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(54) **OXY/FUEL COMBUSTION SYSTEM WITH LITTLE OR NO EXCESS OXYGEN**

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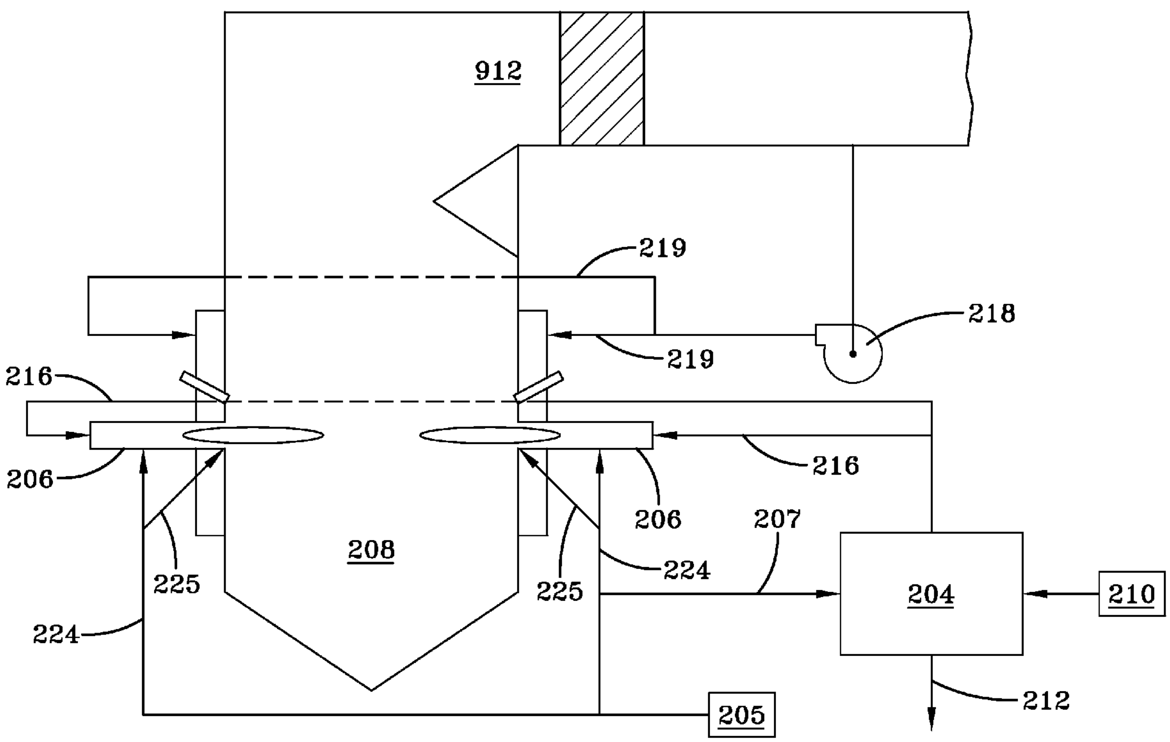
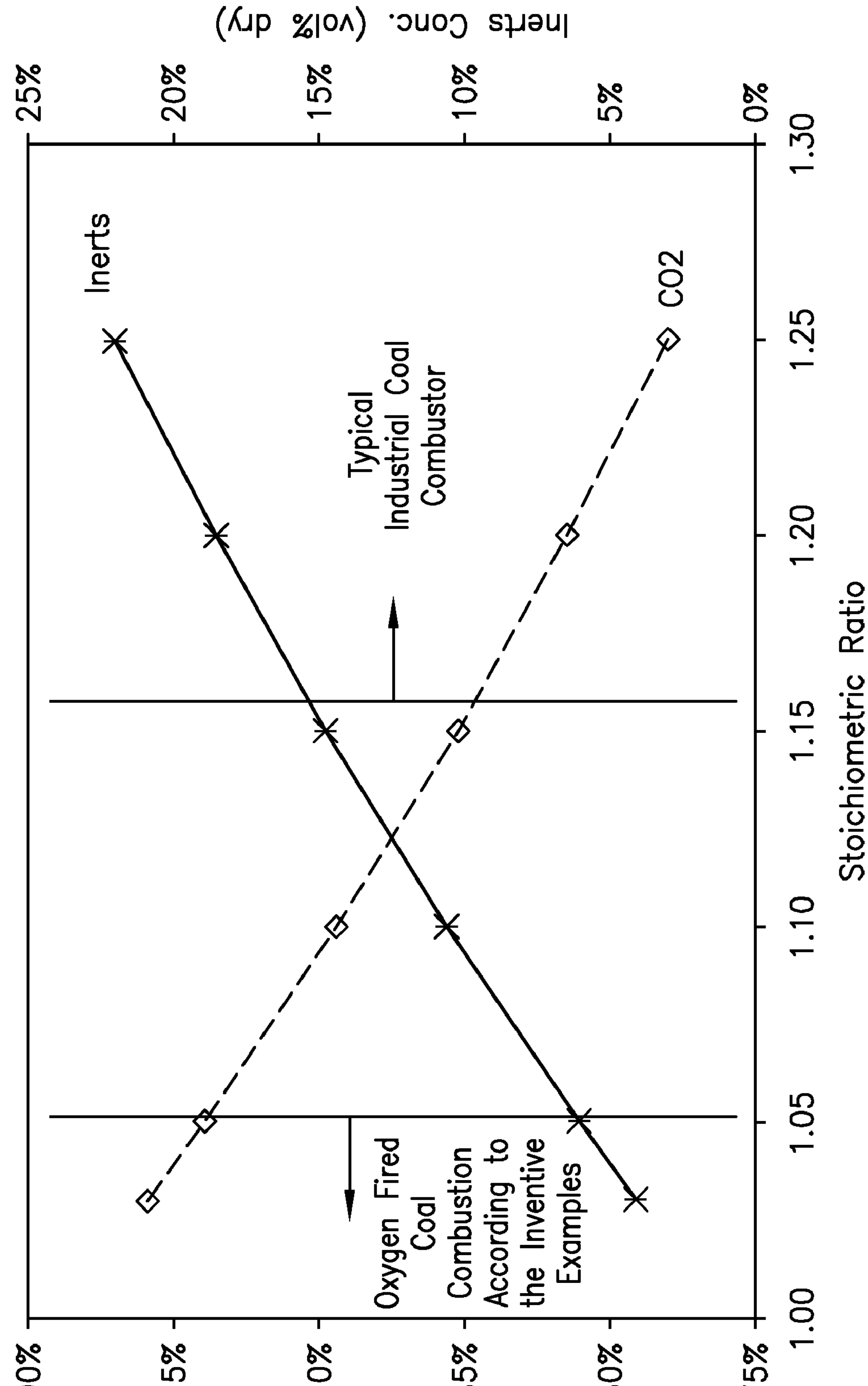
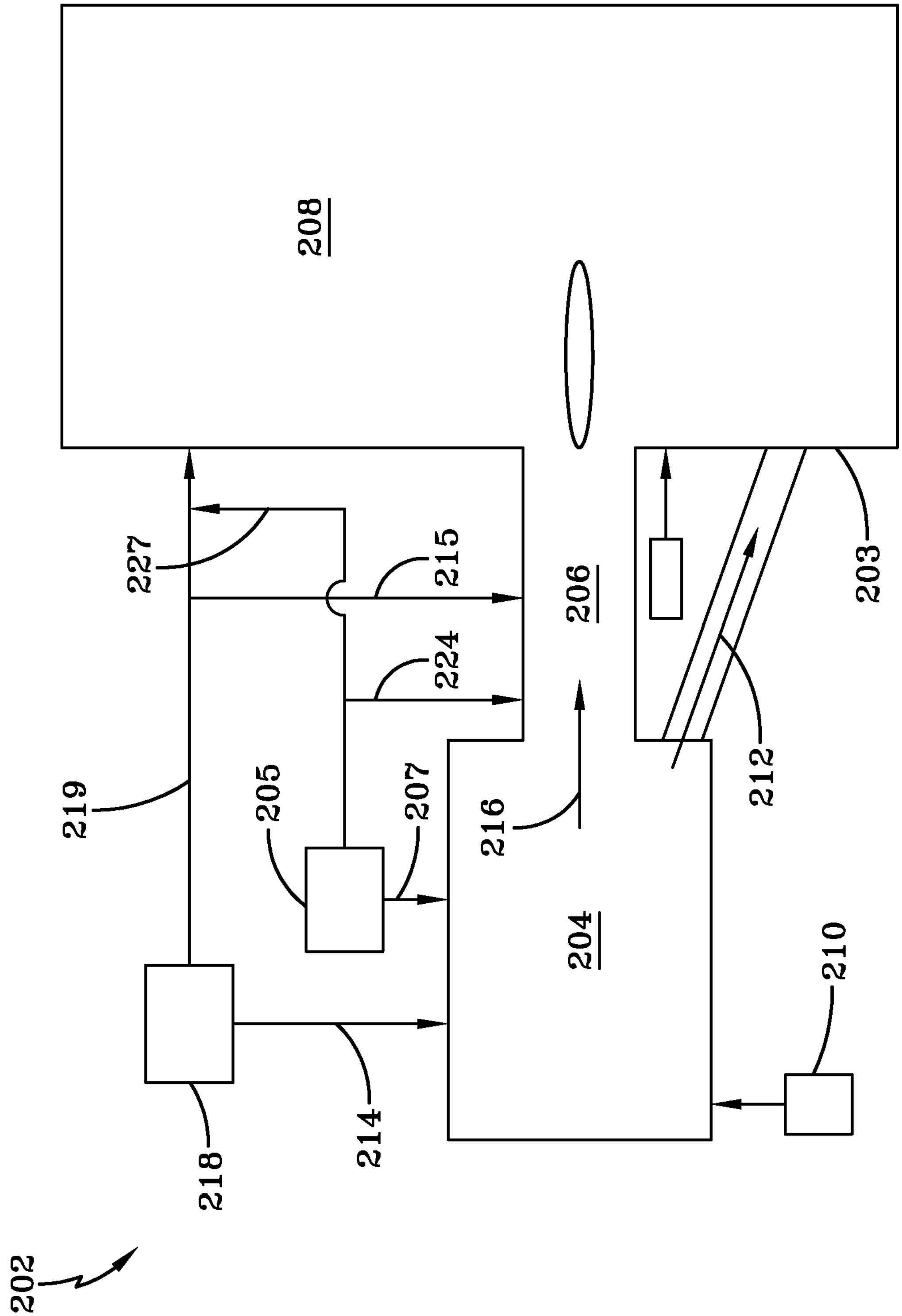
(57) **ABSTRACT**

The disclosure includes a combustion system including a primary reactor arranged and disposed to receive a solid fuel and a first oxygen stream and deliver a first substantially gaseous product and a substantially solid or molten product, a secondary reactor in fluid communication with the primary reactor, and a furnace in fluid communication with the secondary reactor.

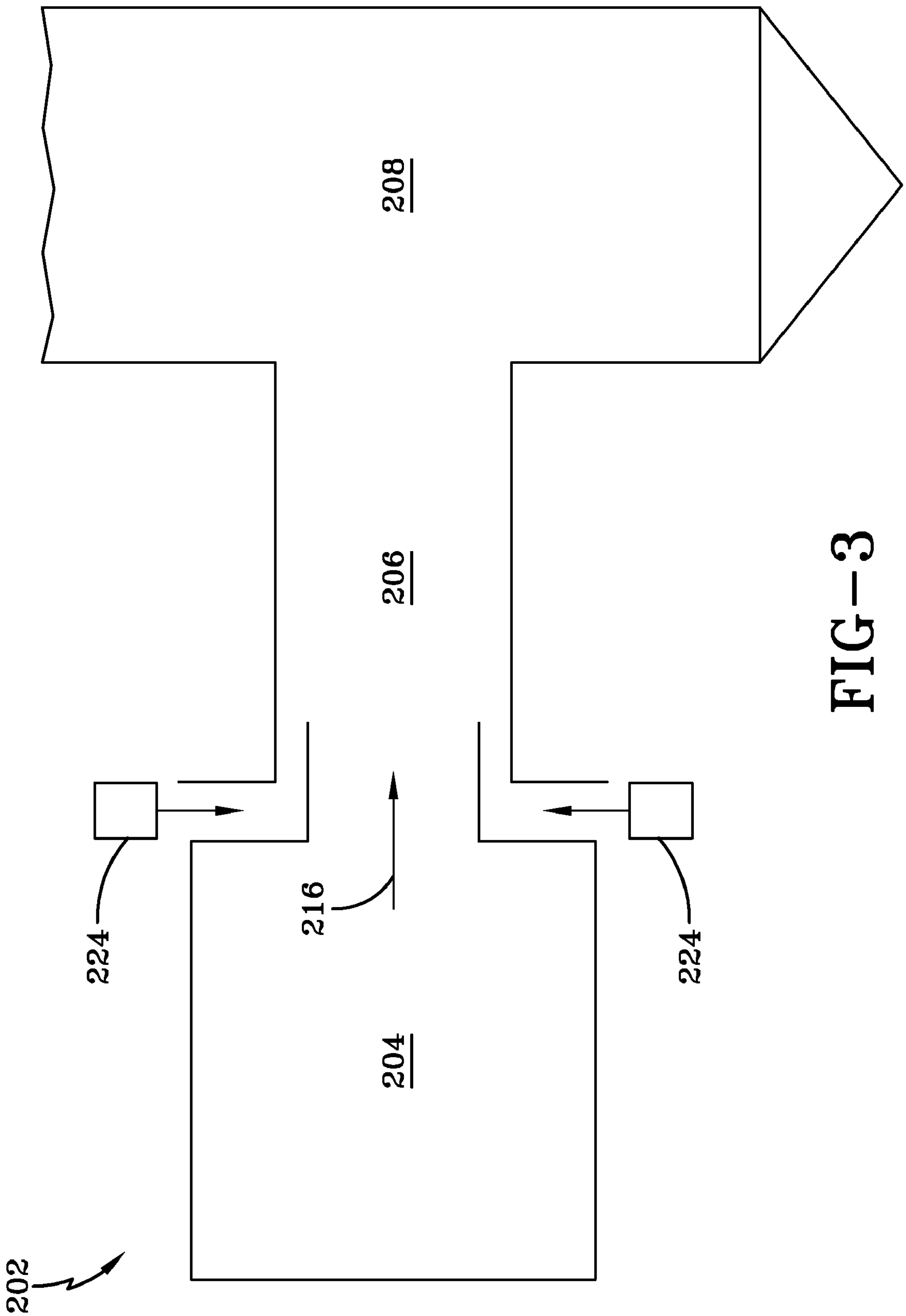



Inerts
CO2
Typical Industrial Coal Combustor
Oxygen Fired Coal Combustion According to the Inventive Examples
Flue Gas CO2 Conc. (vol% dry)
Inerts Conc. (vol% dry)
Stoichiometric Ratio
100%
95%
90%
85%
80%
75%
25%
20%
15%
10%
5%
0%
1.00
1.05
1.10
1.15
1.20
1.25
1.30

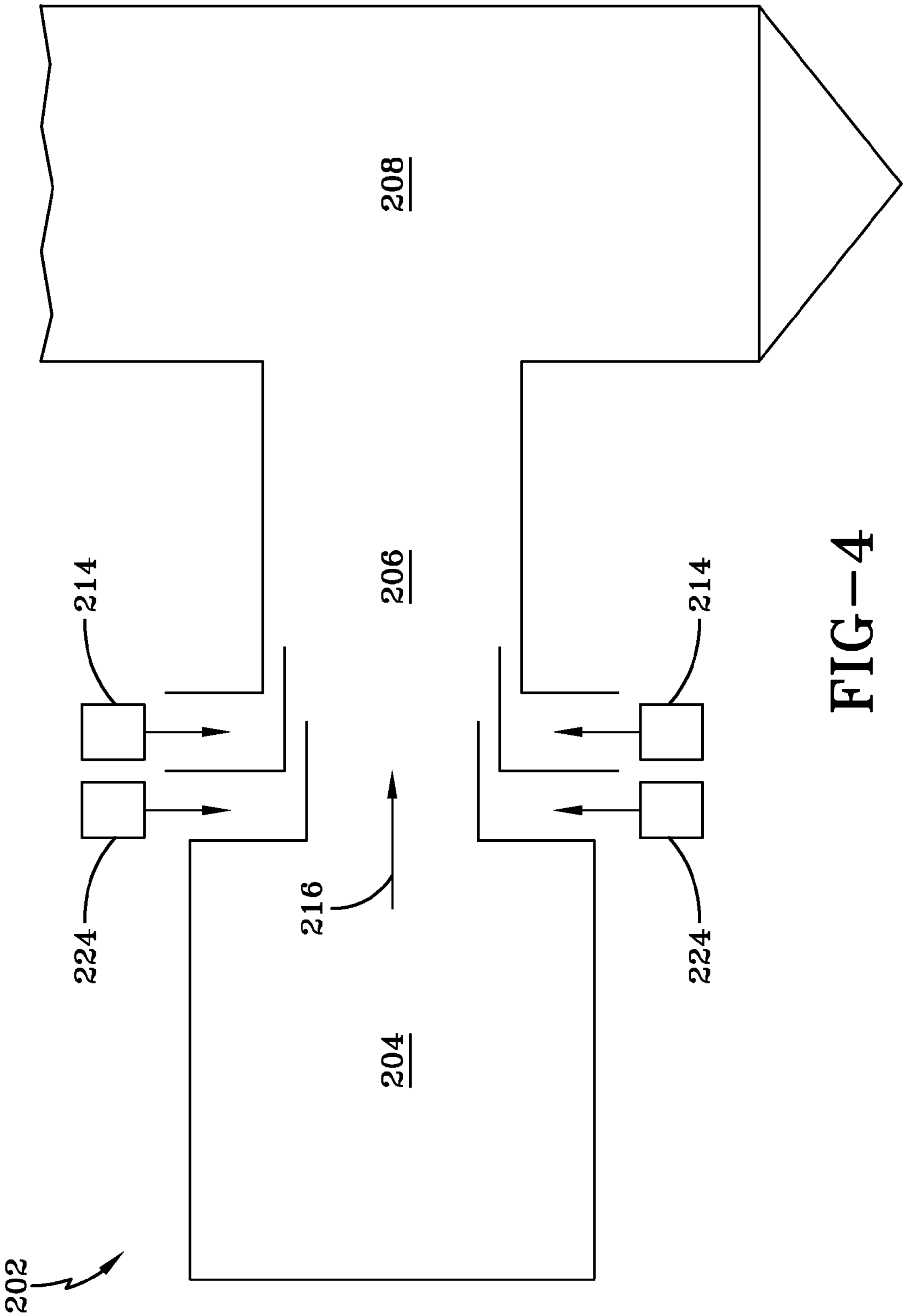
FIG–1



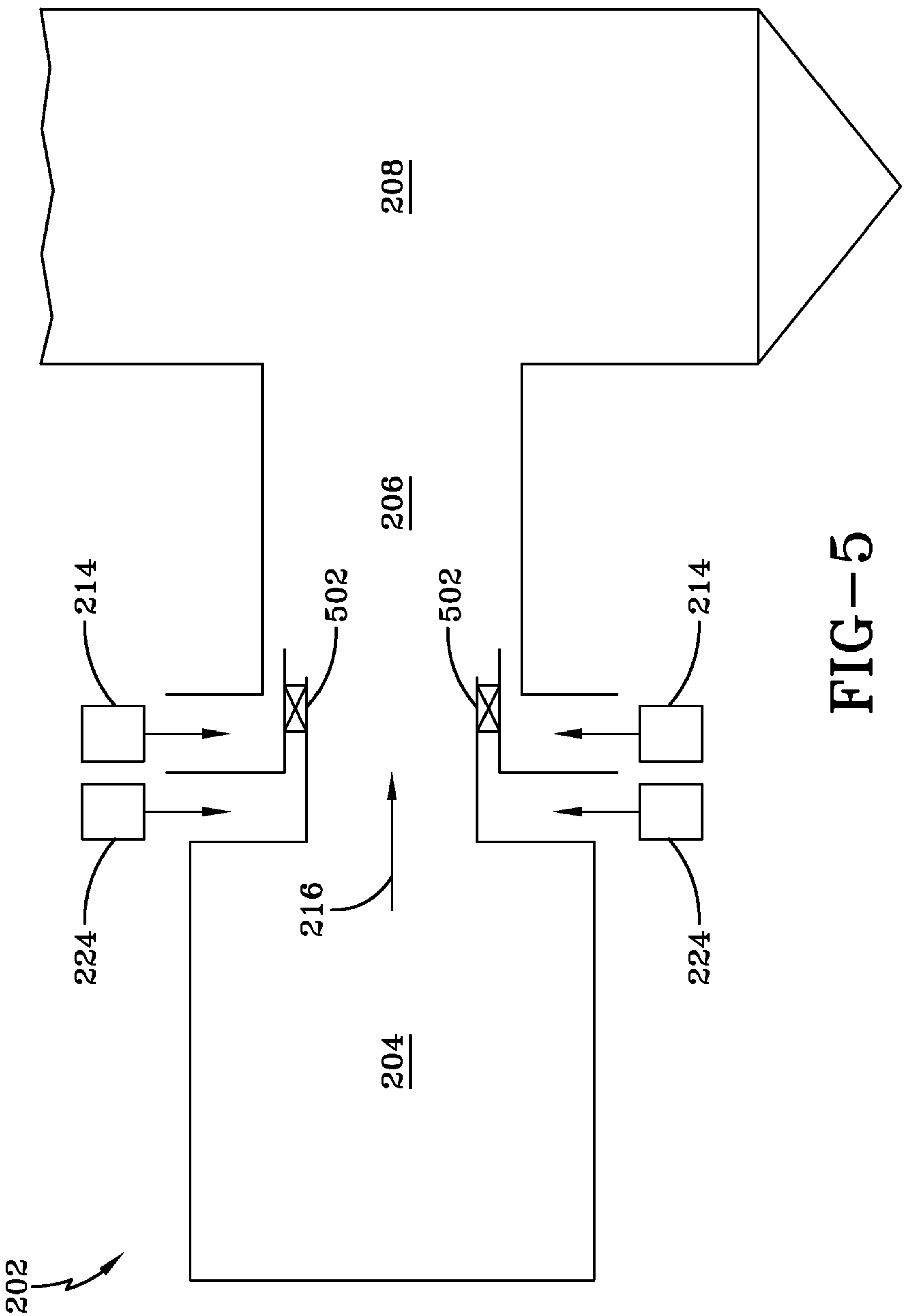
FIG—2



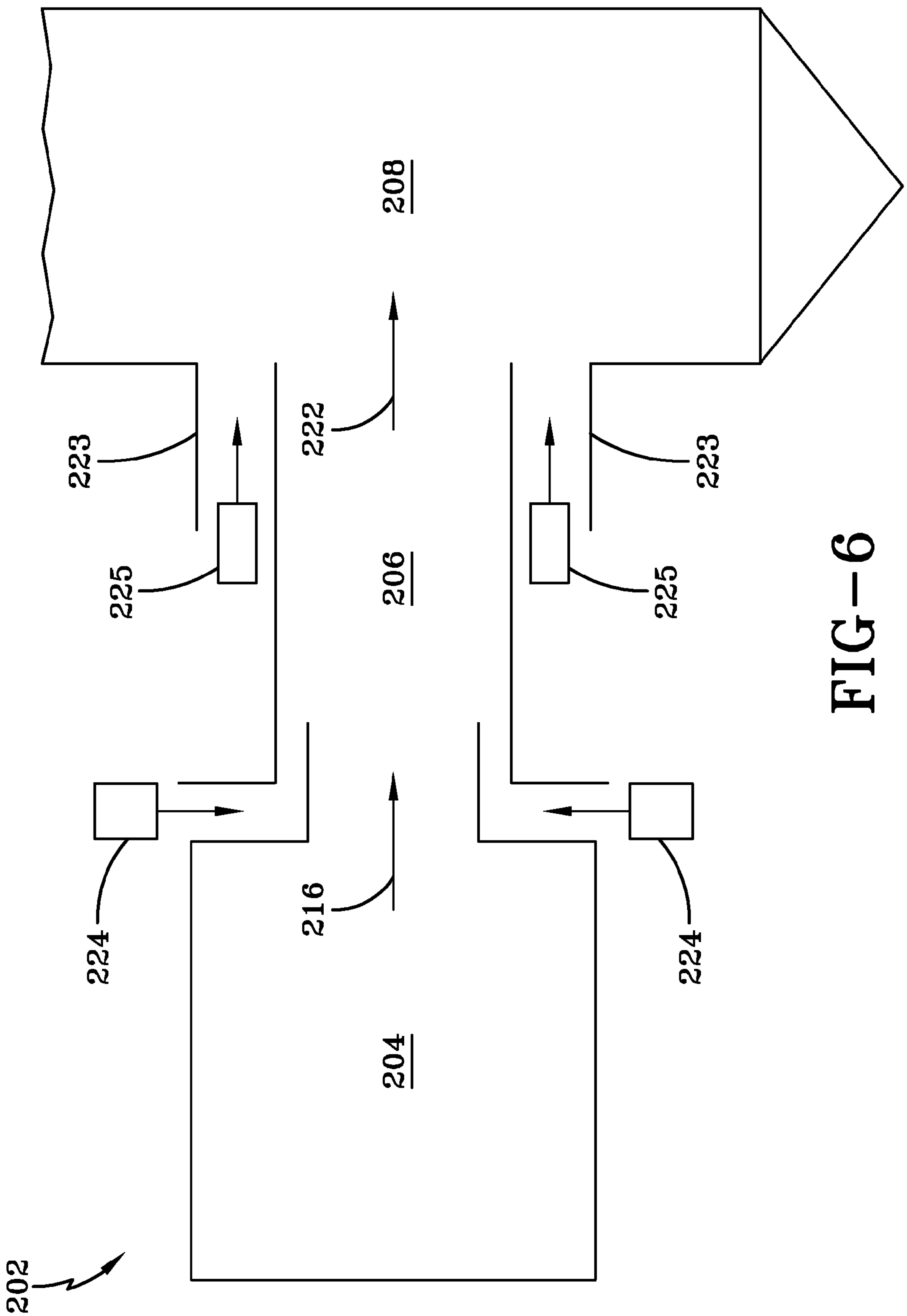
FIG—3



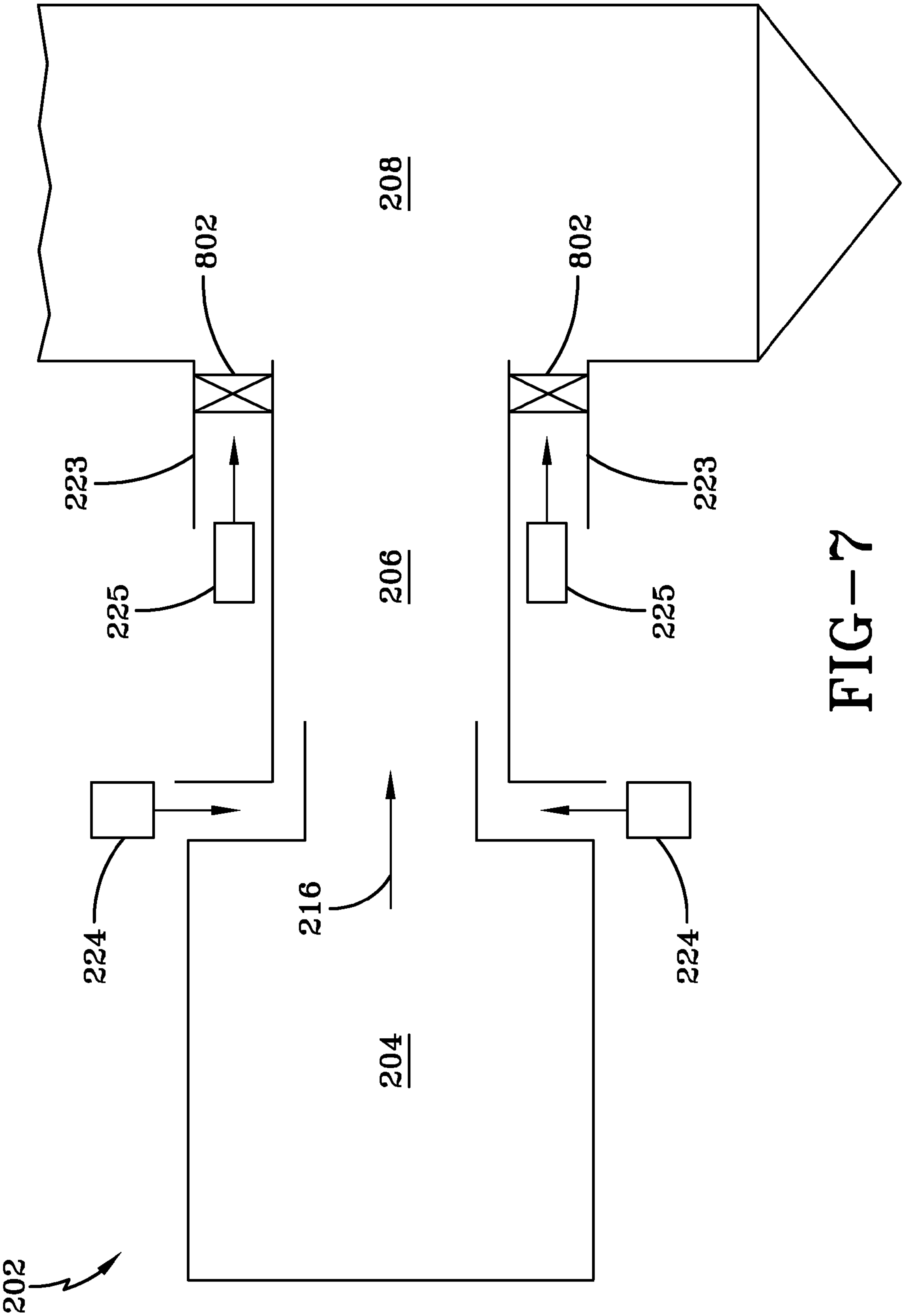
FIG—4



FIG–5



FIG–6



FIG—7

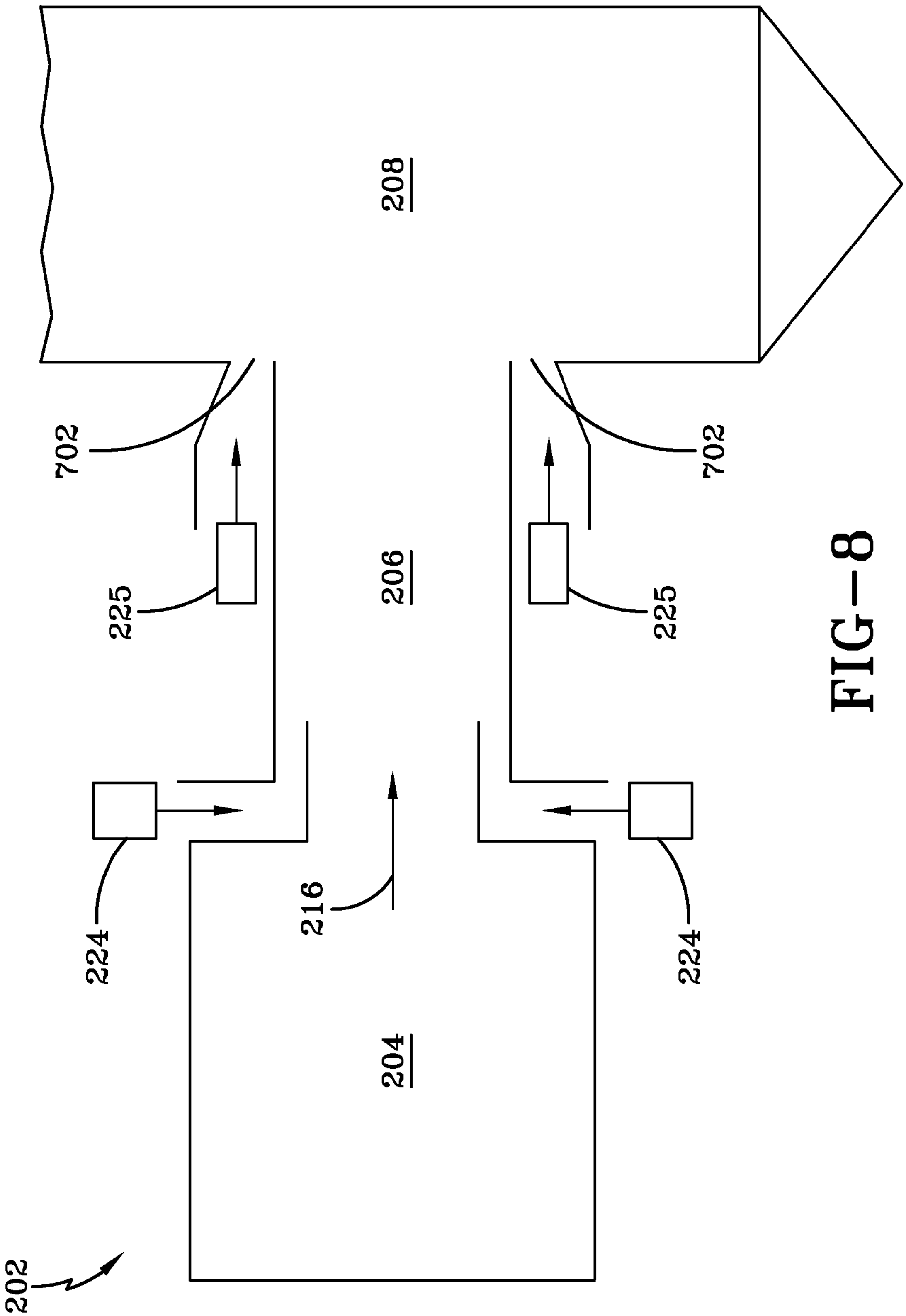


FIG-8

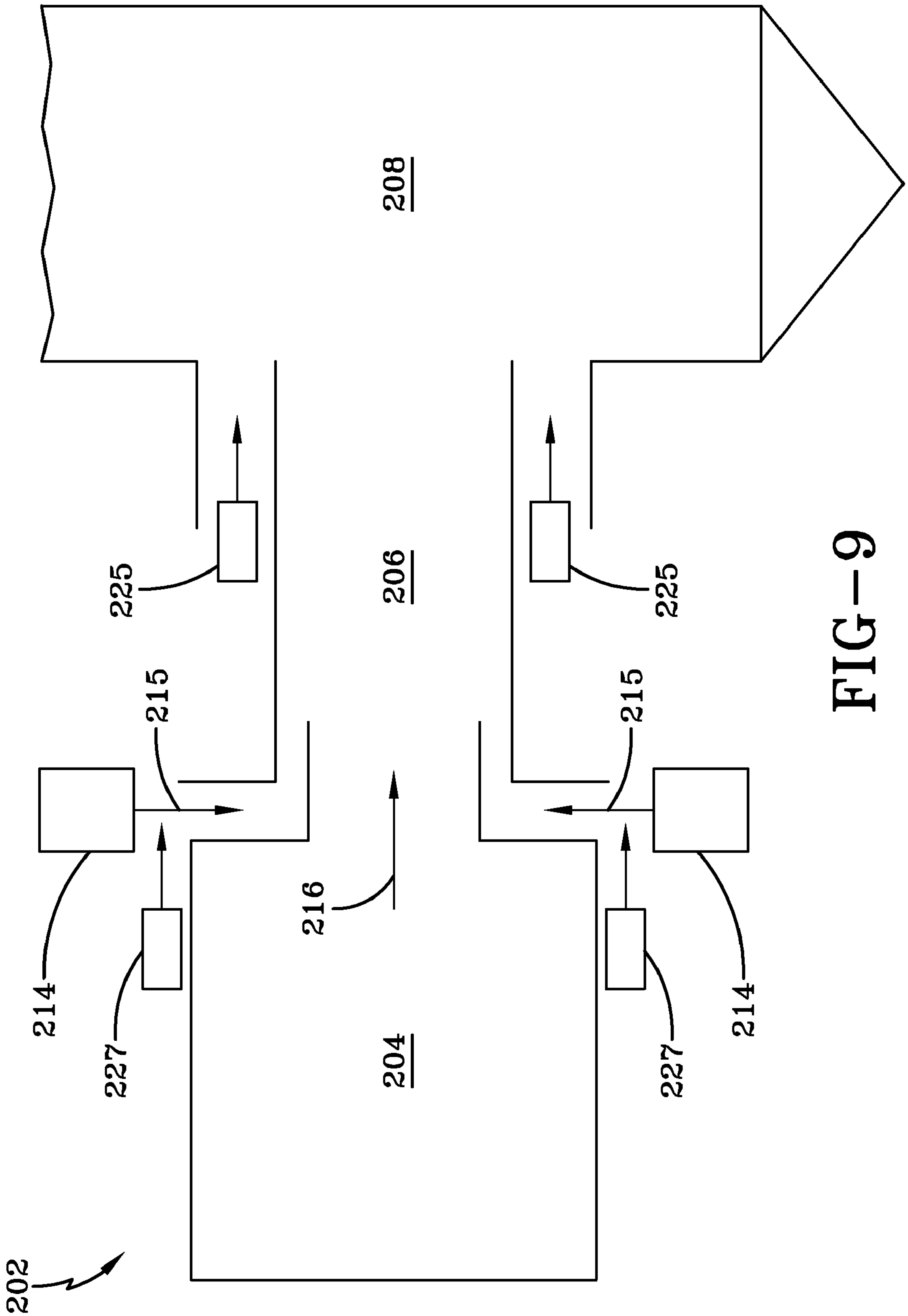


FIG-9

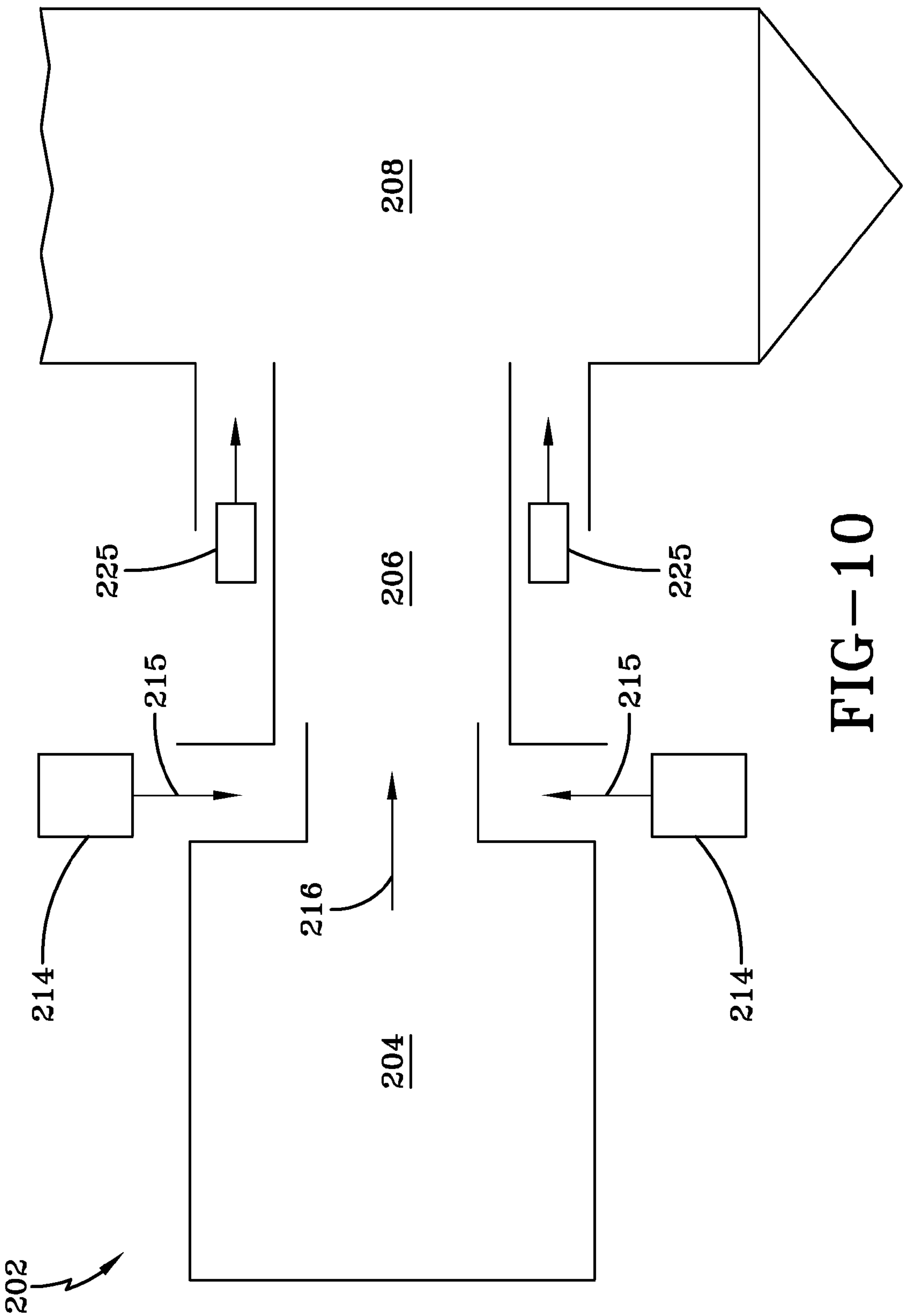
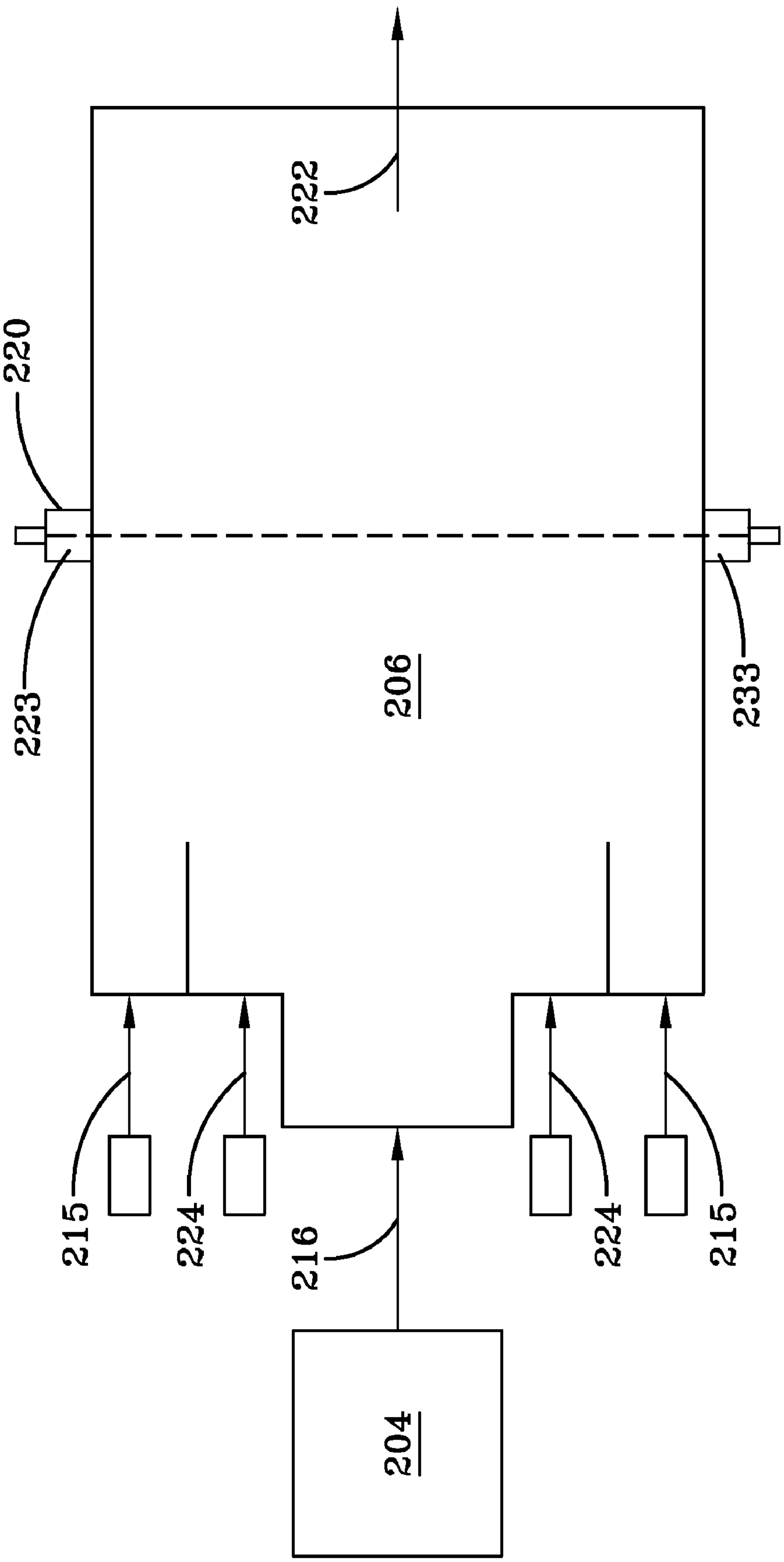


FIG-10



FIG–11

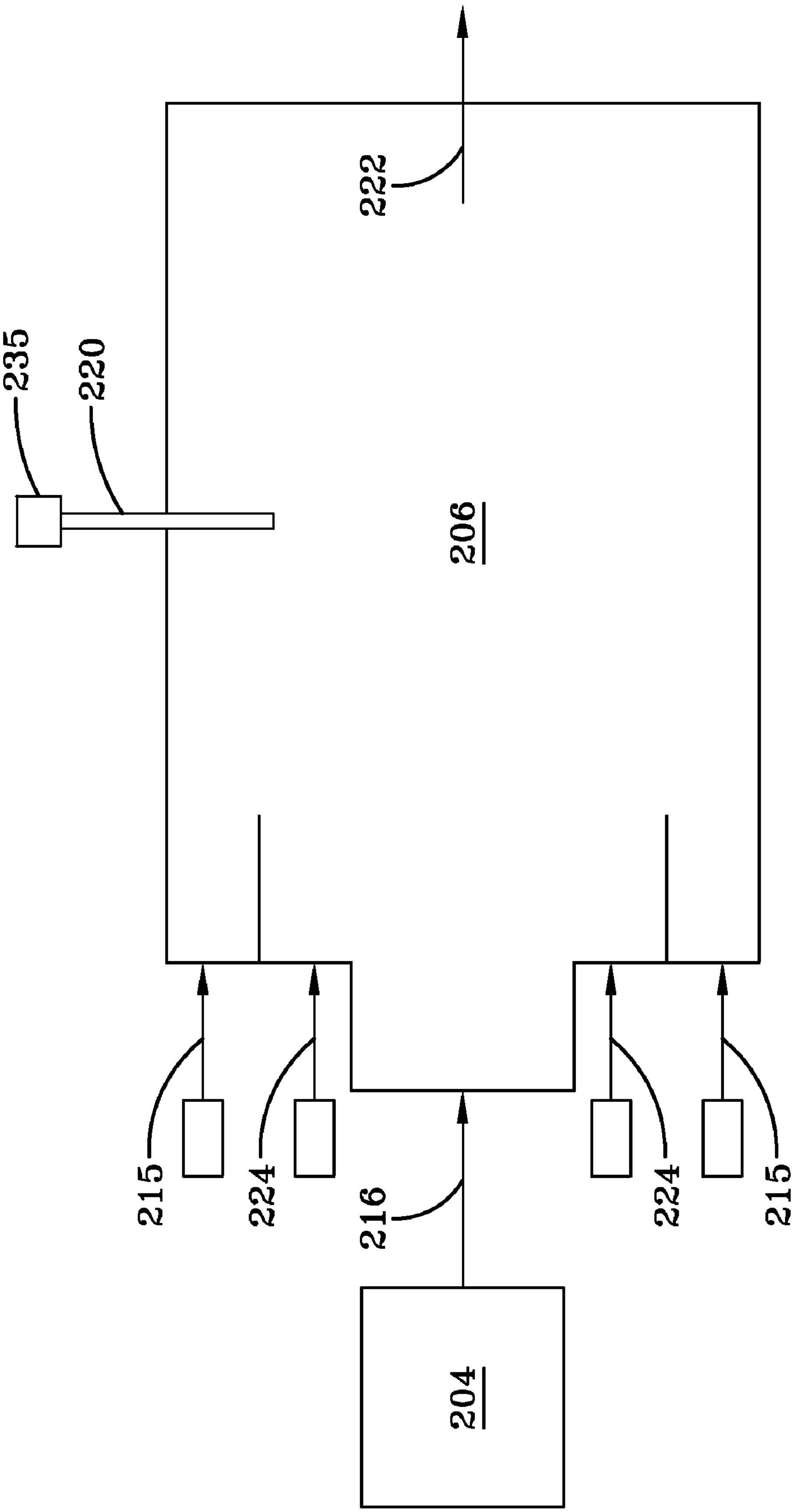


FIG-12

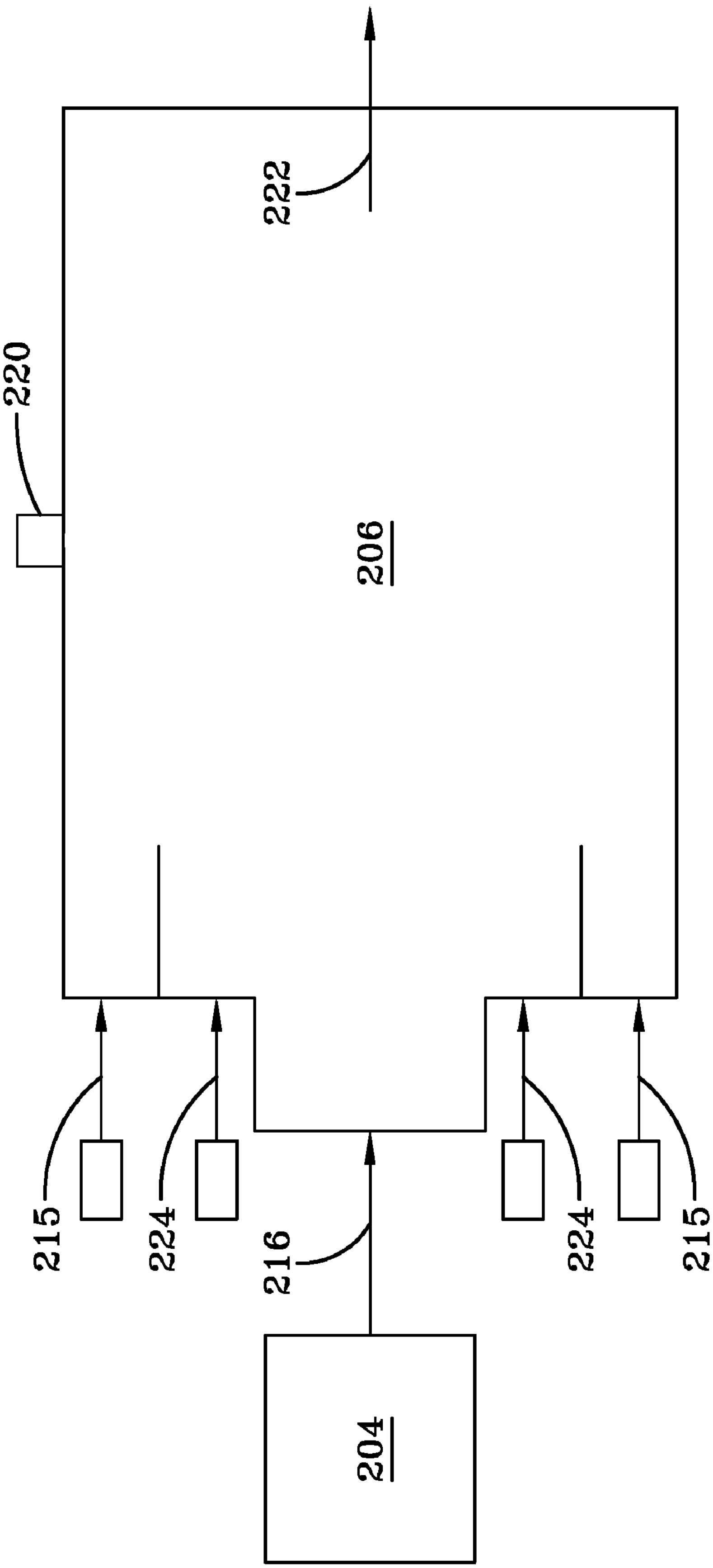


FIG-13

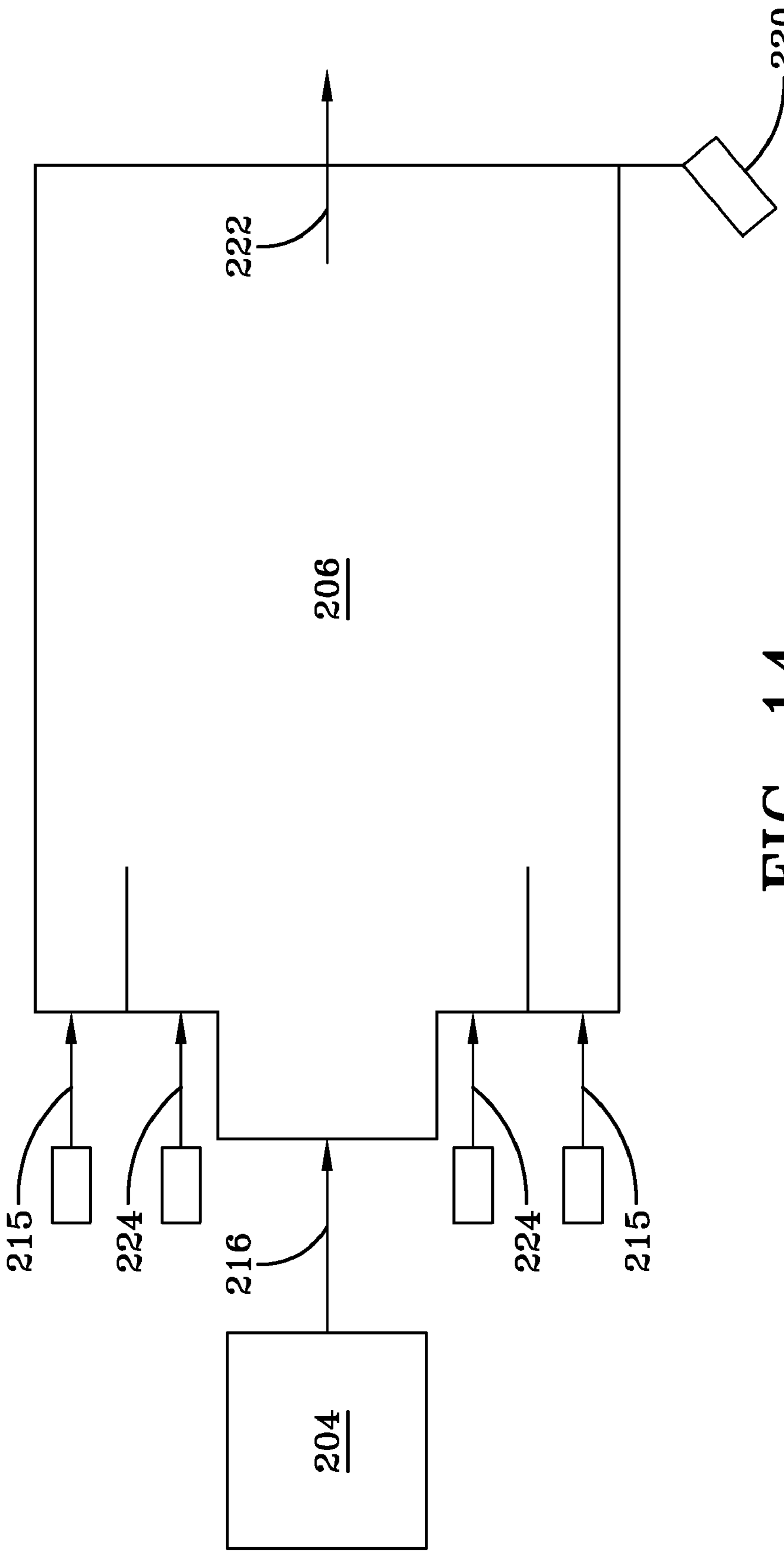
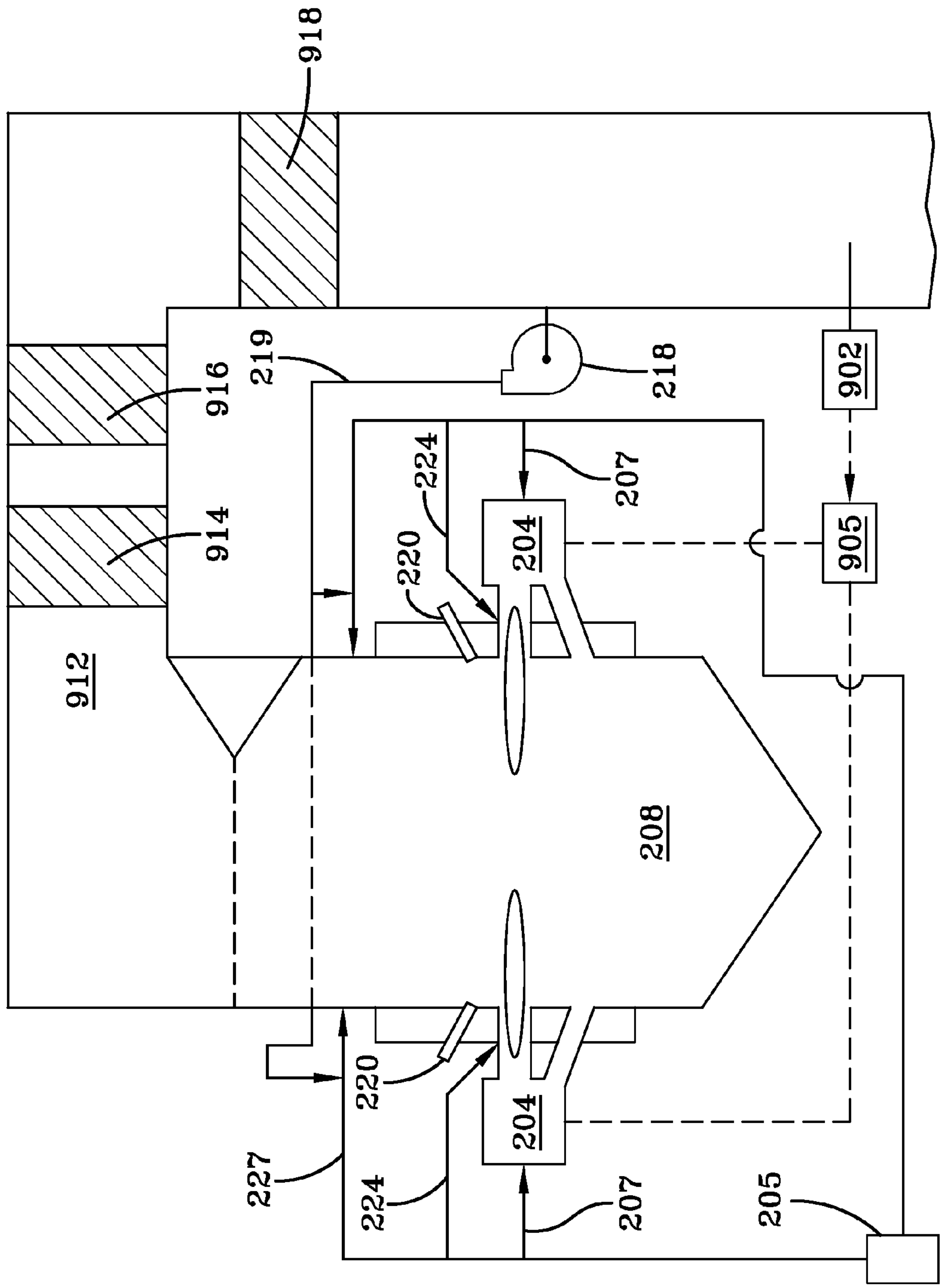
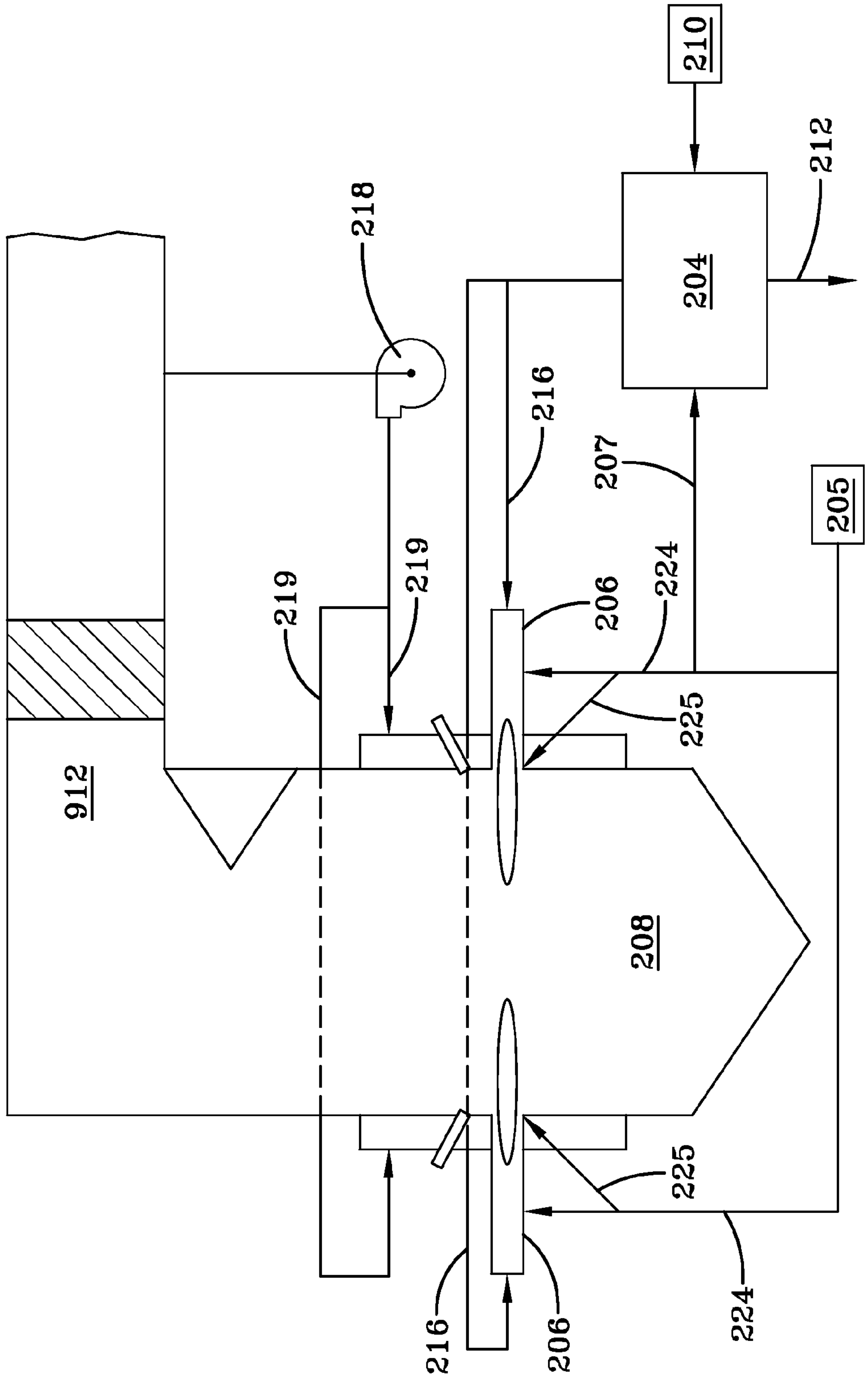


FIG-14


918
916
914
912
219
218
902
905
224
207
204
220
208
227
224
220
204
207
205

FIG—15


210
212
204
218
216
207
205
219
219
206
224
225
912
208
225
224
216
206

FIG—16

OXY/FUEL COMBUSTION SYSTEM WITH LITTLE OR NO EXCESS OXYGEN

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This Application is related to Application No. ______, entitled "COMBUSTION SYSTEM WITH STEAM OR WATER INJECTION", Attorney Docket No. 07238 USA, filed contemporaneously with this Application on Sep. 26, 2008, assigned to the assignee of the present disclosure and which is herein incorporated by reference in its entirety, Application No. ______, entitled "COMBUSTION SYSTEM WITH PRECOMBUSTOR", Attorney Docket No. 07255 USA, filed contemporaneously with this Application on Sep. 26, 2008, assigned to the assignee of the present disclosure and which is herein incorporated by reference in its entirety, Application No. ______, entitled "OXY/FUEL COMBUSTION SYSTEM WITH MINIMIZED FLUE GAS RECIRCULATION", Attorney Docket No. 07257 USA, filed contemporaneously with this Application on Sep. 26, 2008, assigned to the assignee of the present disclosure and which is herein incorporated by reference in its entirety, Application No. ______, entitled "CONVECTIVE SECTION COMBUSTION", Attorney Docket No. 07254 USA, filed contemporaneously with this Application on Sep. 26, 2008, assigned to the assignee of the present disclosure and which is herein incorporated by reference in its entirety, Application No. ______, entitled "OXY/FUEL COMBUSTION SYSTEM HAVING COMBINED CONVECTIVE SECTION AND RADIANT SECTION", Attorney Docket No. 07247 USA, filed contemporaneously with this Application on Sep. 26, 2008, assigned to the assignee of the present disclosure and which is herein incorporated by reference in its entirety, Application No. ______, entitled "PROCESS TEMPERATURE CONTROL IN OXY/FUEL COMBUSTION SYSTEM", Attorney Docket No. 07239 USA, filed contemporaneously with this Application on Sep. 26, 2008, assigned to the assignee of the present disclosure and which is herein incorporated by reference in its entirety, Application No. ______, entitled "COMBUSTION SYSTEM WITH PRECOMBUSTOR", Attorney Docket No. 07262Z USA, filed contemporaneously with this Application on Sep. 26, 2008, assigned to the assignee of the present disclosure and which is herein incorporated by reference in its entirety, and application Ser. No. 12/138,755, entitled "OXYGEN CONTROL SYSTEM FOR OXYGEN ENHANCED COMBUSTION OF SOLID FUELS", Attorney Docket No. 07162 USA, filed Jun. 13, 2008, assigned to the assignee of the present disclosure and which is incorporated herein by reference in its entirety.

FIELD OF THE DISCLOSURE

[0002] The present disclosure is directed to an oxy/fuel combustion system and method. In particular, the present disclosure is directed to an oxygen-enriched solid fuel combustion system and method.

BACKGROUND OF THE DISCLOSURE

[0003] As the world-wide demand for electric power continues to grow, so does the urgency for developing sustainable and environmentally responsible methods for power generation. Considering the abundance of global coal reserves, the recent emergence of oxygen fired coal technology, which is ideally suited for CO_2 capture, will be called upon to play a leading role. There is consequently a need to develop refinements to the technology which will improve its energy efficiency and reduce its cost of implementation. The disclosure disclosed herein is directed toward the accomplishment of this objective.

[0004] Due to slower overall combustion kinetics, excess oxygen requirements for coal combustion are generally much higher than for gaseous and liquid fuels. For example, whereas the stoichiometric ratio (i.e. ratio of actual to theoretical minimum O_2 required) for gaseous phase combustion (e.g. natural gas) is often 1.05 (5% excess) or less, the stoichiometric ratio for coal combustion is more typically in the vicinity of 1.2 (20% excess).

[0005] Therefore, there is an unmet need to provide efficient methods and systems for generating energy by solid fuel combustion in oxygen-based systems.

SUMMARY OF THE DISCLOSURE

[0006] This disclosure provides a device and method for burning solid fuel, such as coal, with oxygen and recycled flue gas in a multi-stage combustion process.

[0007] According to an embodiment, a combustion system includes a primary reactor arranged and disposed to receive a solid fuel and a first oxygen stream and deliver a first substantially gaseous product and a substantially solid or molten product, a secondary reactor in fluid communication with the primary reactor, and a furnace in fluid communication with the secondary reactor. In the embodiment, the secondary reactor is disposed to receive a second oxygen stream thereby converting the first substantially gaseous product from being oxygen deficient upon entering the secondary reactor to oxygen rich upon exiting the secondary reactor.

[0008] According to another embodiment, a method of operating a combustion system includes providing a primary reactor arranged and disposed to receive a solid fuel and a first oxygen stream and deliver a first substantially gaseous product and a substantially solid or molten product, providing a secondary reactor in fluid communication with the primary reactor, providing a furnace in fluid communication with the secondary reactor, and determining a stoichiometric ratio selected from the group consisting of the stoichiometric ratio of the primary reactor, the stoichiometric ratio of the secondary reactor, the stoichiometric ratio of the furnace, and combinations thereof. In the embodiment, the secondary reactor is disposed to receive a second oxygen stream converting the first substantially gaseous product from being oxygen deficient upon entering the secondary reactor to oxygen rich upon exiting the secondary reactor.

[0009] An advantage of the present disclosure is the ability to achieve substantially complete combustion of coal with a reduced amount of O_2.

[0010] Another advantage of the present disclosure is the ability to produce a product gas with high CO_2 purity.

[0011] Yet another advantage of the present disclosure is the ability to remove fly ash and other contaminants resulting in reduced fouling.

[0012] Further aspects of the method and system are disclosed herein. The features as discussed above, as well as other features and advantages of the present disclosure will be appreciated and understood by those skilled in the art from the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** illustrates a graphic representation of the effect of the stoichiometric ratio on flue gas CO_2 in oxygen-enriched coal combustion.

[0014] FIG. **2** illustrates a diagrammatic representation of an exemplary embodiment of a combustion system according to the disclosure.

[0015] FIG. **3** illustrates a diagrammatic representation of a portion of a combustion system according to an embodiment of the disclosure.

[0016] FIG. **4** illustrates a diagrammatic representation of a portion of a combustion system according to another embodiment of the disclosure.

[0017] FIG. **5** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0018] FIG. **6** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0019] FIG. **7** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0020] FIG. **8** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0021] FIG. **9** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0022] FIG. **10** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0023] FIG. **11** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0024] FIG. **12** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0025] FIG. **13** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0026] FIG. **14** illustrates a diagrammatic representation of a portion of a combustion system according to still another embodiment of the disclosure.

[0027] FIG. **15** illustrates a diagrammatic representation of an alternate exemplary embodiment of a combustion system according to the disclosure.

[0028] FIG. **16** illustrates a diagrammatic representation of an alternate exemplary embodiment of a combustion system according to the disclosure.

[0029] Wherever possible, the same reference numbers will be used throughout the drawings to represent the same parts.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0030] The present disclosure now will be described more fully hereinafter with reference to the accompanying drawings, in which a preferred embodiment of the disclosure is shown. This disclosure may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete and will fully convey the scope of the disclosure to those skilled in the art.

[0031] Certain embodiments of the present disclosure include systems and methods for combusting solid fuel. As used herein, the term "solid fuel" and grammatical variations thereof refers to any solid fuel suitable for combustion purposes. For example, the disclosure may be used with many types of carbon-containing solid fuels, including but not limited to: anthracite, bituminous, sub-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. As used herein, the term "oxygen" and grammatical variations thereof refers to an oxidizer having an O_2 concentration greater than that of atmospheric or ambient conditions. As used herein, the term "oxy/coal combustion" and grammatical variations thereof refers to coal combustion in oxygen, the term "air/coal combustion" and grammatical variations thereof refers to coal combustion in air, the term "oxy/fuel combustion" and grammatical variations thereof refers to fuel combustion in oxygen, and the term "air/fuel combustion" and grammatical variations thereof refers to fuel combustion in air. As used herein, the term "combustion fluid" and grammatical variations thereof refers to a fluid formed from and/or mixed with the products of combustion, which may be utilized for 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. Although not so limited, one such example is flue gas. As used herein, the term "recycled flue gas" and grammatical variations thereof refers to combustion fluid exiting the system that is recirculated to any portion of the system. As used herein, the term "flue gas recycle" and grammatical variations thereof refers to a configuration permitting the combustion fluid to be recirculated.

[0032] FIG. **1** illustrates a graphic representation of the effect of the stoichiometric ratio on flue gas CO_2 during the combustion of coal with oxygen; hereinafter referred to as oxygen fired coal or oxygen fired fuel combustion. In the context of air fired fuel combustion, operation with a relatively high stoichiometric ratio results in relatively high stack sensible enthalpy losses and fan power requirements, the latter being typically only a fraction of a percent of gross power generation of the steam turbine. However, the penalty of relatively high stoichiometric ratio operation during oxygen fired fuel combustion is much greater. This is principally due to higher power requirements for compression within the Air Separation Unit (ASU), as well as the need for higher capacity ASU equipment, leading to higher capital costs. As a basis for comparison, the ASU compressor power is typically several percent of gross generation, rather than the fraction of a percent for fan power in air fired fuel systems.

[0033] Another reason for the greater need for reducing the stoichiometric ratio during oxygen fired coal boiler operation is that the products of oxygen fired coal combustion comprise principally CO_2, H_2O, and several inert species; the most abundant among them being O_2. Hence, as the stoichiometric ratio is reduced, the CO_2 concentration of the product gas stream increases, reducing the burden of downstream equipment required for CO_2 purification. Moreover, the total volume of gases processed in the CO_2 purification is lowered, leading to lower capital and operating costs. It should be noted that CO_2 compression power requirements may be of the same order of magnitude as for compression within the ASU.

[0034] The challenge in low stoichiometric ratio operation during coal combustion is in attaining high combustion efficiency. Emissions of CO and unburned carbon are known to increase substantially as the stoichiometric ratio is lowered beneath about 1.2, leading to poor thermal efficiency, a higher propensity for fouling, potentially hazardous conditions within the plant and a higher collection burden on downstream particulate control equipment. Known systems do not provide means for generating electric power in oxygen fired coal boilers with simultaneously low stoichiometric ratio and high thermal efficiency.

[0035] Specifically, FIG. **1** illustrates the variation of CO_2 purity and balance of inert gases, principally O_2, SO_2 and N_2 formed from fuel nitrogen, with stoichiometric ratio for oxygen fired fuel combustion of a typical low sulfur (~1 wt %) coal. As illustrated in FIG. **1**, lowering the stoichiometric ratio from about 1.2 to about 1.05 reduces the concentration of inerts from about 18% to about 6% and increases the CO_2 concentration from about 81.5% to about 94%. Note that all concentrations are presented on a dry basis. Methods of combustion according to the present disclosure provide low excess oxygen and serve as a method for reducing the size of, or potentially eliminating, CO_2 purification equipment. Moreover, both the size/extent of purification equipment and the respective operating costs may be lower due to the smaller volume of gases to be removed. The reduction or removal of this equipment may lead to significant savings, particularly in relation to flue gas compression required for efficient CO_2 transport, for example to an external pipeline, where pressures of 1000 psia or greater, depending upon end use, may be required.

[0036] The combustion system according to certain embodiments operates at stoichiometric ratios of about 1.05 or less. Known coal combustion systems typically operate at a stoichiometric ratio of about 1.2 or greater. Operation of a solid fuel combustion system of a stoichiometric ratio of less than about 1.05 results in additional features being desired for efficient combustion system operation. For example, it is desirable to provide additional residence time between the solid fuel and oxidizer to facilitate complete evolution of fuel carbon into a gaseous phase. It is also desirable to provide oxygen instead of air as an oxidizer in order to attain sufficiently high temperature within the primary reactor to melt ash constituent of the solid fuel, and to increase the combustion reaction rates throughout the system. It is further desirable to provide a controlled environment for mixing of oxygen and fuel evolved from the solid to the gaseous phase in order to minimize the required residence time for complete burnout and avoid high temperature damage that could otherwise result during oxygen fired fuel combustion. It is also desirable to provide close-coupled combustion instrumentation to provide feedback with which to control the combustion process.

[0037] FIG. **2** illustrates a diagrammatic representation of an exemplary embodiment of a combustion system according to the disclosure. Specifically, FIG. **2** illustrates an embodiment of an oxygen fired coal combustion system **202** required to facilitate efficient, low-excess O_2 operation. As illustrated, oxygen fired coal combustion system **202** includes a primary reactor **204**, a secondary reactor **206**, and a furnace **208** (which includes, but is not limited to a combustion chamber). Primary reactor **204** is in fluid communication with secondary reactor **206**. Secondary reactor **206** is in fluid communication with primary reactor **204** and furnace **208**. Furnace **208** is in fluid communication with secondary reactor **206**.

[0038] In one embodiment, primary reactor **204** may be a slagging combustor/gasifier such as, for example, a slagging cyclone. The type of reactor is selected to provide the ability to achieve relatively long solid particle residence times and withstand high gas temperatures, thus promoting efficient gasification and/or combustion of the feed coal with little or no carbon residue. Residual solid material **212**, which includes ash, may be removed as a viscous slag and delivered into the boiler where it is captured in the bottom of furnace **208**, thus minimizing the concentration of particulate in flue gas. Residual solid material **203** may be integral, as illustrated in the embodiment of FIG. **2**. Alternatively, slag collection may be separate from furnace **208** as illustrated in the embodiment of FIG. **16**. In another embodiment, primary reactor **204** may be a slagging cyclone which is operated with less than the stoichiometric amount of oxygen required for complete combustion of the fuel. That is, the stoichiometric ratio of the fuel and oxidant introduced into the primary reactor is less than 1.0. More preferably it is less than 0.95, and still more preferably it is the range of 0.3 to 0.95, wherein the lower limit is sufficiently high to ensure that the slag can be maintained in a molten state and the higher limit is dictated by the preference, for control purposes, to maintain at least a minimal amount of oxygen that must be added outside the primary reactor to complete the low excess oxygen combustion process. Suitable arrangements of slagging combustor/gasifiers include, for example, the arrangement disclosed in U.S. Pat. No. 5,291,841, and U.S. Pat. No. 5,052,312, which are both incorporated herein by reference in their entirety, while not intending to be limiting.

[0039] Referring to FIG. **2**, primary reactor **204** is arranged and disposed to receive fuel **210** and oxygen **205**. Fuel **210** may be crushed or pulverized fuel in a proportion dictated by the need to attain a specific temperature for primary reactor **204**. The fuel may also be conveyed by a small amount of a transport fluid. Although not so limited, the transport fluid may be air, CO_2, N_2, liquid or gaseous H_2O, recycled flue gas, or combinations thereof. The desired temperature of primary reactor **204** may be determined based upon the slag melting temperature, and monitored using commercially available instrumentation for temperature measurement. These temperatures permit conversion of essentially all of a solid carbon fuel into a gaseous phase. Primary reactor **204** is arranged and disposed to permit a residual solid material **212** to be expelled from it (i.e. slag). Generally, residual solid material **212** is in a molten state and is essentially free of residual carbon. Primary reactor **204** is arranged and disposed to permit a partially combusted gaseous product **216** to be expelled from it into secondary reactor **206**. In one embodiment, residual solid material **212** is expelled separate from partially combusted gaseous product **216** expelled from primary reactor **204**.

[0040] In another embodiment, oxygen fired coal combustion system **202** includes a recirculator **218** arranged and disposed to permit a recycled flue gas **214** to be transported from a recirculator **218** to primary reactor **204**. In the embodiment, recycled flue gas **214** is injected into primary reactor **204** with a stream of primary oxygen **207** and crushed or pulverized fuel in a proportion dictated by the preference to maintain a predetermined temperature in primary reactor **204** in excess of residential solid material **212** temperature and convert essentially all of the solid carbon into a gaseous phase. Other process constraints such as moderation of boiler radiant heat flux and final steam temperatures may also contribute to the selection of primary reactor **204** operating conditions. As discussed below, embodiments of the present disclosure also include streams of tertiary oxygen **225** and quaternary oxygen **227**. In addition, embodiments include additional streams of recycled flue gas **215**, **219**.

[0041] In one embodiment, secondary reactor **206** may be arranged and disposed to receive recycled flue gas **214** from recirculator **218** thereby adding it to partially combusted gaseous product **216**.

[0042] The placement of the streams of the oxygen illustrated in FIGS. **3** through **8** may permit increased control of oxygen fired coal combustion system **202**. Referring to FIG. **3**, secondary reactor **206** includes an inner stream comprised of partially combusted gaseous product **216** expelled from primary reactor **204**. Partially combusted gaseous product **216** may also include trace amounts of fully or partially combusted particulates. In one embodiment, secondary reactor **206** may further include at least one stream of secondary oxygen **224** (see also FIG. **2**) bounding partially combusted gaseous product **216** as it enters secondary reactor **206**. Reactants introduced into secondary reactor **206** in this manner afford several advantages. Primarily, the configuration of secondary reactor **206** allows for control of the extent of reaction and the momentum of the reacting gases. This control or operation is exerted principally through the relative amounts of fuel and oxygen present within secondary reactor **206**, the manner in which reactants are introduced into secondary reactor **206**, and the size of secondary reactor **206**.

[0043] For example, as the amount of oxygen in secondary oxygen **224** is increased relative to fuel **210**, equilibrium favors an increase in the extent of fuel oxidation. The increase in fuel oxidation should lead to greater energy release prior to the gases discharging into furnace **208** where the gases are diluted with furnace **208** gases. This in turn translates to higher mixture temperature and faster chemical kinetics within secondary reactor **206**. The faster reaction speeds will further increase the extent of reaction (i.e. shortening the approach to equilibrium). Moreover, the higher temperature gas will possess a lower density and, hence, a higher velocity. Therefore it will also possess greater momentum as it enters furnace **208**.

[0044] As another illustration, if the length of secondary reactor **206** is increased, the time available for reaction also increases. Consequently, the energy release, mixture temperature, velocity and momentum should again increase.

[0045] As a further example, the manner of mixing illustrated in FIG. **3** has two principal advantages. First, arranging the stream of secondary oxygen **224** around partially combusted gaseous product **216** entering from primary reactor **204** creates a layer of relatively cool gas adjacent to secondary reactor **206** wall to cool and protect the wall from high temperature damage. The potential for high temperature damage is much greater for oxygen fired fuel combustion relative to air fired fuel combustion since the flame temperature attained using oxygen can be as much as 1500° F. higher than the temperature attained with air, and the reaction rates can be increased by a factor of 10 or more relative to combustion with air. Further, by streamlining partially combusted gaseous product **216** at secondary reactor **206** intake such that the flow vectors of oxygen and primary reactor **204** effluent are directed essentially along the axis of secondary reactor **206**, transverse mixing can largely be eliminating. That is, the initial mixing between oxidizer (e.g. oxidizer) and reactant occurs can be confined to a shear layer between the two fluids. By largely eliminating transverse mixing, it is possible to minimize the deposition of particulate onto the reactor walls (i.e. carry-over from primary reactor **204**) and additionally minimize the contact of high temperature gases, which thereby further reduces the risk of high temperature damage.

[0046] Referring to FIG. **4**, in another embodiment, secondary reactor **206** may include recycled flue gas **214** provided or injected to bound or otherwise surround the stream of secondary oxygen **224**. The advantage of this is that it provides an additional buffer to protect against high temperature gases and/or particulate coming into contact with the walls of secondary reactor **206** while permitting intimate contact between the oxygen and products from primary reactor **204**. In addition, it permits more aggressive reactant mixing within secondary reactor **206** without increasing the risk of high temperature damage.

[0047] As illustrated in FIG. **5**, the use of recycled flue gas **214** in secondary reactor **206** may be mixed with stream of secondary oxygen **224** by means of a swirler generator **502**. In other embodiments, other techniques known in the art for enhancing mixing stream of secondary oxygen **224** and partially combusted gaseous product **216** may be included. Mixing the stream of secondary oxygen **224** and partially combusted gaseous product **216** provides control for adjusting the momentum of the gases discharged from secondary reactor **206** into the furnace **208**. That is, adding more of the recycled flue gas **214** increases the momentum of partially combusted gaseous product **216**, while reducing the amount of recycled flue gas **214** reduces the momentum.

[0048] Referring to FIG. **6**, in yet another embodiment, secondary reactor **206** may include at least one oxygen injector **223** providing the stream of tertiary oxygen **225** (see also FIG. **1**) immediately adjacent to the area bounding a secondary reactor expellant **222** being transported from secondary reactor **206** to furnace **208** (not shown in FIG. **6**). The stream of tertiary oxygen **225** illustrated in FIG. **6** enables increased control over the properties of the reacting mixture exiting secondary reactor **206**, which can afford certain performance advantages. For example, it may in certain circumstances be advantageous to operate the system with a stoichiometric ratio less than 1.0 at the exit of secondary reactor **206** instead of adding tertiary oxygen to complete the combustion process. Operation in this manner should extend the reaction zone (or flame) farther into furnace **208**, thereby lowering the peak temperature and creating a more evenly distributed heat release pattern. Delaying of the completion of combustion also extends the life of transient, but highly radiative species, in the flame. This enhancement of the radiant species of the flame will further assist in lowering the peak flame temperature and in improving the efficiency of heat transfer from the flame to the surroundings. The use of tertiary oxygen **225** is also advantageous in that it can be introduced into secondary reactor expellant **222** in such a way as to promote rapid mixing without the constraint of overheating the secondary reactor walls. For example, tertiary oxygen **225** can be introduced through a plurality of swirl vanes **702** as illustrated in FIG. **7**, or through a plurality of converging nozzles **802** as illustrated in FIG. **8**. Those skilled in the art will appreciate that there are numerous other ways to introduce tertiary oxygen within this disclosure.

[0049] Two additional embodiments which incorporate the use of tertiary oxygen **225** are provided in FIGS. **9** and **10**. FIG. **9** illustrates an embodiment wherein stream of quaternary oxygen **227** is premixed with recycled flue gas **214** prior to introduction into secondary reactor **206** (see also FIG. **3**). The embodiment in FIG. **10** does not include quaternary oxygen **227**, but relies solely on oxygen in recycled flue gas **215** as the oxidizing agent. Since coal combustion system **202** is operated with some excess oxygen, recycled flue gas **214** typically includes oxygen. It will be appreciated that the two embodiments disclosed in FIGS. **9** and **10** result in attenuation of the reactions within secondary reactor **206** compared with embodiments wherein undiluted secondary oxygen **224** is introduced adjacent to partially combusted gaseous product **216** exiting primary reactor **204** (not shown in FIG. **10**).

[0050] Systems employing this disclosure operate in a dynamic or changing mode. Moreover, a plurality of reactors (**204** and/or **206**) may operate in parallel. In such cases, maintaining optimal operation with low excess oxygen requires combustion instruments to measure properties associated with secondary reactor **206** in the system (i.e. local properties). Referring to FIGS. **11** through **14**, secondary reactor **206** may include one or more local combustion instruments **220** arranged and disposed to provide information (including, but not limited to, feedback signals to the fuel control system, the oxygen control system and/or the recycled flue gas control system) regarding conditions within secondary reactor **206**. For systems employing a plurality of secondary reactors **206**, local combustion instruments **220** generally are disposed on or within each of secondary reactors **206** in the system. Local combustion instrument **220** may be selected from the group of instruments consisting of a flame scanner, a thermocouple, a non-intrusive instrument such as a tunable diode laser, an optical or acoustic sensor, and other instruments. Local combustion instrument **220** may provide information including, but not limited to, fluid temperature, fluid composition, and/or temperature of portions of furnace **208**. Local combustion instruments **220** may be located at any point within secondary reactor **206** or furnace **208** permitting local combustion instrument **220** to measure properties of secondary reactor expellant **222** discharged from secondary reactor **206** to furnace **208**. Information from local combustion instrument **220** may subsequently deliver a control signal based upon the measurement by local combustion instrument **220**. The control signal may result, for example, in adjustment of the individual flow rate of secondary oxygen **224** or tertiary oxygen **225** to the radiant to secondary reactor **206**. As illustrated in the embodiment in FIG. **11**, local combustion instrument **220** may include a transmitter **223** and/or a receiver **233**. As illustrated in the embodiment in FIG. **12**, local combustion instrument **220** may include a thermocouple **235**.

[0051] In systems operating with a plurality of secondary reactors **206** operating in parallel, an additional "global" combustion instrument **902** is included to sample the mixed products of combustion, in particular the concentrations of excess oxygen and carbon monoxide (CO), from all of secondary reactors **206**. Such an embodiment is illustrated in FIG. **15**. In this embodiment, the control system is configured to take both the local and global measurements as input. Signals from global measurement instrument **902** are used by a controller **905** to determine whether or not more or less total oxygen is required, while signals from local combustion instruments **220** are used to determine the balance of combustion conditions among all parallel reactors. If, for example, controller **905** indicates that more oxygen is needed to improve combustion efficiency (i.e. lower CO emission), then local combustion instruments **220** are examined to determine which of secondary reactor(s) **206** require the additional O_2. It will be appreciated by those of ordinary skill in the art that this mode of control permits balancing of multiple secondary reactors **206** operating in parallel, which will in turn facilitate efficient combustion with minimal excess oxygen.

[0052] Another mode of operation of the embodiment illustrated in FIG. **15** includes the use of stream of quaternary oxygen **227** (see also FIG. **2**) and/or recycled flue gas **219** in a region of furnace **208** downstream of secondary reactors **206**. This would be desirable for operating with a stoichiometric ratio below 1.0, as may be necessary after addition of tertiary oxygen **225**. Such an operating mode should be advantageous, for example, to reduce emissions of NO_x. The use of the recycled flue gas in this area has a two-fold advantage. First, it may help to promote mixing of gases. Second, it may be used in a boiler with a convective pass section **912** downstream of furnace **208** radiant section to adjust furnace **208** exit gas temperature and flow rate to optimize the transfer of the flue gas energy to produce steam. Quaternary oxygen **227** and recycled flue gas **219** may be introduced as separate streams or premixed and introduced as a composite stream or streams. As illustrated in FIG. **15**, the embodiment of coal combustion system **202** includes heat exchangers in convective pass section **912**. The heat exchangers may include a secondary superheater **914**, a reheat superheater **916**, and a primary superheater **918**. In another embodiment, an economizer is also included. In yet other embodiments, additional heat exchangers may be included.

[0053] Another embodiment of the disclosure is illustrated in FIG. **16**. In this embodiment, primary reactor **204** delivers a partially oxidized gas stream to a plurality of secondary reactors **206** configured as described above. It will be appreciated by those of ordinary skill in the art that an advantage of this embodiment is the reduction in solid fuel handling, metering and transport equipment needed compared to a system wherein multiple primary reactors are employed. A further advantage is simplification of the balancing of secondary reactors **206**. This is because a principal cause of secondary reactor **206** imbalance in a system employing a plurality of primary reactors **204** is the relative imbalance of fuel and oxygen flows to each of primary reactors **204**. The simplification of secondary reactor **206** balancing operation should lead to improved system reliability and the ability to achieve complete combustion at even lower excess oxygen level than attainable in coal combustion system **202** including a plurality of primary reactors **204**.

[0054] While the disclosure has been described with reference to a preferred embodiment, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the disclosure. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the disclosure without departing from the essential scope thereof. Therefore, it is intended that the disclosure not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this disclosure, but that the disclosure will include all embodiments falling within the scope of the appended claims.

What is claimed is:

1. A combustion system comprising:

a primary reactor arranged and disposed to receive a solid fuel and a first oxygen stream and deliver a first substantially gaseous product and a substantially solid or molten product;

a secondary reactor in fluid communication with the primary reactor; disposed to receive a second oxygen stream thereby converting the first substantially gaseous product from being oxygen deficient upon entering the secondary reactor to oxygen rich upon exiting the secondary reactor; and

a furnace in fluid communication with the secondary reactor.

2. The system of claim **1**, wherein at least one of the oxygen streams is substantially devoid of fluids selected from the group consisting of air, nitrogen, and combinations thereof.

3. The system of claim **1**, wherein at least one of the oxygen streams comprises at least about 30% by weight O_2.

4. The system of claim **1**, wherein the primary reactor is configured to operate with a stoichiometric ratio of less than 1.0.

5. The system of claim **1**, wherein the secondary reactor is configured to operate with a stoichiometric ratio of greater than 1.0.

6. The system of claim **1**, wherein the combustion system is configured to measure one or more properties of the combustion gases that can be correlated with the overall stoichiometric ratio of the system.

7. The system of claim **1**, wherein the primary reactor is configured to operate with a stoichiometric ratio of less than 0.95.

8. The system of claim **1**, wherein the secondary reactor is configured to operate with a stoichiometric ratio of between 1.0 and 1.10.

9. The system of claim **1**, wherein the secondary reactor is configured to operate with a stoichiometric ratio of between 1.0 and 1.05.

10. The system of claim **1**, wherein the partially combusted gaseous product is substantially surrounded by an oxidizing gas within at least a portion of the secondary reactor.

11. The system of claim **10**, wherein the oxidizing gas includes oxygen.

12. The system of claim **10**, wherein the oxidizing gas includes recycled flue gas.

13. The system of claim **10**, wherein the oxidizing gas comprises both oxygen and recycled flue gas.

14. The system of claim **1**, wherein the second oxygen stream is mixed with the partially combusted gaseous product as it exits the secondary reactor.

15. The system of claim **1**, wherein the primary reactor is configured to permit a residual solid material in a molten state and substantially free of residual carbon to be removed from it.

16. The system of claim **1**, further comprising a recirculator arranged and disposed to permit a flue gas to be transported from a flue to the primary reactor.

17. The system of claim **1**, wherein a local combustion instrument is arranged and disposed to provide information on conditions within the secondary reactor and/or of an expellant fluid from the secondary reactor.

18. The system of claim **1**, further comprising at least one additional secondary reactor in fluid communication with the primary reactor; wherein the additional secondary reactor and the first secondary reactor are arranged and disposed to communicate at least one stream of an oxidizing gas to the first substantially gaseous product, wherein the additional secondary reactor and the first secondary reactor are in fluid communication with the furnace, wherein the primary reactor is configured to operate with a stoichiometric ratio of less than 1.0, wherein the secondary reactor is configured to operate with a stoichiometric ratio of greater than 1.0, and wherein the combustion system is configured to measure at least a property of the combustion gases that can be correlated with the overall stoichiometric ratio of the system.

19. The system of claim **1**, wherein the furnace is arranged and disposed to receive a fluid selected from the group of fluids consisting of oxygen, recycled flue gas, and combinations thereof, wherein the furnace is arranged and disposed to receive the fluid in a portion of the furnace substantially removed from the secondary reactors thereby permitting an overall stoichiometric ratio of the system greater than 1.0.

20. A combustion system as in claim **1**, further comprising:

a local combustion instrument arranged and disposed to provide information selected from the group consisting of conditions within the secondary reactor, conditions of an expellant fluid from the secondary reactor, and combinations thereof;

a global combustion instrument arranged and disposed to provide information on conditions within the flue gas at a point downstream from the furnace; and

a controller arranged and disposed to controllably provide oxygen streams in response to the information.

21. A method of operating a combustion system comprising:

providing a primary reactor arranged and disposed to receive a solid fuel and a first oxygen stream and deliver a first substantially gaseous product and a substantially solid or molten product;

providing a secondary reactor in fluid communication with the primary reactor; disposed to receive a second oxygen stream converting the first substantially gaseous product from being oxygen deficient upon entering the secondary reactor to oxygen rich upon exiting the secondary reactor;

providing a furnace in fluid communication with the secondary reactor; and

determining a stoichiometric ratio selected from the group consisting of the stoichiometric ratio of the primary reactor, the stoichiometric ratio of the secondary reactor, the stoichiometric ratio of the furnace, and combinations thereof.

22. The method of claim **21**, further comprising:

providing a controlled amount of oxygen to the primary reactor to maintain a stoichiometric ratio of less than about 1.0; and

providing a controlled amount of oxygen to the secondary reactor to maintain a stoichiometric ratio of greater than about 1.0.

23. The method of claim **22**, further comprising operating with the stoichiometric ratio of the primary reactor below 0.95.

24. The method of claim **22**, further comprising operating with the stoichiometric ratio of the secondary reactor between 1.0 and 1.10.

25. The method of claim **22**, further comprising operating with the stoichiometric ratio of the secondary reactor between 1.0 and 1.05.

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