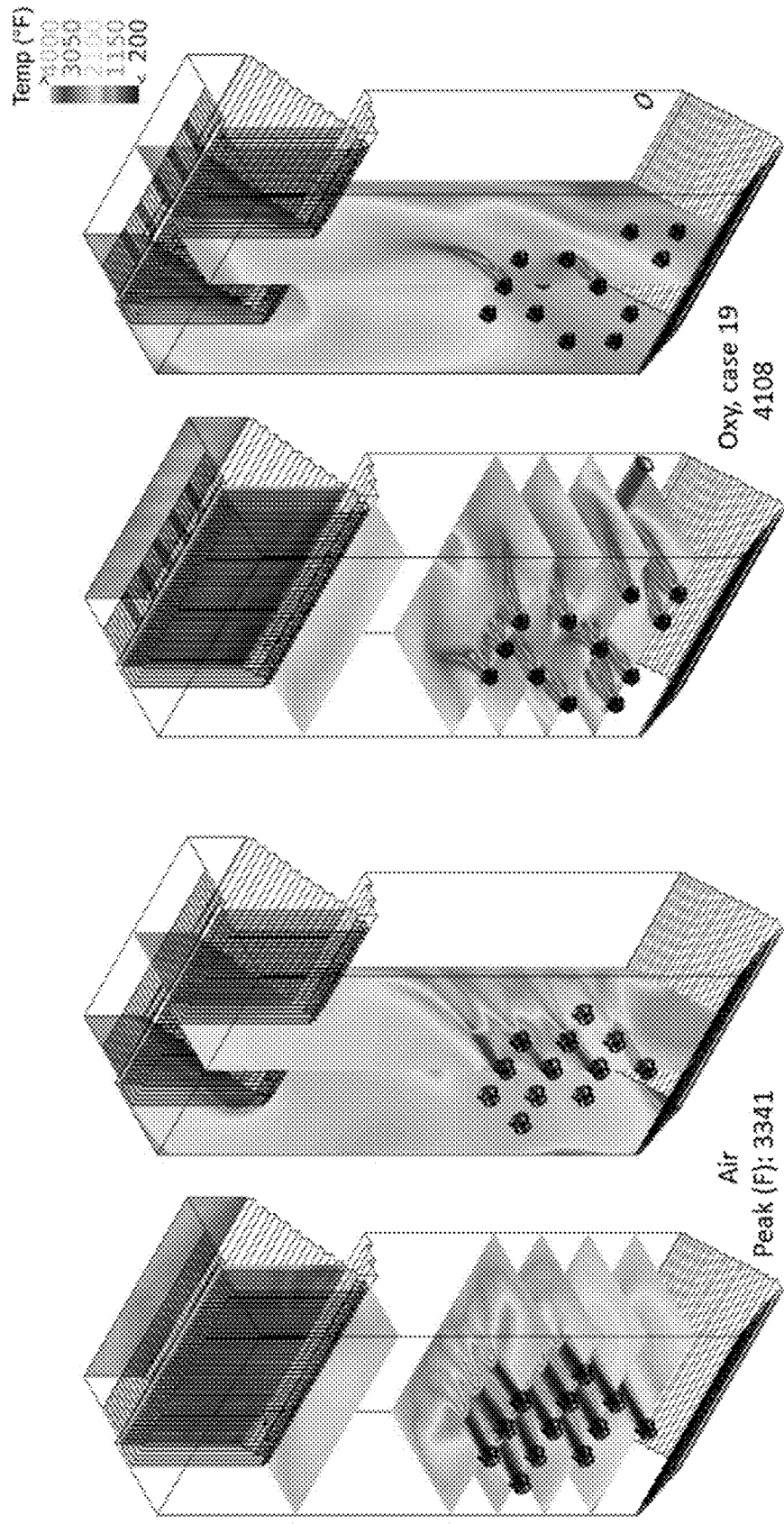


FIG. 14

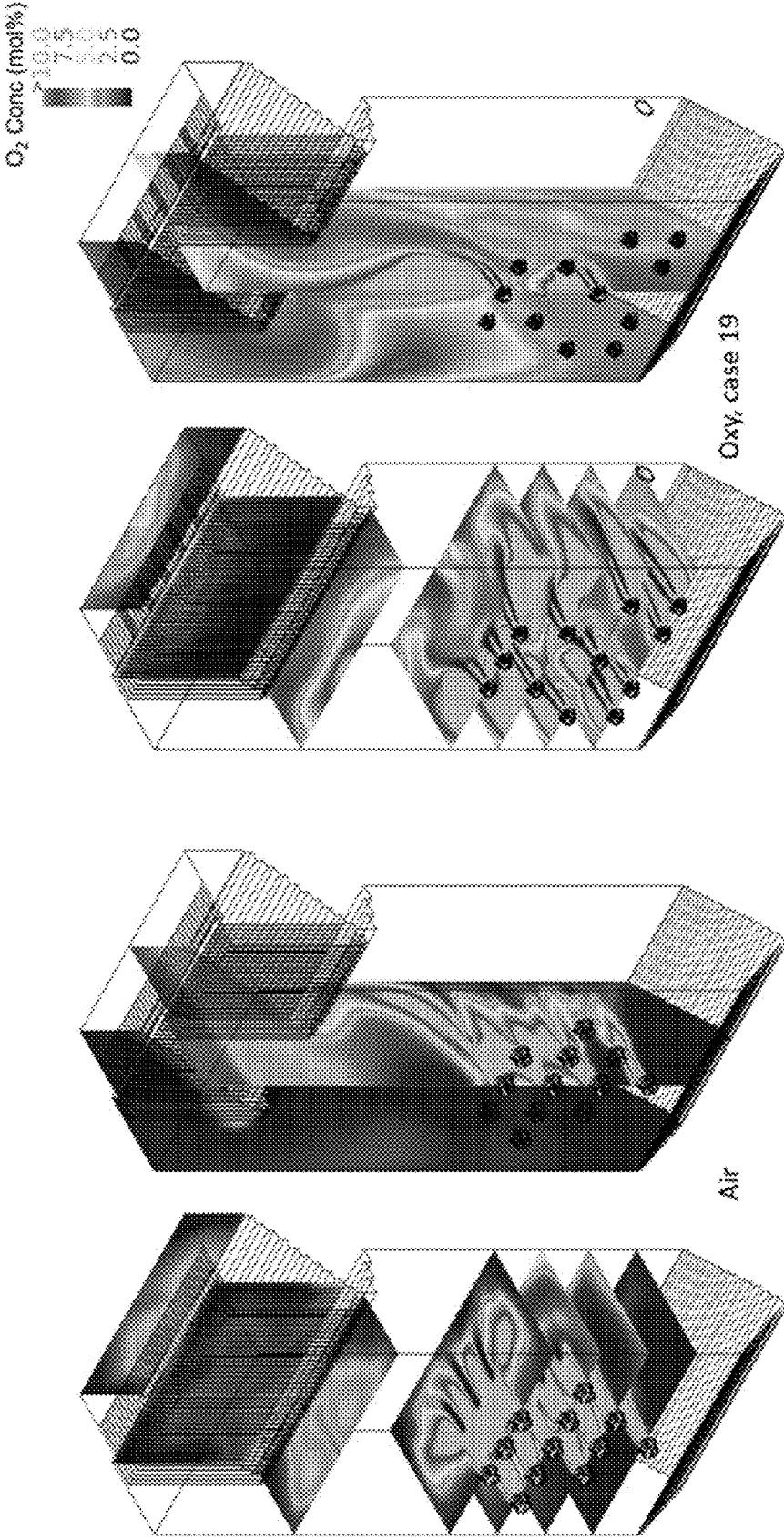


FIG. 15

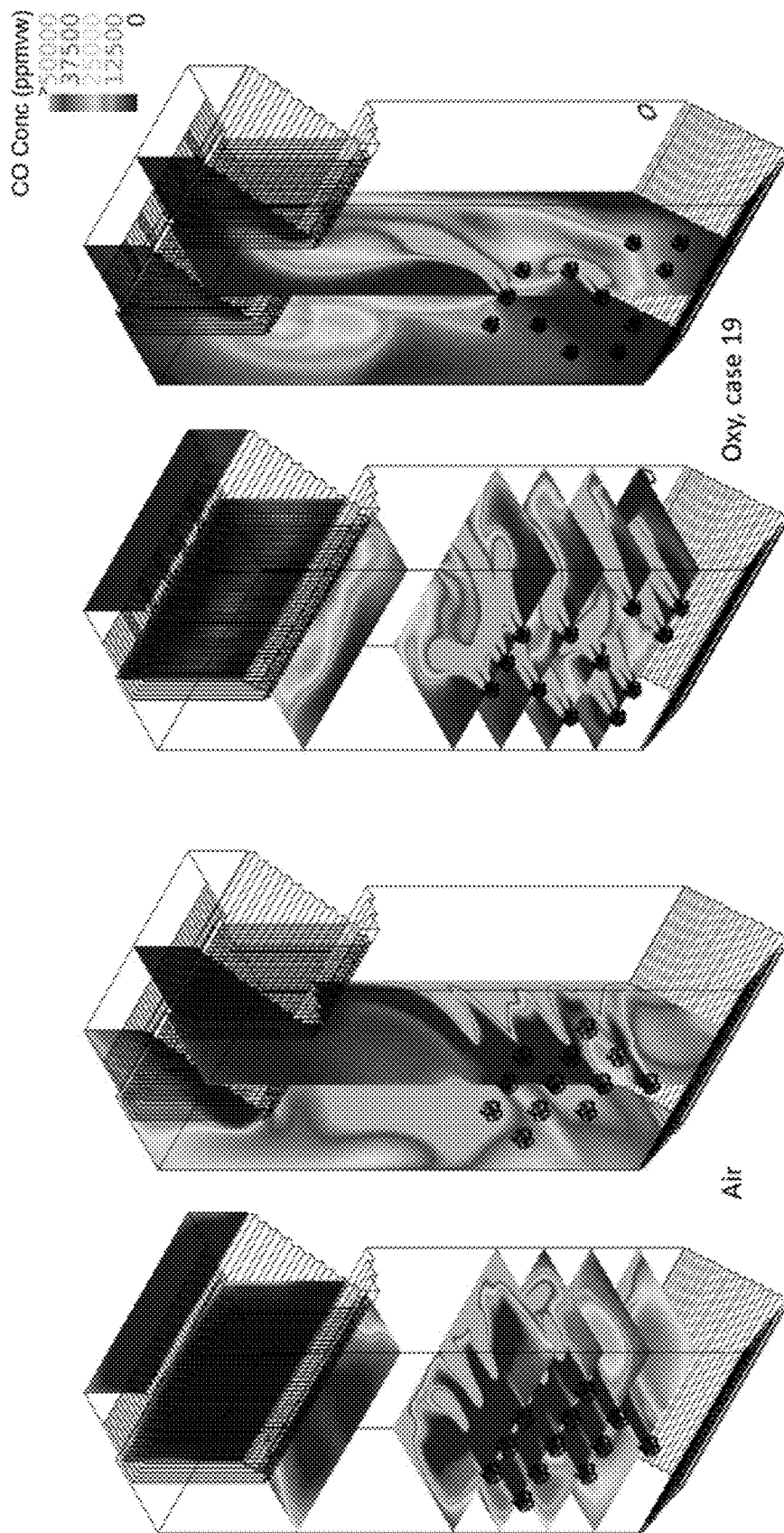


FIG. 16

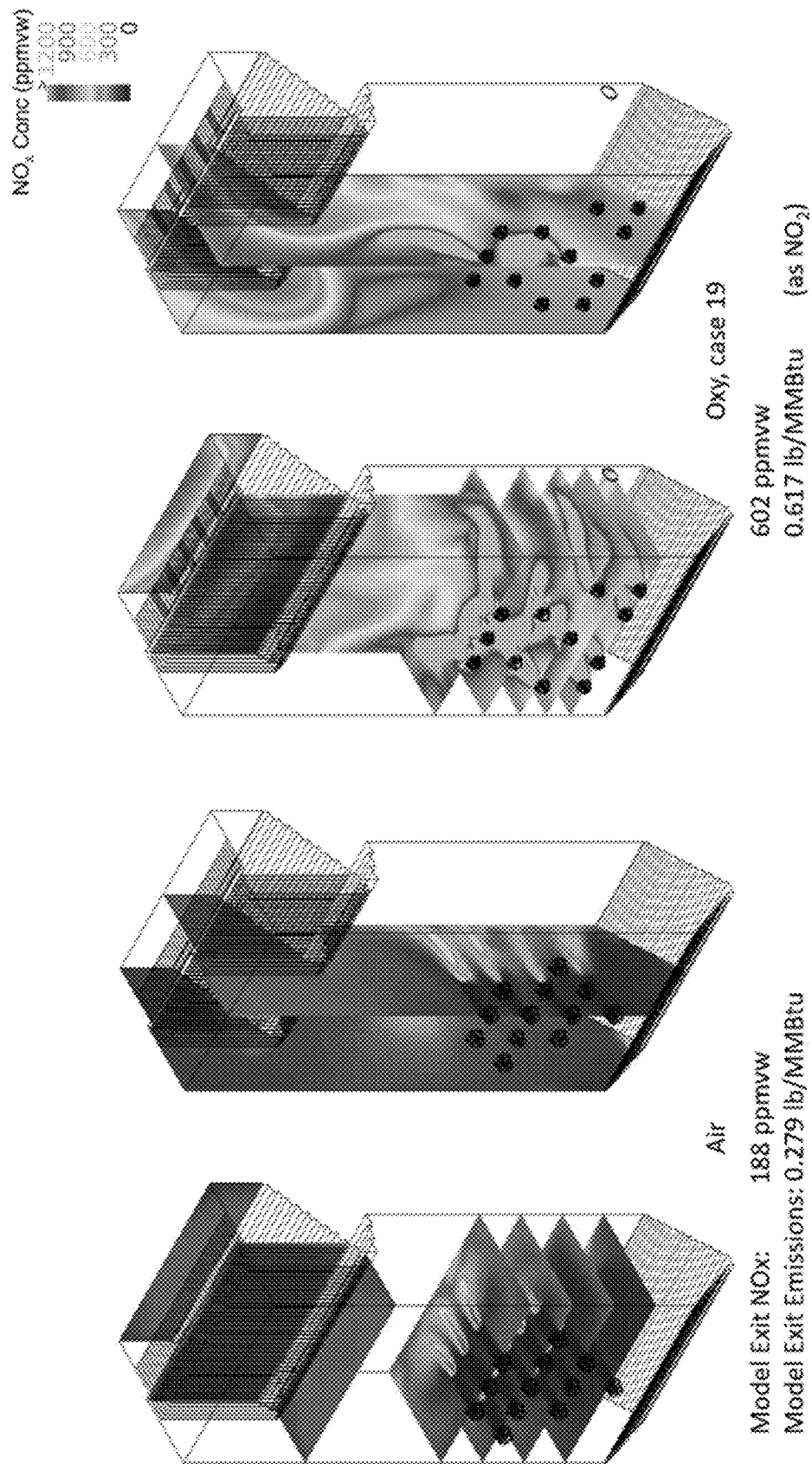


FIG. 17

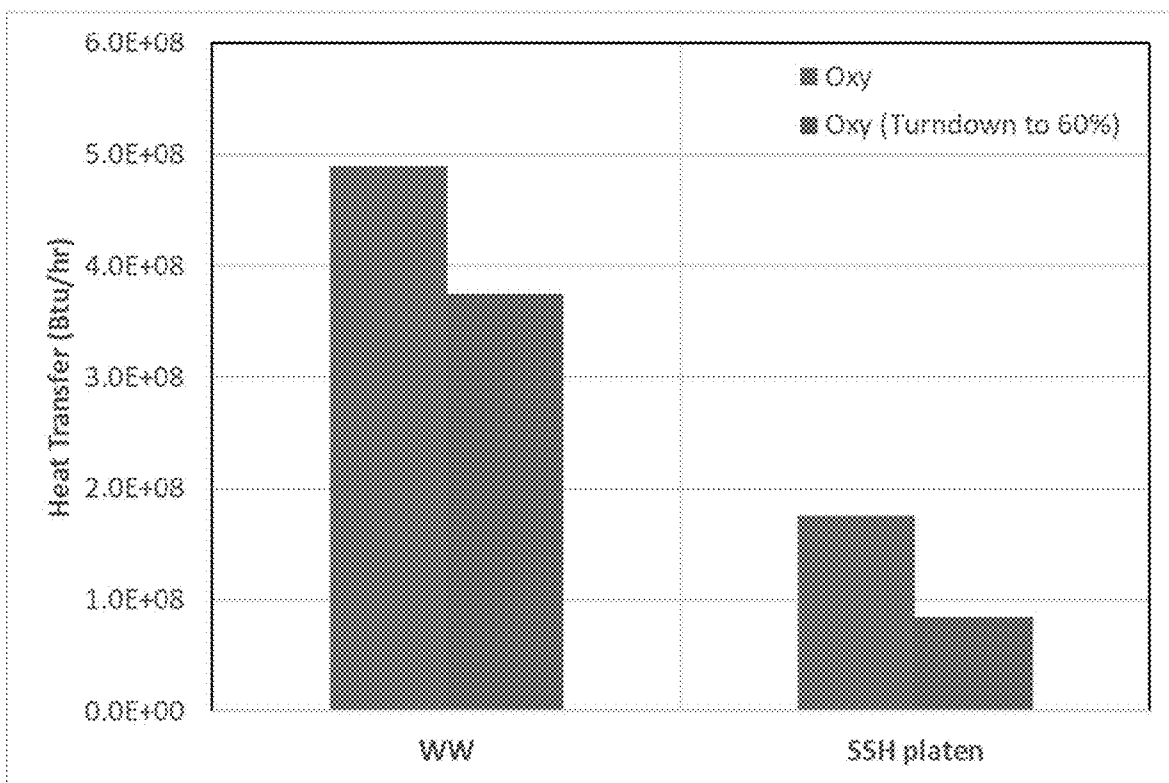


FIG. 18

COMBUSTION SYSTEM COMPRISING AN ANNULAR SHROUD BURNER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part application claiming priority to U.S. application Ser. No. 16/952,737, entitled "COMBUSTION SYSTEM COMPRISING AN ANNULAR SHROUD BURNER," filed on Nov. 19, 2020, which is a continuation of U.S. application Ser. No. 16/722,010, filed on Dec. 20, 2019, now U.S. Pat. No. 10,845,052, which issued on Nov. 24, 2020, the entirety of which is hereby incorporated by reference herein for all purposes.

TECHNICAL FIELD

[0002] The present disclosure relates to methods and systems for combustion and carbon capture, more particularly, methods and systems involving high flame temperature oxy-combustion of fuel and the efficient capture of carbon dioxide.

BACKGROUND

[0003] Fossil fuels are the main source of energy in the world today, particularly in the electrical power generation, industrial and transportation industries. However, due to the large CO₂ production associated with fossil fuel use, it is also considered by many as a major contributor to global warming. One of these fossil fuels is coal, where the future use of coal as a fuel for power generation and industrial applications depends on new economical technologies being made available to capture and store the CO₂ emitted as a product of the combustion process. These carbon capture technologies are commonly referred to as carbon capture and storage (CCS) and carbon capture utilization and storage (CCUS).

[0004] Some of the available technologies include air-fueled and oxy-fueled combustion technologies. In the case of air-fueled combustion (air comprises about 79% nitrogen and 21% oxygen), NO_x and other greenhouse gases such as CO₂ and SO₂ are produced as a result of the combustion process. The higher percentage of impurities for air-fueled combustion makes carbon capture (such as CCS and CCUS) more complicated and costly than that of oxy-fueled combustion. In addition to this disadvantage, air-fueled combustion suffers from lower fuel efficiency due to the amount of fuel required to heat the nitrogen present in the air.

[0005] A more advantageous system is the oxy-fuel combustion system (or oxy-combustion). In the case of oxy-combustion, oxygen that is >95% pure is used as the oxidant in the combustion process in lieu of air. The use of high purity oxygen results in a significantly lower percentage of impurities and higher concentrations of CO₂ and H₂O, thereby making processes such as CCS and CCUS more cost effective than that of air-fueled combustion. The CO₂ and H₂O can easily be separated and the CO₂ purified in a carbon purification unit (CPU) leaving high purity CO₂ that can be recycled, stored, or utilized as a valuable commodity as part of the CCS or CCUS processes. This reduces the amount of greenhouse gases produced.

[0006] However, this process requires pure oxygen (O₂), which is often obtained via cryogenic distillation. Cryogenic distillation is a very mature process that has been operational

since the 1930s, but is still an expensive process. In addition to an increased expense, traditional oxy-combustion suffers from other deficiencies, such as high capital costs, air ingress and the associated higher impurities, high oxygen requirements, and lower carbon capture, utilization, and sequestration of CO₂.

[0007] Regardless of the drawbacks associated with traditional oxy-combustion of fuels, it is still an improvement over air-fueled combustion. Thus, there is a desire to replace the air-fuel combustion burners present in the boilers and process heaters in existing fuel processing plants with the more environmentally friendly oxy-combustion burners.

[0008] Generally, the systems in the existing fuel processing plants were configured to provide optimal performance while limiting negative results associated with air-fueled combustion burners. Thus, replacing one burner with another is not easily accomplished, much less replacing an air-fueled with oxy-fueled combustion process. Potential drawbacks associated with this type of change include a significant change in the heat transfer between the various systems as well as an increased likelihood of component damage due to differing heating characteristics, stream flows, and stream characteristics. One reason for this difficulty is the fact that an oxy-combustion burner will produce a hotter flame temperature than a traditional air-fuel burner. For example, when an existing air-fueled combustion burner is replaced with an oxy-combustion burner, the peak temperature will increase, thus increasing the amount of heat transfer (heat flux) to the components surrounding the oxy-combustion burner. This requires modification of the existing parts of the plant, a process which is both time consuming and extremely expensive.

[0009] Reports on prior attempts to design an oxy-coal burner appropriate for application to different systems comprise overly complex designs (See U.S. Pat. Nos. 8,584,605, 7,028,622, and 6,843,185). This partly results from the nature of oxy-combustion, which involves burning of fuel using pure oxygen as the oxidant rather than air. Since heat from combustion does not go toward the heating of nitrogen in the air, flame temperatures with oxy-combustion increase dramatically. Still others have described oxy-combustion technology that uses minimal FGR and produces high temperature flames (see Gross in U.S. Pat. Nos. 6,436,337 and 6,596,220). However, the burners described in these publications have the potential to cause damage to the systems surrounding the oxy-coal burner due to the nature of their designs.

[0010] Others have tempered the oxy-combustion flame temperature by creating a synthetic air stream consisting of a mixture of oxygen and flue gas recycle (FGR) resulting in a lower flame temperature in addition to the use of a precombustor (see U.S. Pat. Nos. 9,243,799 and 8,689,710). While the burners described in U.S. Pat. Nos. 9,243,799 and 8,689,710 may operate at a much lower flame temperature and therefore may not necessarily cause damage to the system surroundings, they have other design and operational challenges. Large volumes of FGR may require additional energy to heat prior to entering the furnace (similar to an air preheater). Air ingress may also increase as FGR increases. More FGR leads to a large volume of flue gas leaving the furnace, which necessitates increased downstream equipment size (e.g., air pollution control devices, ductwork, fans, carbon capture and purification equipment).

[0011] In sum, the existing patents referenced above do not have burner design characteristics or operational approaches suitable to effectively utilize and regulate heat flux to the burner components and furnace walls when utilizing a high flame temperature oxy-combustion approach.

[0012] As such, there is a need for an oxy-combustion firing system that addresses the deficiencies of the prior art, namely the development of a burner design capable of efficiently and cost effectively producing and sustaining the high flame temperature oxy-combustion conditions for coal-firing. Further needed is an oxy-combustion firing system that is capable of replacing traditional air-fueled combustion burners in existing fuel combustion systems while simultaneously preventing damage to burner components and furnace internal surfaces arising from high heat fluxes.

SUMMARY

[0013] A carbon sequestration system is disclosed. In various embodiments, the system includes a furnace having an oxy-combustion burner; a mill configured to receive a fuel and to provide the fuel to the oxy-combustion burner; a waste heat recovery exchanger configured to receive a flue gas from the furnace; an electrostatic precipitator configured to receive the flue gas from the waste heat recovery exchanger; a direct contact cooler/polishing scrubber configured to receive the flue gas downstream of the waste heat recovery exchanger and to exhaust the flue gas as a cooled flue gas; a first cooled flue gas recycle supply stream configured to supply the cooled flue gas to a first flue gas recycle supply stream, the first flue gas recycle supply stream configured for input to a flue gas recycle heater and for output from the flue gas recycle heater as a heated flue gas recycle supply stream configured for input to at least one of an overfire air port of the furnace or the oxy-combustion burner as a secondary flue gas recycle stream, and a second flue gas recycle supply stream, the second flue gas recycle supply stream configured for input to the mill; and a second cooled flue gas recycle supply stream configured to supply the cooled flue gas to a CO₂ purification unit, the CO₂ purification unit configured to produce a purified CO₂ stream from the second cooled flue gas recycle stream for sequestration.

[0014] In various embodiments, a flue gas desulfurizer is in fluid communication with the electrostatic precipitator and the direct contact cooler/polishing scrubber. In various embodiments, the flue gas recycle heater is configured to receive the flue gas from the furnace to heat the first flue gas recycle supply stream to produce the heated flue gas recycle supply stream. In various embodiments, the heated flue gas recycle supply stream is configured to be provided to the mill as a primary flue gas recycle stream. In various embodiments, a flow temperature control valve is configured to mix a portion of the second flue gas recycle supply stream and the heated flue gas recycle supply stream to produce a cooled primary flue gas recycle stream. In various embodiments, the heated flue gas recycle supply stream is configured to be received by both the overfire air port of the furnace and the oxy-combustion burner as the secondary flue gas recycle stream. In various embodiments, the primary flue gas recycle stream is mixed or the cooled primary flue gas recycle stream is diluted with an oxidant.

[0015] In various embodiments, the oxy-combustion burner is an annular shroud burner, comprising a quarl, the

quarl having a diverging conical shape that is positioned to extend along a central axis and defining a combustion zone radially inward and downstream of a radially inner surface of the quart, the quarl extending from a burner face to a furnace interior wall; a first conduit, the first conduit positioned to extend along the central axis and configured to provide a first stream of oxygen into the combustion zone at the burner face; a second conduit, the second conduit positioned to extend along the central axis, radially outward of the first conduit, and configured to provide a mixed stream of a fuel and a carrier to the combustion zone at the burner face; a third conduit, the third conduit positioned to extend along the central axis, radially outward of the second conduit, and configured to provide a second stream of oxygen to the combustion zone at the burner face; and a fourth conduit, the fourth conduit positioned to extend along the central axis, radially outward of the third conduit, and configured to provide a stream of recycled flue gas in a form of a conical shroud that extends along the inner surface of the quarl, from the burner face to the furnace interior wall, the stream of recycled flue gas surrounding a peak flame temperature region within the combustion zone.

[0016] In various embodiments, the first stream of oxygen and the second stream of oxygen of the annular shroud burner comprise undiluted oxygen. In various embodiments, the first stream of oxygen and the second stream of oxygen of the annular shroud burner comprise an oxygen content of at least about 90%. In various embodiments, the carrier comprises a recycled flue gas. In various embodiments, the recycled flue gas comprises at least a portion of the secondary flue gas recycle supply stream. In various embodiments, the stream of recycled flue gas surrounding the peak flame temperature region within the combustion zone comprises at least a portion of the heated flue gas recycle supply stream.

[0017] A method for generating purified carbon dioxide for sequestration using a system comprising a furnace having an oxy-combustion burner, a mill configured to receive a fuel and to provide the fuel to the oxy-combustion burner, a waste heat recovery exchanger configured to receive a flue gas from the furnace, an electrostatic precipitator configured to receive the flue gas from the waste heat recovery exchanger, and a direct contact cooler/polishing scrubber configured to receive the flue gas downstream of the waste heat recovery exchanger and to exhaust the flue gas as a cooled flue gas is disclosed. In various embodiments, the method includes: supplying the cooled flue gas via a first cooled flue gas recycle supply stream to a first flue gas recycle supply stream, the first flue gas recycle supply stream configured to for input to a flue gas recycle heater and for output from the flue gas recycle heater as a heated flue gas recycle supply stream configured for input to at least one of an overfire air port of the furnace or the oxy-combustion burner as a secondary flue gas recycle stream, and a second flue gas recycle supply stream, the second flue gas recycle supply stream configured for input to the mill; and supplying the cooled flue gas via a second cooled flue gas recycle supply stream to a CO₂ purification unit, the CO₂ purification unit configured to produce a purified CO₂ stream from the second cooled flue gas recycle stream for sequestration.

[0018] In various embodiments, the oxy-combustion burner includes an annular shroud burner having a quarl, the quarl having a diverging conical shape that is positioned to extend along a central axis and defining a combustion zone radially inward and downstream of a radially inner surface

of the quarl, the quarl extending from a burner face to a furnace interior wall, and the method further includes: providing a first stream of oxygen into the combustion zone via a first conduit, the first conduit positioned to extend along the central axis and configured to open into the quarl at the burner face; providing a mixed stream of the fuel and a carrier to the combustion zone via a second conduit, the second conduit positioned to extend along the central axis, radially outward of the first conduit, and configured to open into the quarl at the burner face; providing a second stream of oxygen to the combustion zone via a third conduit, the third conduit positioned to extend along the central axis, radially outward of the second conduit, and configured to open into the quarl at the burner face; and providing a stream of recycled flue gas, that surrounds a portion of the combustion zone, via a fourth conduit, the fourth conduit positioned to extend along the central axis, radially outward of the third conduit, and configured to provide the stream of recycled flue gas in a form of a conical shroud that extends along the inner surface of the quarl, from the burner face to the furnace interior wall, the stream of recycled flue gas surrounding a peak flame temperature area within the combustion zone.

[0019] In various embodiments, the first stream of oxygen and the second stream of oxygen of the annular shroud burner comprise undiluted oxygen. In various embodiments, the first stream of oxygen and the second stream of oxygen of the annular shroud burner comprise an oxygen content of at least about 90%. In various embodiments, the carrier comprises a recycled flue gas. In various embodiments, the recycled flue gas comprises at least a portion of the secondary flue gas recycle supply stream. In various embodiments, the stream of recycled flue gas surrounding the peak flame temperature region within the combustion zone comprises at least a portion of the heated flue gas recycle supply stream.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] The accompanying drawings illustrate various embodiments employing the principles described herein and are a part of the specification. The illustrated embodiments are meant for description and not to limit the scope of the claims.

[0021] FIGS. 1A and 1B depict an annular shroud burner. FIG. 1A depicts the general configuration of the annular shroud burner. FIG. 1B depicts four specific areas of the annular shroud burner, specifically the center O₂ port, fuel annulus, outer O₂ annulus, and FGR annulus for localized cooling.

[0022] FIGS. 2A-2C depict different aspects of the annular shroud burner.

[0023] FIG. 3 shows a process flow diagram of a high flame temperature oxy-fired system.

[0024] FIG. 4 shows the gas temperature profile for the annular shroud burner with a peak temperature of 4,572° F. (2,522° C.) when firing a bituminous coal.

[0025] FIG. 5 shows the gas temperature profile for an oxy-combustion burner with discrete O₂ ports where the peak temperature is 4,581° F. (2,527° C.).

[0026] FIG. 6 shows the gas temperature profile for the annular shroud burner with a peak temperature of 4,133° F. (2,278° C.) when firing sub-bituminous coal.

[0027] FIG. 7 shows a model of the quarl surface temperature, where the quarl is in the annular shroud burner and the burner is a single burner model.

[0028] FIG. 8 shows a model of the gas temperature in a burner, where the burner is a single burner model. The turndown is 60% of a full load, but the shroud FGR flowrate was maintained and the peak temperature is 4,251° F. (2,344° C.).

[0029] FIG. 9 shows an energy balance summary for the boiler radiant and convective sections.

[0030] FIG. 10 shows a process flow diagram of the high flame temperature oxy-combustion system firing coal.

[0031] FIG. 11 shows the burner layout and geometry of a burner unit for a single wall fired sub-critical boiler.

[0032] FIG. 12 shows the net heat flux for a single wall fired sub-critical boiler.

[0033] FIG. 13 shows the tube OD surface temperature for a single wall fired sub-critical boiler.

[0034] FIG. 14 shows the gas temperature for a single wall fired sub-critical boiler.

[0035] FIG. 15 shows the O₂ concentration for a single wall fired sub-critical boiler.

[0036] FIG. 16 shows the CO concentration for a single wall fired sub-critical boiler.

[0037] FIG. 17 shows the NO_x concentration where the NO_x values are uncontrolled (no NO_x removal in the entire system) for a single wall fired sub-critical boiler.

[0038] FIG. 18 shows the net heat flux following turn-down.

[0039] FIG. 19 shows a process flow diagram of a carbon sequestration system using a high flame temperature oxy-combustion system for firing coal.

DETAILED DESCRIPTION

[0040] The subject matter disclosed herein includes a high flame temperature oxy-coal firing system designed to combust coal using undiluted oxygen and minimal flue gas recycle (FGR). In an embodiment, the system comprises a quadruple burner capable of producing an axial jet flame with a peak temperature in excess of 4,000° F. (2,204° C.). In a further embodiment, the amount of FGR distributed around the combustion zone may be regulated to ensure optimal cooling and shielding from the high temperature flame. This FGR distribution, referred herein as a shroud, surrounds the areas of peak flame temperature. This shroud functions to prevent damage to burner components and near-burner surfaces from extreme temperatures and heat fluxes while minimizing the impact on the peak flame temperature.

[0041] In another embodiment, an annular shroud burner system employing undiluted directed oxygen in combination with a complex mixing strategy is effective at producing a stable high flame temperature. Application of this technology to various systems, such as power production by steam generation, leads to a system with increases in efficiency, lower capital costs, and improved CO₂ capture and sequestration. The technology may also be used in greenfield applications or as a retrofit to existing steam generating power plants. The advantages of the technology are not limited to the power generation industry. Enhancing combustion of coal with pure oxygen has the potential to benefit any industry that uses the combustion of coal or other fossil fuels as a fuel source.

[0042] The present invention can be understood more readily by reference to the following detailed description of the invention and the Examples included therein.

[0043] Before the present systems, devices, or methods are further disclosed and described, it is to be understood that they are not limited to specific methods unless otherwise specified, as such may, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting. Although any methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, example systems, devices, and methods are now described.

[0044] While aspects of the present invention can be described and claimed in a particular statutory class, such as the system statutory class, this is for convenience only and one of skill in the art will understand that each aspect of the present invention can be described and claimed in any statutory class. Unless otherwise expressly stated, it is in no way intended that any method or aspect set forth herein be construed as requiring that its steps be performed in a specific order. Accordingly, where a method claim does not specifically state in the claims or descriptions that the steps are to be limited to a specific order, it is no way intended that an order be inferred, in any respect. This holds for any possible non-express basis for interpretation, including matters of logic with respect to arrangement of steps or operational flow, plain meaning derived from grammatical organization or punctuation, or the number or type of aspects described in the specification.

[0045] Throughout this application, various publications are referenced. The disclosures of these publications in their entireties are hereby incorporated by reference into this application in order to more fully describe the state of the art to which this pertains. The references disclosed are also individually and specifically incorporated by reference herein for the material contained in them that is discussed in the sentence in which the reference is relied upon.

A. DEFINITIONS

[0046] Listed below are definitions of various terms used to describe this invention. These definitions apply to the terms as they are used throughout this specification, unless otherwise limited in specific instances, either individually or as part of a larger group.

[0047] As used in the specification and the appended claims, the singular forms “a,” “an” and “the” include plural referents unless the context clearly dictates otherwise.

[0048] Ranges can be expressed herein as from “about” one particular value, or to “about” another particular value. When such a range is expressed, another aspect includes from the one particular value or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent “about,” it will be understood that the particular value forms another aspect. It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint. It is also understood that there are a number of values disclosed herein, and that each value is also herein disclosed as “about” that particular value in addition to the value itself. For example, if the value “10” is disclosed, then “about 10” is also disclosed. It is also understood that each unit between two particular units are also disclosed. For example, if 10 and 15 are disclosed, then 11, 12, 13, and 14 are also disclosed. Further, as used herein, the term “about,” when referring to a value, is meant to encompass variations of, in some embodiments $\pm 20\%$, in

some embodiments $\pm 15\%$, in some embodiments $\pm 10\%$, in some embodiments $\pm 5\%$, in some embodiments $\pm 1\%$, in some embodiments $\pm 0.5\%$, and in some embodiments $\pm 0.1\%$ from the specified amount, as such variations are appropriate to perform the disclosed methods or employ the disclosed compositions.

[0049] Where a range of values is provided, it is understood that each intervening value, to the tenth of the unit of the lower limit, unless the context clearly dictates otherwise, between the upper and lower limit of the range and any other stated or intervening value in that stated range, is encompassed. The upper and lower limits of these small ranges which may independently be included in the smaller ranges is also encompassed, subject to any specifically excluded limit in the stated range. Where the stated range includes one or both of the limits, ranges excluding either or both of those included limits are also included.

[0050] As used herein, the terms “optional” or “optionally” mean that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where said event or circumstance occurs and instances where it does not.

[0051] The term “comprising” (and its grammatical variations) as used herein is used in the inclusive sense of “having” or “including” and not in the exclusive sense of “consisting of.”

[0052] As used herein, the term “fuel” refers to any fuel suitable for combustion purposes. For example, the disclosure may be used with many types of fuels, including but not limited to: natural gas, hydrogen, refinery off gas, refinery fuel gas, blast furnace gas, propane, fuel oils, coal (such as peat, anthracite, semi-anthracite, super anthracite, bituminous, sub-bituminous, semi-bituminous, and lignite coals); tar; bitumen; petroleum coke; paper mill sludge solids and sewage sludge solids; wood; peat; grass; and combinations and mixtures of all of those fuels.

[0053] As used herein, the term “oxygen” refers to an oxidizer with an O_2 concentration greater than about 30 mol %; typically greater than about 90 mol % and includes oxygen FGR. As used herein, the term oxy/coal combustion refers to coal combustion in oxygen, the term air/coal combustion refers to coal combustion in air, the term oxy/fuel combustion refers to fuel combustion in oxygen, and the term air/fuel combustion refers to fuel combustion in air.

[0054] As used herein, the term “ O_2 stream” refers to a stream of oxygen (02) that is at least 90 mol % oxygen.

[0055] As used herein, the term “substantially pure oxygen” refers to the degree of purity of oxygen as needed to provide the correct ratio of fuel and oxygen for the desired burn and by-products without departing from the scope of the present invention. Non-limiting examples of substantially pure oxygen are 90% or 99% pure.

[0056] As used herein, the term “combustion fluid” refers to a fluid formed from or mixed with the products of combustion, which may be utilized for radiant and convective heat transfer. The term is not limited to the products of combustion and may include fluids mixed with or otherwise traveling through at least a portion of combustion system.

[0057] As used herein, the term “recycled flue gas” or “RFG” refers to fluid exiting at any suitable location along (including the end) the convective section that is recirculated to any portion of the system. If desired, oxygen can be added

to the RFG at any suitable location (e.g., the RFG can comprise up to 30 mole % O₂ prior to being introduced into the burner or precombustor).

[0058] As used herein, the term “flue gas recycle” or “FGR” refers to a configuration permitting the combustion fluid to be recycled into recycled flue gas. While any suitable flue gas source can be employed (including, without limitation, flue gas from an adjoining or a distinct process), typically the flue gas comprises products of combustion from usage of the inventive system.

[0059] As used herein, the term “precombustor” refers to an apparatus where burner streams are mixed and ignited prior to entering the burner or furnace. If present, the precombustor may be physically located before a burner. Examples of such precombustors are described in U.S. Pat. No. 9,243,799.

[0060] As used herein, the terms “conduit” or “pipe” are used interchangeably and refer to a passageway for conveying fuel, an O₂ stream, or other material from one area to another.

B. ANNULAR SHROUD BURNER

[0061] a. Burner Design

[0062] Disclosed herein is a high flame temperature oxy-combustion burner, referred to herein as an annular shroud burner. Turning to the figures, one embodiment of the annular shroud burner is depicted in FIGS. 1A and 1B. More specifically, FIG. 1B shows the annular shroud burner with a quadruple concentric burner design with an O₂ inner annulus **301**, followed by a fuel annulus for coal **302**, then an O₂ outer annulus **303**, and finally an outer flue gas recycle (FGR) annulus **304**. The outer FGR annulus **304** provides local cooling while minimizing negative impacts from the high temperature flame. These negative impacts can include an alteration in flame shape or temperature. In an embodiment, the FGR annulus **304** creates a stream of gas, referred to herein as a shroud. The annular shroud burner also comprises a quarl **305**.

[0063] The quarl **305** provides a key surface for diffusion of heat during the combustion process. In an embodiment, the quarl is designed for high temperature operations and penetrates a furnace wall through which fuel and oxidant are injected. The quarl may be a diverging conical shape that extends from the burner face to the furnace interior wall. The shape of the quarl allows for aerodynamic flame stabilization through recirculation zones. In an embodiment, the quarl provides a surface for the diffusion of heat, resulting in reduced heat flux to near-burner surfaces. In an embodiment, the quarl provides additional protection of surrounding materials from the high flame temperatures achieved with the annular shroud burner.

[0064] As disclosed in more detail herein, the multi-register annular shroud burner allows the heat release and heat flux to be stretched out to avoid damage to near-burner surfaces while still producing flame stability. Specifically, the outer FGR annulus **304** is capable of providing adequate cooling to the burner and near-burner surfaces while keeping surface temperatures within tolerable limits of materials conventionally used in an industrial furnace. This annular shroud burner thus provides high flame temperatures exceeding 4,000° F. (2,204° C.) while simultaneously preventing damage to burner components and furnace internal surfaces arising from high heat fluxes.

[0065] A resultant functional aspect of the annular shroud burner is that it extracts a maximum amount of energy (in the form of heat transfer from the combustion of products) from the combustion process, without adversely affecting the high flame temperature or systems surrounding the burner. Thus, maximum practicable use of the higher flame temperatures is achieved. For example, the annular shroud burner provides a considerably larger proportion of heat transfer from the combustion products to the desired areas (such as boiler tubes or working fluid) without unwanted radiant heat flux to undesired areas, when compared to more traditional burner designs.

[0066] Other advantages observed with the currently disclosed annular shroud burner include: ease of introduction of fuel, oxygen and flue gas; simpler design than prior burner designs; improved ease of control of many properties, such as flow rate and source of gas; high temperature flame that improves radiant heat transfer and efficiency; a novel shroud cooling design to minimize flame temperature impacts for maximizing efficiency; reduction in radiant heat flux; improved flame characteristics such as peak flame temperature, flame shape and stability; and the ability to use reclaimed flue gas.

[0067] It is known that as temperature increases, the radiant heat transfer is proportional to T⁴, where T=the flame temperature. Thus, as described in U.S. Pat. No. 9,353,945, the radiant heat transfer increases with the increase of flame temperature, thereby increasing overall system efficiency.

[0068] In an embodiment, as schematically represented in FIGS. 2A and 2B, is the annular shroud burner. FIG. 2A shows an embodiment of the annular shroud burner with four registers. FIG. 2B shows the same annular shroud burner with fuel **310**, FGR **320**, and O₂ **331** and O₂ **336**. Fuel **310** flows through fuel conduit **312** to fuel annulus **302**. O₂ **331** flows through conduit **330** to O₂ inner annulus **301**. O₂ **336** flows through conduit **335** to O₂ outer annulus **303**. FGR **320** flows through conduit **325** to FGR annulus **304**. FIG. 2C shows a front view of the annular shroud burner with the exit points for the fuel **310**, the FGR **320**, and O₂ **331** and O₂ **336**.

[0069] In an embodiment, the annular shroud burner flow schematic is depicted in FIG. 3. An ignitor **315** is located at the center of the burner. In an embodiment, the fuel **310**, such as coal, is combined with a carrier **311** and introduced to the burner through conduit **312**, which feeds to the fuel annulus **302**. In an embodiment, carrier **311** is recycled flue gas. In a further embodiment, the recycled flue gas is treated recycle flue gas, where treated recycle flue gas has been dehydrated and impurities removed as part of the CO₂ capture process. In a separate portion of the annular shroud burner, FGR **320** is fed through an FGR conduit **321** and then fed through conduit **325** to FGR annulus **304**. In a further embodiment, oxygen is mixed with the flue gas.

[0070] In an embodiment, an O₂ conduit supplies two separate paths. One path feeds an undiluted O₂ stream through conduit **330** to O₂ inner annulus **301**. In the other path, an undiluted O₂ stream is delivered through conduit **335** to O₂ outer annulus **303** which is immediately outside of fuel conduit **312** (leading to fuel annulus **302**). In an embodiment, the O₂ streams are derived from the same source. In another embodiment, the O₂ streams are derived from alternate sources. In an embodiment, O₂ outer annulus **303** is located between fuel annulus **302** and FGR annulus **304**. In a preferred embodiment, the O₂ streams are on both sides of fuel **310** leading to fuel annulus **302**. This configura-

ration provides enhanced flame stability and control. In contrast to a diluted O₂ stream, the undiluted O₂ streams used in an embodiment allow peak flame temperatures to exceed 4,000° F. (2,204° C.).

[0071] In an embodiment, the fuel **310** may be a fossil fuel. Fossil fuels comprise oil, coal, and natural gas. In an embodiment, the fuel **310** may be coal. The coal may be peat, anthracite, semi-anthracite, super anthracite, bituminous, sub-bituminous, semi-bituminous, or lignite coals. As a point of reference, the U.S. coal production in 2010 by coal type is further described. The production by tonnage comprised 45% bituminous, 47% sub-bituminous, 7% lignite, and 0.2% anthracite. The production by total energy was 54% bituminous, 41% sub-bituminous, 4.7% lignite, and 0.3% anthracite. In an embodiment, the fuel is bituminous or sub-bituminous coal.

[0072] Fuel, oxygen, and recycled flue gas are connected and supplied to their respective conduits or pipes in accordance with conventional apparatus and methods. Each stream is fed directly into the combustion zone **350** where the fuel reacts with the oxidant and the shroud FGR acts as a temperature shield. When the oxygen and fuel react in the annular shroud burner, the fuel is combusted. The oxygen and fuel reaction can be initiated by heat absorbed from an outside source or by a distinct energy source such as an ignitor or pilot flame. In an embodiment, the oxygen and fuel reaction are initiated by an ignitor **315**. In an embodiment, ignitor **315** is located at the center of the annular shroud burner.

[0073] In addition to supplying the motive force for fuel transport, the FGR **320** can be directed to the FGR annulus **304**, which provides protection to burner internals and near-burner surfaces from the high heat fluxes produced. The inlets for each stream into the furnace are configured such that the flame produced is an axial jet that extends the rate of mixing of the fuel and O₂ in the furnace. The resultant heat release profile is extended through elongation compared to other burner designs configured to rapidly mix fuel and oxidant that involve swirl or a blunt object. This extended heat release profile provides protection from the intense radiant fluxes created by the high temperature flames.

[0074] In a further embodiment, the annular shroud burner comprises a control scheme that individually regulates the flow of fuel, the flow of FGR, and the flow of O₂ as required to control the ratio of FGR flow to fuel flow and the ratio of fuel flow to O₂ flow.

[0075] The flow rate of the O₂ streams is controlled such that the flow rate is in the range from about 25 ft/s to about 125 ft/s. In an embodiment the flow rate is in the range from 30 to 110 ft/s, 40 to 90 ft/s, or 50 to 70 ft/s. In an embodiment, the flow rate is greater than about 30 ft/s, 40 ft/s, 50 ft/s, 60 ft/s, 70 ft/s, 80 ft/s, 90 ft/s, or 100 ft/s. In an embodiment, the flow rate is about 30 ft/s, 35 ft/s, 40 ft/s, **45**, ft/s, 50 ft/s, 55 ft/s, 60 ft/s, 65 ft/s, 70 ft/s, 75 ft/s, 80 ft/s, 85 ft/s, 90 ft/s, 95 ft/s, 100 ft/s, 105 ft/s, or 110 ft/s.

[0076] In an embodiment, the percentage of oxygen in the O₂ streams may be at least 90% oxygen. In embodiments, the O₂ stream may be at least about 91%, at least about 92%, at least about 93%, at least about 94%, at least about 95%, at least about 96%, at least about 97%, at least about 98%, at least about 99%, at least about 99.5%, at least about 99.6%, at least about 99.7%, at least about 99.8%, or at least about 99.9% oxygen. The O₂ stream may contain between 90% to 100%, 95% to 100%, 97% to 100%, 98% to 100%,

or 99% to 100% oxygen. In some embodiments, the O₂ stream may contain between 91% to 99.5%, between 92% to 99%, between 93% to 98%, or between 94% to 97% oxygen.

[0077] The percentage of oxygen in the O₂ streams may be adjusted to control the flame temperature. In an embodiment, the use of undiluted O₂ streams allows the peak flame temperature of the annular shroud burner to be greater than 4,000° F. In contrast, when a stream of O₂ is diluted with other gases or contains less than 90% oxygen, peak flame temperatures of greater than 4,000° F. cannot be obtained.

[0078] The flow rate of the primary fuel is controlled such that the flow rate is in the range from about 20 ft/s to about 150 ft/s. In an embodiment the flow rate is in the range from 30 to 125 ft/s, 40 to 100 ft/s, or 50 to 75 ft/s. In an embodiment, the flow rate is greater than about 30 ft/s, 40 ft/s, 50 ft/s, 60 ft/s, 70 ft/s, 80 ft/s, 90 ft/s, 100 ft/s, 110 ft/s, 120 ft/s, 130 ft/s, or 140 ft/s. In an embodiment, the flow rate is about 30 ft/s, 35 ft/s, 40 ft/s, **45**, ft/s, 50 ft/s, 55 ft/s, 60 ft/s, 65 ft/s, 70 ft/s, 75 ft/s, 80 ft/s, 85 ft/s, 90 ft/s, 95 ft/s, 100 ft/s, 105 ft/s, 110 ft/s, 115 ft/s, 120 ft/s, 125 ft/s, 130 ft/s, 135 ft/s, 140 ft/s, 145 ft/s, or 150 ft/s. In an embodiment, the flow rate of the fuel stream is directly related to the type of fuel used. In an embodiment, the fuel flow rate may result in a change in position for where the flame originates. In an embodiment, the flame originates at the burner face. In another embodiment, the flame originates at a position moved away from the burner face. When the annular shroud burner is installed in a fuel processing plant and in the vicinity of a boiler, this is seen as the flame origination point moves away from the burner face towards the boiler.

[0079] In an embodiment, the percentage of oxygen in the carrier is between 0% and 30% oxygen. In embodiments, the percentage of oxygen may be from 0% to 3%, from 3% to 10%, from 10% to 20%, or from 20% to 30%. In alternate embodiments, the percentage of oxygen is from about 3% to 25%, from about 5% to 20%, from about 10% to 15%, or from 10% to 23.5%. In embodiments, the percentage of oxygen is about 0%, 1%, 2%, 3%, 4%, 5%, 10%, 15%, 20%, 23.5%, 25%, or 30%. In some embodiments, the percentage of oxygen is at least about 1%, at least about 5%, at least about 10%, at least about 15%, at least about 20%, or at least about 23.5%. In an embodiment, the percentage of oxygen is less than about 30%, less than about 23.5%, less than about 20%, less than about 15%, less than about 10%, less than about 5%, less than about 3%, or less than about 1%. The amount of oxygen present has an effect on the target peak flame temperature. In an embodiment, the percentage of oxygen is variable, for example where the percentage of oxygen is at 23.5% for a period of time and then the percentage of oxygen is reduced, wherein such reduction may be to about 0% oxygen.

[0080] Use of high purity oxygen (>95%) has several advantages when compared to air fired burners. One is that when placed into a boiler system, the oxy-fuel combustion may allow for the boiler to be physically smaller than a conventional boiler. That is, because oxygen rather than air is used as the oxidizing agent (combustion agent), the entirety of the oxidizing agent is available for combustion and the volume of gas input to the boiler is less (up to 21% less) than would be needed if air was used as the oxidizing agent. Thus, the boiler could be considerably smaller because substantially high purity oxygen rather than air is used.

[0081] The flow rate of the FGR stream **320**, with or without additional O₂ streams, is controlled such that the flow rate is in the range from about 10 ft/s to about 75 ft/s. In an embodiment, the flow rate is in the range from 10 to 30 ft/s, 30 to 50 ft/s, or 50 to 75 ft/s. In an embodiment, the flow rate is greater than about 10 ft/s, 20 ft/s, 30 ft/s, 40 ft/s, 50 ft/s, or 60 ft/s. In an embodiment, the flow rate is about 10 ft/s, 15 ft/s, 20 ft/s, 25 ft/s, 30 ft/s, 35 ft/s, 40 ft/s, 45 ft/s, 50 ft/s, 55 ft/s, 60 ft/s, 65 ft/s, 70 ft/s, or 75 ft/s.

[0082] In an embodiment, the percentage of FGR in the FGR stream **320** may be at least 90%. In embodiments, the FGR may be at least about 91%, at least about 92%, at least about 93%, at least about 94%, at least about 95%, at least about 96%, at least about 97%, at least about 98%, at least about 99%, at least about 99.5%, at least about 99.6%, at least about 99.7%, at least about 99.8%, or at least about 99.9%. The FGR stream may contain between 90% to 100%, 95% to 100%, 97% to 100%, 98% to 100%, or 99% to 100% oxygen. In some embodiments, the FGR stream may contain between 91% to 99.5%, between 92% to 99%, between 93% to 98%, or between 94% to 97%.

[0083] In an embodiment, the oxygen to fuel ratios may be varied. This ratio may depend upon the purity of the oxygen supply and the nature of the fuel. For example, in an embodiment where the oxygen is 100% pure, the oxygen/fuel ratio may be about 2:1. Those skilled in the art will understand that the ratios may vary depending on the purity of the fuel and oxygen and the ratios may be adjusted accordingly. In an embodiment, the ratio of oxygen to fuel is about 1:1, about 1.5:1, about 2:1, about 2.5:1, or about 3:1.

[0084] The proportion of oxygen to fuel provides a number of advantages. For example, approximately stoichiometric proportions provide for complete combustion of the fuel, thus resulting in substantially smaller volume of impurities, such as NO_x and other noxious emissions. Further, accurately controlling the ratio of oxygen to fuel facilitates complete combustion of the fuel.

[0085] In an embodiment, the conduits **312**, **325**, **330**, and **335** may comprise different streams than described above. For example, fuel conduit **312** may comprise an O₂ stream rather than a fuel stream. In an alternative embodiment, O₂ conduit **330** may comprise a fuel stream. Such examples are not intended to be limiting as feeding alternate streams through the various conduits is possible in the annular shroud burner.

[0086] The annular shroud burner disclosed herein provides a design that offers advantages not just in terms of simplicity, but in the uniformity of O₂ and FGR distribution. In an embodiment, the design simplifies the delivery of O₂ and FGR by replacing individual O₂ and FGR ports with annular registers. Thus, in an embodiment, the annular shroud burner may be described as a multi-register axial jet burner which allows the heat release and heat flux to be stretched out to avoid damage to near-burner surfaces while still producing stable flames. Further, the outer annulus **304** of FGR is capable of providing adequate cooling to the burner and near-burner surfaces, thereby keeping surface temperatures within tolerable limits of materials conventionally used in an industrial furnace.

[0087] In a further embodiment, the annular shroud burner does not comprise a precombustor.

[0088] In an alternate embodiment, FGR may be added into either of the O₂ streams.

[0089] In a further embodiment, the streams **310**, **320**, **331**, or **336** avoid the inclusion of nitrogen associated with air. In embodiments, the streams **310** and **320** can comprise less than about 20% air, less than about 15% air, less than about 10% air, less than about 5% air, or less than about 1% air. In embodiments, the streams **310**, **320**, **331**, or **336** comprise about 0% air.

[0090] b. Flame Characteristics of the Annular Shroud Burner

[0091] A firing system designed to produce flame temperatures more than 4,000° F. (2,204° C.) must be configured such that it would prevent damage to burner components and furnace internal surfaces arising from high heat fluxes. The currently disclosed annular shroud burner accomplishes this goal by surrounding the high flame temperature areas with a cooler stream of gas, termed the shroud. The presence of the shroud reduces the exposure of surrounding systems to high heat flux and reduces damage when compared to traditional burner designs.

[0092] As detailed further herein is heat flux data for undiluted oxygen inputs under oxy-coal combustion conditions. Design considerations for atmospheric oxy-coal systems using directed undiluted oxygen with minimal FGR must include an understanding of appropriate radiant heat transfer profiles as a function of burner aerodynamics.

[0093] Described herein are models for accurately predicting heat transfer and surface temperatures in high flame temperature oxy-coal combustion units. Heat transfer and surface temperature are critical parameters on which oxy-coal combustion applications depend. These predictive models allow evaluation of multi-scale experiments coupled with mechanism development and computational fluid dynamics (CFD) modeling. The models are used to characterize and predict flame behavior, heat transfer, ash deposition and ash chemistry during high flame temperature oxy-coal combustion at atmospheric pressure.

[0094] The predictive CFD model was used to evaluate burner designs applied to a 30 MWt burner in varied arrangements. In one embodiment, the arrangement comprises a front-wall fired steam boiler equipped with four of these burners. The heat release profile of the annular shroud burner differs from that of burners with discrete ports.

[0095] FIGS. 4 and 5 show a detailed comparison of the flame shapes for the annular shroud burner (FIG. 4) and a more conventional burner (FIG. 5) with discrete ports. As seen in FIG. 4, the annular shroud burner produces an elongated heat release profile as the concentric registers of O₂, fuel, O₂, and FGR result in slower rates of mixing between the fuel and O₂ while the outer register of flue gas recycle creates an external envelope of relatively cool conditions. The resultant heat profile signature shows discrete bands with different flame temperatures, which depend on the source. For example, in an embodiment, the inner O₂ stream flame produces flame region **361**, the fuel produces flame region **362**, the outer O₂ stream produces flame region **363**, and the FGR stream produces flame region **364** (the shroud). Peak flame temperature in this embodiment is 4,572° F. (2,522° C.). The temperature of the shroud **364** is significantly less, between about 2,000° F. (1,093° C.) and 3,000° F. (1,649° C.). The shroud **364** surrounds the high temperature flame regions **361**, **362**, and **363**, thereby primarily exposing any surrounding materials only to the cooler shroud flame region **364**. The exposure of such

surrounding materials to high heat flux is thus greatly reduced when compared to burners currently known in the art.

[0096] In contrast, as can be seen in FIG. 5, alternating regions of high and low velocity gases at the same radial distance from the conventional burner centerline accelerate the rate of mixing in the design with discrete ports. Specifically, flame region 373 is a high temperature region which is extending radially away from the center of the flame. This radial extension increases heat flux to surrounding systems, thus increasing damage to those systems.

[0097] The experiments described herein are the first to provide heat flux data for undiluted oxygen inputs under oxy-coal combustion conditions. This has been accomplished under sufficiently well-defined conditions to allow it to be used to validate heat transfer correlations in CFD simulation codes. CFD model predictions corroborated by radiant heat flux data for select test conditions in the program suggest that aerodynamic staging using axial flames with slow mixing sufficiently extends the heat released in the furnace to avoid excessive heat fluxes to the furnace walls and burner components. It has also been found that delayed mixing and high peak flame temperatures are not necessarily mutually exclusive. In other words, heat release can be extended to distribute heat flux over larger areas of the furnace while simultaneously achieving flame temperatures that exceed 4,000° F. (2,204° C.).

[0098] Correspondingly, the approach for modeling larger scale systems includes quantification of radiant heat fluxes to establish a design suitable for the technology to be applied at scales far beyond those of the test furnaces. Sensitivity analyses have been carried out to evaluate impacts of burner design on flame behavior and the associated profiles for heat release and heat flux. Several design configurations have been simulated with varying degrees of complexity. In one case, designs are based on an axial jet burner with O₂-enriched motive FGR used to convey the fuel along with discrete ports to introduce O₂. In this system, heat fluxes to the burner and furnace walls are unacceptably high.

[0099] In contrast, as described herein, it has been found that target peak temperatures above 4,000° F. (2,204° C.) could be maintained contemporaneously with reduced heat flux by introducing non-motive supplementary FGR through the use of the novel shroud design. The supplementary FGR is introduced in the burner shroud to provide local cooling and prevent burner surface temperatures from exceeding tolerable limits. The annulus is sized to achieve a relatively low velocity stream that would keep the recycled gas close to the burner and absorb heat radiated from adjacent hot spots.

[0100] In embodiments, the peak flame temperature is in the range from about 4,000° F. (2,204° C.) to about 5,000° F. (2,760° C.), about 4,100° F. (2,260° C.) to about 4,900° F. (2,704° C.), about 4,200° F. (2,316° C.) to about 4,800° F. (2,649° C.), 4,300° F. (2,371° C.) to about 4,700° F. (2,593° C.), or about 4,400° F. (2,427° C.) to about 4,600° F. (2,538° C.). In other embodiments, the peak flame temperature is in the range from about 4,000° F. (2,204° C.) to about 4,100° F. (2,260° C.), about 4,100° F. (2,260° C.) to about 4,200° F. (2,316° C.), about 4,200° F. (2,316° C.) to about 4,300° F. (2,371° C.), about 4,300° F. (2,371° C.) to about 4,400° F. (2,427° C.), about 4,400° F. (2,427° C.) to about 4,500° F. (2,482° C.), about 4,500° F. (2,482° C.) to about 4,600° F. (2,538° C.), about 4,600° F. (2,538° C.) to

about 4,700° F. (2,593° C.), about 4,700° F. (2,593° C.) to about 4,800° F. (2,649° C.), about 4,800° F. (2,649° C.) to about 4,900° F. (2,704° C.), about 4,900° F. (2,704° C.) to about 5,000° F. (2,760° C.). In other embodiments, the peak flame temperature is at least about 4,000° F. (2,204° C.), at least about 4,100° F. (2,260° C.), at least about 4,200° F. (2,316° C.), at least about 4,300° F. (2,371° C.), at least about 4,400° F. (2,427° C.), at least about 4,500° F. (2,482° C.), at least about 4,600° F. (2,538° C.), at least about 4,700° F. (2,593° C.), at least about 4,800° F. (2,649° C.), or at least about 4,900° F. (2,704° C.). In some embodiments, the peak flame temperature is about 4,000° F. (2,204° C.), about 4,050° F. (2,232° C.), about 4,100° F. (2,260° C.), about 4,150° F. (2,288° C.), about 4,200° F. (2,316° C.), about 4,250° F. (2,343° C.), about 4,300° F. (2,371° C.), about 4,350° F. (2,399° C.), about 4,400° F. (2,204° C.), about 4,450° F. (2,454° C.), about 4,500° F. (2,482° C.), about 4,550° F. (2,510° C.), about 4,600° F. (2,538° C.), about 4,650° F. (2,566° C.), about 4,700° F. (2,593° C.), about 4,750° F. (2,621° C.), about 4,800° F. (2,649° C.), about 4,850° F. (2,677° C.), about 4,900° F. (2,704° C.), about 4,950° F. (2,732° C.), or about 5,000° F. (2,760° C.). In an embodiment, the peak flame temperature is about 4,572° F. (2,522° C.), 4,581° F. (2,527° C.), 4,133° F. (2,278° C.), 4,251° F. (2,344° C.), or 4,033° F. (2,223° C.).

[0101] c. Physical Characteristics of the Annular Shroud Burner

[0102] As disclosed herein is an annular shroud burner configured in the dimensions and composition suitable for use in the system which it is employed. The following dimensions and compositions are provided merely as examples and are not intended to be limiting for the annular shroud burner as disclosed herein.

[0103] The igniter 315 has an outer diameter from about 2 to about 6 inches. In an embodiment, the igniter has an outer diameter of about 4 inches.

[0104] The O₂ inner annulus 301 has an inner diameter and an outer diameter. In embodiments, the inner diameter is in a range from about 4 to about 6 inches and the outer diameter is in a range from about 5 to about 7 inches, provided that the outer diameter is larger than the inner diameter. In embodiments, the inner diameter is about 5 or 5.3 inches and the outer diameter is about 6 or 6.3 inches.

[0105] The fuel annulus 302 has an inner diameter and an outer diameter. In embodiments, the inner diameter is in a range from about 10 to about 15 inches and the outer diameter is in a range from about 12 to about 17 inches, provided that the outer diameter is larger than the inner diameter. In embodiments, the inner diameter is about 13, 13.5, 13.6 or 14 inches and the outer diameter is about 14, 14.5, 14.6, or 15 inches.

[0106] The O₂ outer annulus 303 has an inner diameter and an outer diameter. In embodiments, the inner diameter is in a range from about 15 to about 19 inches and the outer diameter is in a range from about 16 to about 20 inches, provided that the outer diameter is larger than the inner diameter. In embodiments, the inner diameter is about 17 inches and the outer diameter is about 18 inches.

[0107] The FGR annulus 304 has an inner diameter and an outer diameter. In embodiments, the inner diameter is in a range from about 18 to about 22 inches and the outer diameter is in a range from about 19 to about 23 inches, provided that the outer diameter is larger than the inner

diameter. In embodiments, the inner diameter is about 20 inches and the outer diameter is about 21 inches.

[0108] In any of the above embodiments, the sizes of the igniter and annulus follow the order from smallest diameter to largest diameter of igniter **315**<O₂ inner annulus **301**<fuel annulus **302**<O₂ outer annulus **303**<FGR annulus **304**.

[0109] In embodiments, the annular shroud burner has a specified length. The length may be configured in the dimensions suitable for use in the system which it is employed.

[0110] A relationship exists between the size of the burner and the flow rate of fuel, O₂ stream, and FGR. Specifically, the higher the fuel flow rate, the larger the burner.

[0111] In embodiments, the annular shroud burner is fabricated from materials suitable for use in the system in which it is employed. In an embodiment, the annular shroud burner may be fabricated from stainless steel. Stainless steel is commonly classified according to a standard alloy numbering system for steel grades maintained by SAE International. The stainless steel grades are separated into separate series, where the series include the 100 series, 200 series, 300 series, 400 series, 500 series, 600 series, and 900 series. Within each series are specified variations, called types of stainless steel. For example, in the 200 series there are types 201, 202, 205, 253, and 254. Non-limiting examples of suitable stainless steel include types 253, 309, and 310.

[0112] In embodiments, the dimensions of the annular shroud burner are modified in order to obtain desired properties, such as flame characteristics, firing rate, velocities or flow rates that can vary with fuel type and heating value. In an embodiment, variations in the size of the annular shroud burner can vary based on firing rate of the burner, fuel type and heating value.

[0113] As disclosed herein, in an embodiment, is an annular shroud burner having a quadruple concentric burner design wherein the design comprises a first, second, third, and fourth conduit wherein each conduit separately injects a first, second, third, and fourth flows into a first, second, third, and fourth annulus, wherein the first flow comprises a first source of oxygen, the second flow comprises a mixture of fuel and a carrier, the third flow comprises a second source of oxygen, the fourth flow comprises FGR, and wherein at the center of the annular shroud burner there is an igniter, and positioned outside the fourth annulus is a quarl.

[0114] As in any above embodiment, an annular shroud burner wherein the first and second sources of oxygen are undiluted sources of oxygen.

[0115] As in any above embodiment, an annular shroud burner wherein the first and second sources of oxygen have an oxygen content of at least about 90%.

[0116] As in any above embodiment, an annular shroud burner wherein the carrier is FGR.

[0117] As in any above embodiment, an annular shroud burner wherein the shroud cooling design minimizes damage to burner components and near burner furnace surfaces when compared to traditional burner configurations.

[0118] As in any above embodiment, an annular shroud burner wherein the annular shroud burner is made from stainless steel.

[0119] As in any above embodiment, an annular shroud burner wherein the steel is a 200 or 300 series type stainless steel.

[0120] As in any above embodiment, an annular shroud burner further comprising a combustion zone at the face of the annular shroud burner.

[0121] As in any above embodiment, an annular shroud burner wherein the peak flame temperature is at least 4,000° F. (2,204° C.). In a further embodiment, an annular shroud burner wherein the peak flame temperature is at least about 4,300° F. (2,371° C.).

[0122] As in any above embodiment, an annular shroud burner wherein the annular shroud burner has a heat profile signature as depicted in FIG. 4. In a further embodiment, the heat profile signature has an outer, cooler layer. In a further embodiment, the heat profile signature has one, two, or more high temperature areas surrounded by a cooler area. In a further embodiment, there are two high temperature areas surrounded by a cooler area.

[0123] As in any above embodiment, an annular shroud burner wherein the fuel conduit comprises at least one fuel selected from the group consisting of natural gas, hydrogen, refinery off gas, refinery fuel gas, blast furnace gas, propane, fuel oils, anthracite, bituminous, sub-bituminous, and lignite coals, tar, bitumen, petroleum coke, paper mill sludge solids and sewage sludge solids, wood, peat, and grass. In a further embodiment, the fuel is selected from the group consisting of bituminous, sub-bituminous, and lignite coals.

[0124] As in any above embodiment, an annular shroud burner wherein the dimensions of the burner are sufficient to achieve a flow rate for the fuel in the range from about 20 ft/s to about 150 ft/s.

[0125] d. Methods of Using the Annular Shroud Burner

[0126] In one aspect, disclosed is a method for combusting fuel using an annular shroud burner as described herein. Variations in flow rates, fuel mixtures, oxygen content, fuel type, and many other variables are disclosed herein and are not to be considered limiting.

[0127] In a further embodiment, the method for combusting fuel comprises the steps of: providing an annular shroud burner, supplying a first O₂ stream through a first conduit to a first annulus, supplying a mixture of fuel and carrier through a second conduit to a second annulus, supplying a second O₂ stream through a third conduit to a third annulus, supplying FGR through a fourth conduit to a fourth annulus, and igniting the flame using an igniter located at the center of the annular shroud burner.

[0128] In an embodiment, the method further comprises the steps of controlling the flow rate of the O₂ streams such that the flow rate is in the range from about 25 ft/s to about 125 ft/s, and controlling the flow rate of the primary fuel such that the flow rate is in the range from about 20 ft/s to about 150 ft/s.

[0129] As in any embodiment above, the method which produces a peak flame temperature of at least about 4,000° F. (2,204° C.).

[0130] As in any embodiment above, the method which produces a peak flame temperature of at least about 4,300° F. (2,371° C.).

[0131] As in any embodiment above, the method wherein the flame has a heat profile signature as depicted in FIG. 4.

C. THE COMBUSTION AND RECYCLING SYSTEM

[0132] The annular shroud burner described herein may be incorporated into a boiler unit which may further be part of a technical system, such as a fossil fuel power generation

plant. In an embodiment, the annular shroud burner design provides a heat release profile in a conventional front-wall fired steam boiler configuration that substantially reduces the maximum incident heat flux on the burner components and to the furnace front walls. The annular shroud burner further regulates the amount of FGR distributed into the combustion zone to prevent damage to burner components and near-burner surfaces from extreme temperatures and heat fluxes while minimizing the impact on the peak flame temperature.

[0133] Advantages associated with a system comprising the annular shroud burner described herein include: a much higher flame temperature than conventional air/fuel and other patented oxy/fuel systems; a more directed heat release profile with less radiant heat; a novel shroud cooling design to eliminate damage to components surrounding the burner and near burner furnace surfaces; and easy replacement of pre-existing air-combustion burners with the annular shroud burner.

[0134] Depicted in FIG. 10 is a process flow schematic of an embodiment of a single wall fired sub-critical boiler plant which comprises the annular shroud burner disclosed herein. As seen in FIG. 10, the fuel 202 flows through mill 206 into annular shroud burner 207, which is connected to furnace 201. Water 208 flows into furnace 201 and flows out as steam 209.

[0135] Additional components may also flow into the burner. For example, primary FGR (PRI FGR) 204 may flow into the mill 206 where it is mixed with fuel 202 prior to being introduced to burner 207. Oxidant 203 (which may be substantially pure oxygen) may flow along several different paths. In one embodiment, oxidant 203 flows into mill 206 where it may mix with fuel 202 or PRI FGR 204 prior to being introduced to burner 207. Oxidant 203 may also flow into burner 207 or furnace 201. An alternate source of FGR may also be present, termed secondary FGR (SEC FGR) 205. The SEC FGR 205 may flow into burner 207 or furnace 201.

[0136] From the furnace, there are at least two output streams, steam 209 and hot flue gas (FG) 210. The steam 209 flows out of the furnace to other parts of the system, such as a turbine/generator set which are not described here, that function to provide power generation. One other possible output stream, hot FG 210 flows into air heater 211. In one capacity, cold FGR 212 flows into air heater 211, which heats the cold FGR 212 and provides hot FGR 213. In another capacity, air heater 211 provides an output of hot FG 214, which flows into coils 215.

[0137] Coils 215 may receive cold feed water (FW) 216, heat the water, and provide hot FW 217 as a result. The flow may continue from coils 215 to electrostatic precipitator (ESP) 218, to flue gas desulfurization (FGD) 220. Following flue gas desulfurization, the FGD out 221 may flow as either secondary FGR 222 to the air heater (AH) or flow into a Direct Contact Cooler Polishing Scrubber (DCCPS) 223. From DCCPS 223, the FGR may flow as primary FGR 224 to the air heater or flow as FG for CO₂ processing 225.

[0138] Because the annular shroud burner produces a high flame temperature, the heat transfer in the overall system is very efficient. Additional modifications to the overall system may further increase this efficiency. Such modifications include changes to the geometry of the boiler (e.g., direct flame exposure of the boiler tubes) which further increases the heat transfer by maximizing the metal surface area over

which heat transfer from the flame to the metal occurs. As a result, the boilers used may be physically smaller than a conventional boiler with a conventional burner.

[0139] Further disclosed in FIGS. 11-18 are results from models of the annular shroud burner operated within a single wall fired sub-critical boiler system.

[0140] In an embodiment, as disclosed herein is a high flame temperature oxy-combustion system, comprising: at least one annular shroud burner, a furnace for combusting, an air separation unit, at least one conduit, and a control system, wherein the annular shroud burner is configured to provide a peak flame temperature of at least 4,000° F. (2,204° C.) with a heat profile signature similar to that depicted in FIG. 4, such that the radiant heat and potential damage to systems surrounding the annular shroud burner is minimized.

[0141] In an embodiment, as disclosed herein is a method of operating an oxy-combustion system, wherein the method comprises: supplying a fuel, carrier, and substantially pure oxygen to the annular shroud burner, burning the fuel, carrier, and substantially pure oxygen to issue a flame, wherein the flame has a radiant heat profile signature similar to that depicted in FIG. 4, heating water in the boiler with the high flame temperature oxy-combustion annular shroud burner to convert water into steam.

D. EXAMPLES

[0142] The following preparations and examples are given to enable those skilled in the art to more clearly understand and to practice the present invention. They should not be considered as limiting the scope of the invention, but merely as being illustrative and representative.

Example 1: Comparison of Air and Oxy-Fired Combustion

[0143]

Air-fired	
Gross MW	112.0
Net MW	105.67
Firing rate (thermal input HHV), MMBtu/hr	1138.6
Net Heat Rate, Btu/kWh	10775
Coal Flow, lb/hr	140302
Total Air Flow, lb/hr	936690
Overall Stoichiometric Ratio	1.1036
Excess O ₂ in FG at furnace exit, vol % wet	1.72
Excess O ₂ in FG at furnace exit, vol % dry	2.0
FG econ outlet temp (AH inlet), F.	688
AH outlet FG temp, F.	283
Atmospheric pressure, psia	12.1
Burners in operation	12
Mills in service	8, 10, 11, 12
Primary Gas/Coal	1.95
Primary Gas Flow, lb/hr	273590
Primary gas temperature entering mill, F.	582
Primary Temperature entering boiler, F.	135
Coal moisture vaporized in mill, %	60
Secondary Temperature entering boiler, F.	580
Oxy-fired	
Firing rate (thermal input HHV), MMBtu/hr	1138.6
Coal Flow, lb/hr	140302
Total O ₂ Flow, lb/hr	205967
Total FGR Flow, lb/hr	525847

-continued

Secondary FGR Flow, lb/hr, external to burner	301975 (57.4% of total FGR)
Shroud FGR Flow, lb/hr	27359 (5.2% of total FGR)
Overall Stoichiometric Ratio	1.054
Excess O ₂ in FG at furnace exit, vol % wet	1.31
Excess O ₂ in FG at furnace exit, vol % dry	1.94
Atmospheric pressure, psia	12.1
Burners in operation	12
Mills in service	7, 8, 9, 12
Primary Gas/Coal	1.75 (1.68 air eq, 4500 ft/min coal pipe)
Primary Gas Flow, lb/hr	245529
Primary FGR Flow, lb/hr	196513 (37.4% of total FGR)
Primary O ₂ Flow, lb/hr	49016
Primary Gas O ₂ concentration, %	23.5
Primary gas temperature entering mill, F.	545
Primary Temperature entering boiler, F.	134
Coal moisture vaporized in mill, %	45
Secondary O ₂ Temperature entering boiler, F.	68
Secondary FGR Temperature entering boiler, F.	645
FG Recycle Rate, mass % of furnace exit FG flow	61
Overall O ₂ in O ₂ /FGR mix, %	30.6

[0144] The following steam conditions were used to set tuning parameters in the air-fired SGE process modeling. Once set, the parameters were held constant to predict steam conditions during oxy-firing.

	Air-fired
SH flow, lb/hr	752646
SH final pressure, psig	1449
SH final temp, F.	1004
SH spray, lb/hr	23881
Primary SH outlet temp, F.	706
Drum Pressure, psig	1615
Saturation temp, F.	607
Econ out temp, F.	537
FW temp to economizer, F.	471
Econ inlet and spray pressure, psig	1826
RH flow, lb/hr	671539
RH final pressure, psig	472
RH final temp, F.	1000
RH spray, lb/hr	86732
RH inlet temp, F.	731
RH inlet pressure, psig	513
Spray temp, F.	303

[0145] The overall results comparing the air-fired and oxy-fired burners.

	Air-fired CFD	Oxy-fired CFD
FEGT (° F.)	1724	1693
Peak Gas Temp in Domain (° F.)	3341	4108
CO at Furnace Exit (ppmv, wet)	2181	5314
O ₂ at Furnace Exit (vol %, wet)	2.16	2.51
Peak Net Heat Flux (kW/m ²)	210	262
Average Net Heat Flux, All surfaces (kW/m ²)	60.0	60.7
Average Net Heat Flux, Surfaces below nose (kW/m ²)	115.9	125.0

-continued

	Air-fired CFD	Oxy-fired CFD
Peak incident Heat Flux (kW/m ²)	406	507
Peak Tube OD Temp (° F.)	768	806
Burnout (%)	99.15	99.44
Carbon in Ash (%)	5.6	<0.1
Ash Carryover (%)	93.7	97.6
NOx at economizer exit (ppmv, wet)	188	602
NOx at economizer exit (lb/MMBtu)	0.28	0.62
NOx emissions at stack/CPU inlet (ppmv, wet) ¹	180	713
NOx emissions at stack/CPU inlet (lb/MMBtu) ¹	0.28	0.24

*Furnace Exit is between SSH platen and RH pendant
¹From process modeling

[0146] Referring now to FIG. 19, a process flow diagram 500 of a carbon sequestration system 501 using a high flame temperature oxy-combustion burner for firing a fuel (e.g., coal) is provided. As illustrated in FIG. 19, a fuel 502 (or a fuel supply unit), typically coal (or a coal silo), flows through a mill 504 into an annular shroud burner 506 (or a plurality of annular shroud burners, e.g., one or more of the annular shroud burners depicted and described with reference to FIGS. 1A and 1B, FIGS. 2A, 2B and 2C and FIG. 3), which is connected to a furnace 508. In various embodiments, the furnace 508 is configured to boil or superheat a supply of water, which is then used to drive a steam turbine 510. The steam turbine 510 is typically connected to a generator 512 that is configured to generate electricity or electric power, which may then be supplied to an energy grid.

[0147] Additional materials or components may also flow into the annular shroud burner 506. For example, a primary FGR (PRI FGR) 514 (or a primary flue gas recycle supply stream or conduit) may flow into the mill 504 and be mixed with the fuel 502 prior to being introduced to the annular shroud burner 506. An oxidant 516 (which may be substantially pure oxygen) may be received and configured to flow along several different paths. In one embodiment, the oxidant 516 flows into the mill 504 where it is mixed with the fuel 502 and the PRI FGR 514 prior to being introduced to the annular shroud burner 506; in various embodiments, the oxidant 516 and the PM FGR 514 are mixed prior to being introduced into the mill 504, as illustrated in FIG. 19. The oxidant 516 may also flow directly into the annular shroud burner 506 (as also illustrated in FIG. 19) and consumed with the fuel 502 as described above. An alternate source of FGR may also be present, termed a secondary FGR (SEC FGR) 518 (or a secondary flue gas recycle supply stream or conduit). The SEC FGR 518 may flow into the annular shroud burner 506 or directly into the furnace 508 as illustrated.

[0148] From the furnace 508, there are at least two output streams, including a high-pressure steam supply 520 and an intermediate-pressure steam supply 521 and a hot flue gas (FG) 522 (or a flu gas from the furnace). As described further below, the high-pressure steam supply 520 and the intermediate-pressure steam supply 521 (or the steam within the steam supplies) flows out of the furnace 508 to other parts of the system, such as the turbine 510 used to drive the generator 512 configured to generate electric power. Another possible output stream, the hot FG 522 flows into a waste heat recovery exchanger 524, where the thermal energy of the hot FG 522 is used to heat other fluids, such as water or

air. The hot FG 522 then exits the waste heat recovery exchanger 524 and is fed to an electrostatic precipitator (ESP) 526 where suspended dust particles and the like are removed from the hot FG 522. The hot FG 522 is then fed to a flue gas desulfurizer (FGD) 528 where sulfur is removed and then to a dehumidifier, scrubber or cooler (e.g., a direct contact cooler/polishing scrubber (DCCPS) 530) where the hot FG 522 is dehumidified and, in various embodiments, may be further scrubbed (e.g., in addition to scrubbing performed via the FGD) or further cooled (e.g., in addition to cooling provided by the waste heat recovery exchanger) to produce a cooled FG 532 (the term cooled FG being in relation or relative to the temperature of the hot FG exiting the furnace). The DCCPS functions, at least in part, to dehumidify the hot FG 522 (or the cooled FG 532, depending on where the DCCPS is located). Dehumidification of the hot FG 522 reduces or prevents, among other things, moisture from being input to the mill 504, where the moisture has a tendency to hamper mixing (e.g., via agglomeration) of the fuel 502 and the flue gas; note that while the disclosure describes and illustrates the DCCPS, it is noted the DCCPS may comprise, without loss of generality, one or more of a dehumidifier (e.g., a dehumidifier 529), a scrubber or a cooler. As illustrated, in various embodiments, a medium used to produce the cooled FG 532 (in addition to any cooling performed upstream of the DCCPS) may comprise a source of cooling water (CW) 523 that is circulated through the direct contact cooler/polishing scrubber (DCCPS) 530. Further, it is noted the flue gas exiting the waste heat recovery exchanger 524 may also be referred to as a cooled FG as thermal energy is transferred from the hot FG 522 to the condensate. Thus, without loss of generality, one or more of the components positioned downstream of the waste heat recovery exchanger 524—e.g., the electrostatic precipitator (ESP) 526, the flue gas desulfurizer (FGD) 528 and the direct contact cooler/polishing scrubber (DCCPS) 530—may or may not be included in various embodiments of the disclosure. Note as well that, in various embodiments, the hot FG 522 may be used to heat the oxidant 516 (e.g., oxygen) prior to its being introduced into the annular shroud burner 506 or the mill 504 (e.g., via the PM FGR 514 following its being mixed with the oxidant 516). For example, a heat exchanger 517 may be positioned upstream of the annular shroud burner 506 or the mill 504, as illustrated, and configured to receive a portion of the hot FG 522 for heating the oxidant 516.

[0149] The cooled FG 532 is then split into various streams, typically via conduits, and fed to the mill 504, the annular shroud burner 506 or directly to the furnace 508. In various embodiments, for example, the cooled FG 532 may be split into a first cooled FGR supply stream 534 (or a first cooled FGR supply stream or conduit configured to transport the first cooled FGR supply stream 534), which is used as a supply for the PRI FGR 514 and the SEC FGR 518. In various embodiments, for example, the first cooled FGR stream 534 is split into one or more FGR supply streams, such as, a first FGR supply stream 536 and a second FGR supply stream 538. The first FGR supply stream 536 is provided to an FGR heater 540 (or a plurality of FGR heaters) where the temperature of the first FGR supply stream 536 is raised to produce a heated FGR supply stream 542. In various embodiments, and as illustrated, the thermal energy used to raise the temperature of the first FGR supply stream 536 is provided by the hot FG 522, prior to the hot

FG 522 being provided to the electrostatic precipitator (ESP) 526. The heated FGR supply stream 542 is then provided to either or both the annular shroud burner 506 and the furnace 508 (e.g., via an overfire air port 509) via the SEC FGR 518 and the mill 504 via the PRI FGR 514. One or more by-pass dampers—e.g., an annular shroud by-pass damper 568 or an overfire air port damper 569—may be used to selectively control the flow rate of the SEC FGR 518 into the two regions of the furnace 508. The second FGR supply stream 538 is provided to the mill 504 and, in various embodiments, as illustrated, a portion of the second FGR supply stream 538 may be mixed with the PM FGR 514 (e.g., via a flow temperature control valve 567) for temperature control—e.g., to cool the heated FGR supply stream 542 used to feed or supply the PM FGR 514.

[0150] A second cooled FGR supply stream 548 (or a second cooled FGR supply stream or conduit configured to transport the second cooled FGR supply stream 548), split from the cooled FG 532, is used as a supply for a CO₂ purification unit (CPU) 550, where carbon dioxide (CO₂) within the second cooled FGR stream 548 is purified and separated from the remaining components within the second cooled FGR stream 548 to produce a purified CO₂ stream 552. The purified CO₂ stream 552 may then be further processed—e.g., compressed—and transported for capture and sequestration—e.g., stored offside or injected into the earth. In various embodiments, a CO₂ compressor 554 (e.g., a motor-driven wet-feed and high-pressure CO₂ compressor, as illustrated) may be used in conjunction with the CO₂ purification unit (CPU) 550 to preprocess the second cooled FGR stream 548 prior to or after entering the CO₂ purification unit (CPU) 550. A source of cooling water (CW) 525 may also be provided to cool operation of the CO₂ purification unit (CPU) 550. A stack 556 may also be incorporated into the system to bypass the CO₂ purification unit (CPU) 550. Note the cooled FG 532 may be selectively delivered to or the flow rate adjusted for each of the stack 556, the first cooled FGR stream 534 (to the furnace 508) and the second cooled FGR supply stream 548 (to the CO₂ purification unit (CPU) 550) via, respectively, a stack bypass damper 570, a first cooled FGR stream bypass damper 571 and a second cooled FGR stream bypass damper 572.

[0151] In addition to the foregoing components and process steps, it is noted that because the carbon sequestration system just described uses a high flame temperature oxy-combustion burner (e.g., the annular shroud burner 506) for firing fuel (e.g., coal), an air separation unit (ASU) 560 is generally employed to separate oxygen (O₂) from atmospheric air. In various embodiments, for example, atmospheric air is input to the air separation unit (ASU) 560 where the O₂ is purified to produce an O₂ stream 562 having a concentration of on the order of greater than 95% by weight. In various embodiments, the O₂ stream 562 is split into a first O₂ stream 564, which is provided to the mill 504 (e.g., following mixing with the PRI FGR 514), and a second O₂ stream 566, which is provided to the annular shroud burner 506, as illustrated and described above. In various embodiments, the PM FGR 514, following mixing with the first O₂ stream 564, exhibits a O₂ to flue gas ratio of between about twenty percent (20%) and about twenty-five percent (25%) (e.g., about twenty-three percent (23%)) oxygen. Adding oxygen to the flue gas stream is beneficial in that a higher flame temperature results in the burner 508 (or at the exit region of the annular shroud burner 506, leading to an

increase in overall thermodynamic efficiency of the furnace **508** and the system used to generate power. Note that during operational startup of the furnace **508**, ambient air (or an ambient air source **574**) is used to replace the various flue gas recycle supply streams. For example, during startup, an ambient air by-pass damper **575** is opened to enable ambient air to be pumped—e.g., via a flue gas recycle supply stream fan **576**—into the first FGR supply stream **536** and the second FGR supply stream **538** and then into the mill **504** and the furnace **508** as described above. Once the furnace **508** is operational under ambient air, the ambient air by-pass damper **575** is closed and normal operation using the flue gas recycle supply streams and oxidant to the oxy-combustion burner is commenced.

[0152] Still referring to FIG. **19**, in various embodiments, the steam turbine **510** includes a high-pressure section **531** (HP), an intermediate-pressure section **533** (IP) and a low-pressure section **535** (LP). The high-pressure section **531** typically receives the high-pressure steam supply **520** from a first steam coil **537** disposed in a radiant heating section **539** (or boiler section) of the furnace **508**. The high-pressure steam supply **520** is typically superheated steam at a pressure on the order of 1,900 psi 13,100 kPa). The steam exhausted from the high-pressure section **531** is then fed to a second steam coil **541** disposed in a convective heating section **543** (or economizer section) of the furnace **508** and configured to supply the intermediate pressure steam supply **521** to the intermediate-pressure section **533** at a pressure on the order of 600 psi 4100 kPa). The steam exhausted from the intermediate-pressure section **533** is then fed to the low-pressure section **535** at a pressure on the order of 200 psi 1375 kPa). The steam exhausted from the low-pressure section **535** is then provided to a condenser **545** and condensed, then pumped via a condensate pump **547** to a deaerator **549** prior to being pumped back into the furnace **508** via a boiler feed water pump **551** and ultimately routed to a feedwater port **553** configured to supply the condensed steam as a condensate to the first steam coil **537**. As described further below, the condensate may be preheated prior to its ultimately being supplied to the feedwater port **553**.

[0153] In various embodiments, for example, feedwater heaters are used in conjunction with the waste heat recovery exchanger **524** to heat the condensate prior to its delivery to the feedwater port **553**. For example, a low-pressure feedwater heater **580** may be configured to receive a first steam supply **581** (e.g., a low-pressure steam supply) via a first extraction tap **582** positioned and configured to extract steam from a first position of one of the turbine sections (e.g., a first position of the low-pressure section **535**). Similarly, an intermediate-pressure feedwater heater **584** may be configured to receive a second steam supply **585** (e.g., an intermediate-pressure steam supply) via a second extraction tap **586** positioned and configured to extract steam from a second position of one of the turbine sections (e.g., a second position of the low-pressure section **535**). The first position and the second positions of the extraction taps are beneficially located to provide different steam supplies exhibiting different pressures and temperatures to the various feedwater heaters. During operation, in accordance with one embodiment, the condensate is provided to the low-pressure feedwater heater **580**, where the condensate is heated via the first steam supply **581** to provide a first heated condensate. The first heated condensate exiting the low-

pressure feedwater heater **580** is then provided to the waste heat recovery exchanger **524**, where the first heated condensate is heated via the hot FG **522** to provide a second heated condensate. The second heated condensate exiting the waste heat recovery exchanger **524** is then provided to the intermediate-pressure feedwater heater **584**, where the second heated condensate is heated via the second steam supply **585** to provide a third heated condensate to the deaerator **549**.

[0154] The above-described method of preheating the condensate benefits from using waste heat from the furnace **508** to pre-heat the condensate rather than from other sources of heat or thermal energy. In various embodiments, for example, waste heat from the furnace—via the hot FG **522**—is used, at least in part, to preheat the condensate. Use of waste heat, as described, is beneficial for systems that otherwise employ steam from the steam turbine **510** to pre-heat the condensate in that less steam is required for extraction, thereby improving the thermal efficiency and power output of the steam turbine **510**. Further, as described above and illustrated at FIG. **19**, the waste heat provided to the waste heat recovery exchanger **524** may be combined with other sources of thermal energy to preheat the condensate. In various embodiments, for example, one or more feedwater heaters may be used, where the feedwater heaters are operated using steam extracted from a steam turbine (e.g., the steam turbine **510**). The embodiment depicted in FIG. **19** and described above employs the low-pressure feedwater heater **580** and the intermediate-pressure feedwater heater **584** to tailor the temperature rise across each heater, such that thermodynamic efficiency of an overall system (e.g., the carbon sequestration system **501**) is maximized or otherwise improved in accordance with various design aspects required of the overall system.

[0155] It will be apparent to those skilled in the art that various modifications and variations can be made in the present invention without departing from the scope or spirit of the invention. Other aspects of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the invention being indicated by the following claims.

What is claimed is:

1. A carbon sequestration system, comprising:
 - a furnace having an oxy-combustion burner;
 - a mill configured to receive a fuel and to provide the fuel to the oxy-combustion burner;
 - a waste heat recovery exchanger configured to receive a flue gas from the furnace;
 - an electrostatic precipitator configured to receive the flue gas from the waste heat recovery exchanger;
 - a direct contact cooler/polishing scrubber configured to receive the flue gas downstream of the waste heat recovery exchanger and to exhaust the flue gas as a cooled flue gas;
 - a first cooled flue gas recycle supply stream configured to supply the cooled flue gas to
 - a first flue gas recycle supply stream, the first flue gas recycle supply stream configured for input to a flue gas recycle heater and for output from the flue gas recycle heater as a heated flue gas recycle supply stream configured for input to at least one of an

- overfire air port of the furnace or the oxy-combustion burner as a secondary flue gas recycle stream; and a second flue gas recycle supply stream, the second flue gas recycle supply stream configured for input to the mill; and
- a second cooled flue gas recycle supply stream configured to supply the cooled flue gas to a CO₂ purification unit, the CO₂ purification unit configured to produce a purified CO₂ stream from the second cooled flue gas recycle stream for sequestration.
2. The carbon sequestration system of claim 1, further comprising a flue gas desulfurizer in fluid communication with the electrostatic precipitator and the direct contact cooler/polishing scrubber.
3. The carbon sequestration system of claim 2, wherein the flue gas recycle heater is configured to receive the flue gas from the furnace to heat the first flue gas recycle supply stream to produce the heated flue gas recycle supply stream.
4. The carbon sequestration system of claim 3, wherein the heated flue gas recycle supply stream is configured to be provided to the mill as a primary flue gas recycle stream.
5. The carbon sequestration system of claim 4, further comprising a flow temperature control valve configured to mix a portion of the second flue gas recycle supply stream and the heated flue gas recycle supply stream to produce a cooled primary flue gas recycle stream.
6. The carbon sequestration system of claim 5, wherein the heated flue gas recycle supply stream is configured to be received by both the overfire air port of the furnace and the oxy-combustion burner as the secondary flue gas recycle stream.
7. The carbon sequestration system of claim 6, wherein the primary flue gas recycle stream is mixed or the cooled primary flue gas recycle stream is diluted with an oxidant.
8. The carbon sequestration system of claim 1, wherein the oxy-combustion burner is an annular shroud burner, comprising:
- a quarl, the quarl having a diverging conical shape that is positioned to extend along a central axis and defining a combustion zone radially inward and downstream of a radially inner surface of the quarl, the quarl extending from a burner face to a furnace interior wall;
 - a first conduit, the first conduit positioned to extend along the central axis and configured to provide a first stream of oxygen into the combustion zone at the burner face;
 - a second conduit, the second conduit positioned to extend along the central axis, radially outward of the first conduit, and configured to provide a mixed stream of a fuel and a carrier to the combustion zone at the burner face;
 - a third conduit, the third conduit positioned to extend along the central axis, radially outward of the second conduit, and configured to provide a second stream of oxygen to the combustion zone at the burner face; and
 - a fourth conduit, the fourth conduit positioned to extend along the central axis, radially outward of the third conduit, and configured to provide a stream of recycled flue gas in a form of a conical shroud that extends along the inner surface of the quarl, from the burner face to the furnace interior wall, the stream of recycled flue gas surrounding a peak flame temperature region within the combustion zone.
9. The carbon sequestration system of claim 8, wherein the first stream of oxygen and the second stream of oxygen of the annular shroud burner comprise undiluted oxygen.
10. The carbon sequestration system of claim 9, wherein the first stream of oxygen and the second stream of oxygen of the annular shroud burner comprise an oxygen content of at least about 90%.
11. The carbon sequestration system of claim 10, wherein the carrier comprises a recycled flue gas.
12. The carbon sequestration system of claim 11, wherein the recycled flue gas comprises at least a portion of the secondary flue gas recycle supply stream.
13. The carbon sequestration system of claim 12, wherein the stream of recycled flue gas surrounding the peak flame temperature region within the combustion zone comprises at least a portion of the heated flue gas recycle supply stream.
14. A method for generating purified carbon dioxide for sequestration using a system comprising a furnace having an oxy-combustion burner, a mill configured to receive a fuel and to provide the fuel to the oxy-combustion burner, a waste heat recovery exchanger configured to receive a flue gas from the furnace, an electrostatic precipitator configured to receive the flue gas from the waste heat recovery exchanger, and a direct contact cooler/polishing scrubber configured to receive the flue gas downstream of the waste heat recovery exchanger and to exhaust the flue gas as a cooled flue gas, the method comprising:
- supplying the cooled flue gas via a first cooled flue gas recycle supply stream to a first flue gas recycle supply stream, the first flue gas recycle supply stream configured to for input to a flue gas recycle heater and for output from the flue gas recycle heater as a heated flue gas recycle supply stream configured for input to at least one of an overfire air port of the furnace or the oxy-combustion burner as a secondary flue gas recycle stream, and
 - a second flue gas recycle supply stream, the second flue gas recycle supply stream configured for input to the mill; and
 - supplying the cooled flue gas via a second cooled flue gas recycle supply stream to a CO₂ purification unit, the CO₂ purification unit configured to produce a purified CO₂ stream from the second cooled flue gas recycle stream for sequestration.
15. The method of claim 14, wherein the oxy-combustion burner includes an annular shroud burner having a quarl, the quarl having a diverging conical shape that is positioned to extend along a central axis and defining a combustion zone radially inward and downstream of a radially inner surface of the quarl, the quarl extending from a burner face to a furnace interior wall, the method further comprising:
- providing a first stream of oxygen into the combustion zone via a first conduit, the first conduit positioned to extend along the central axis and configured to open into the quarl at the burner face;
 - providing a mixed stream of the fuel and a carrier to the combustion zone via a second conduit, the second conduit positioned to extend along the central axis, radially outward of the first conduit, and configured to open into the quarl at the burner face;
 - providing a second stream of oxygen to the combustion zone via a third conduit, the third conduit positioned to

extend along the central axis, radially outward of the second conduit, and configured to open into the quarl at the burner face; and

providing a stream of recycled flue gas, that surrounds a portion of the combustion zone, via a fourth conduit, the fourth conduit positioned to extend along the central axis, radially outward of the third conduit, and configured to provide the stream of recycled flue gas in a form of a conical shroud that extends along the inner surface of the quarl, from the burner face to the furnace interior wall, the stream of recycled flue gas surrounding a peak flame temperature area within the combustion zone.

16. The method of claim **15**, wherein the first stream of oxygen and the second stream of oxygen of the annular shroud burner comprise undiluted oxygen.

17. The method of claim **16**, wherein the first stream of oxygen and the second stream of oxygen of the annular shroud burner comprise an oxygen content of at least about 90%.

18. The method of claim **17**, wherein the carrier comprises a recycled flue gas.

19. The method of claim **18**, wherein the recycled flue gas comprises at least a portion of the secondary flue gas recycle supply stream.

20. The method of claim **19**, wherein the stream of recycled flue gas surrounding the peak flame temperature region within the combustion zone comprises at least a portion of the heated flue gas recycle supply stream.

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