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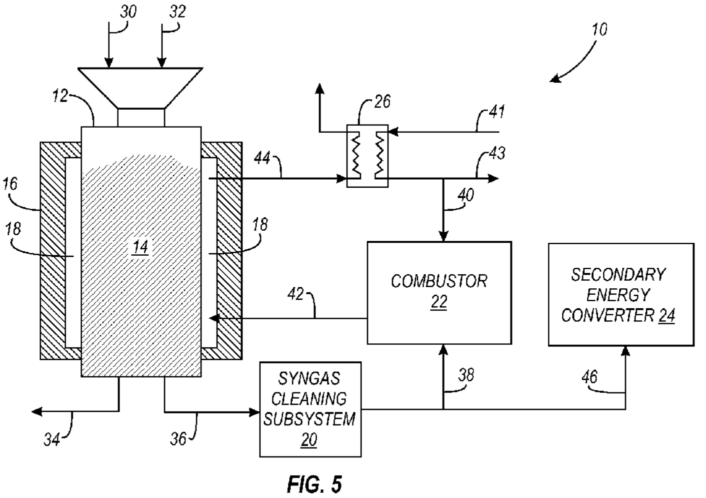

FIG. 5

(57) **Abstract:** A method and apparatus, in one example, relates to a system and method for the generation of very low-tar, high-energy synthesis gas from a large variety of carbonaceous feedstock, including those with higher moisture levels than conventional gasifiers. The system comprises a gasification reactor (12) wherein a portion of the energy of the output syngas of the reactor is used to heat the gasification zone of the reactor (12) via an annular space (18) surrounding the gasification zone of the gasifier (12), to maintain a temperature condition above 800°C. The maintenance of a long, quasi-uniform high-temperature gasification zone reduces the amount of input air or oxygen, reduces bridging within the gasifier, cracks pyrolysis oils, increases the conversion of char, minimizes heat losses from the bed, and converts moisture within the packed bed (14) into a gasification medium. This results in a very low tar synthesis gas with less nitrogen dilution and higher energy content than conventional gasifiers. The reduction in bridging reduces operating costs.

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# THERMALLY STABLE COCURRENT GASIFICATION SYSTEM AND ASSOCIATED METHODS

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## CROSS REFERENCE TO RELATED APPLICATIONS

[01] This application claims priority to co-pending, commonly owned United States provisional patent application serial number 60/890,884 filed on 2/21/2007, entitled "THERMALLY STABLE COCURRENT GASIFICATION SYSTEM", which is incorporated by reference herein.

## FIELD OF THE INVENTION

[02] The present invention relates to a gasification apparatus for producing high-caloric combustible gases with low tar content.

## BACKGROUND OF THE INVENTION

[03] Gasification technology development dates back to the early 1880s. In its simplest form, gasification of any solid carbonaceous fuel occurs through partial or substochrometaic oxidation of the fuel. Partial oxidation is the limited addition of oxygen to the fuel at elevated temperatures. This causes partial combustion of the fuel, which releases heat and the gaseous products $H_2O$ and $CO_2$. The heat pyrolizes fuel, releasing volatiles, evaporates moisture, and provides the energy for the endothermic gasification reactions between unconverted carbon and partial combustion products. The principle gasification reactions are the primary water–carbon reaction, $C_{(s)} + H_2O \rightarrow H_2 + CO$; the secondary water–carbon reaction, $CO + H_2O \rightarrow H_2 + CO_2$; and the Boudouard reaction, $C_{(s)} + CO_2 \rightarrow 2CO$. These reactions produce a synthesis gas high in CO and $H_2$.

[04] Gasifiers are generally classified within three types depending on the movement of the bed material relative to the gases. In a fluidized-bed gasifier, the feed is sized such that a high velocity gas, such as air, oxygen, or steam, passing through the bed will “fluidize” the bed, providing very good mixing and uniform temperature of all of the reactants within the bed. In this type of gasifier, the pyrolysis, combustion, and reduction reactions are uniformly mixed throughout the bed. The drawbacks to this type of gasifier are the low gas residence times within the bed and the capital cost of the system.

[05] In countercurrent gasifiers (otherwise known as updraft gasifiers), the bed material flows in the opposite direction of the gases. Fuel is dropped onto a packed bed

with hot reducing gases, such as $CO_2$ and $H_2O$, flowing upward through the bed. The partial combustion of the bed occurs at the bottom of the bed. The reduction reactions occur in the middle of the bed, and the pyrolysis reactions occur toward the top. This type of gasifier is relatively simple in construction and costs less. However, since the pyrolysis reactions occur toward the top, near the gas exit, a large portion of pyrolysis gases do not react inside the gasifier, producing a high-tar-content producer gas.

[06] Cocurrent gasifiers (also known as downdraft gasifiers) overcome the high tar content by flowing the gases in the same direction as material flow. In this type of gasifier, material is also dropped onto a packed bed. A very high temperature combustion zone is located in the middle of the bed. Heat from the combustion zone pyrolizes the material above it. This forces the pyrolysis gases to flow through the combustion zone. This oxidizes and cracks the pyrolysis gases. These then react with the char below the combustion zone to form the synthesis gases. This type of gasifier is simple to construct, low cost, and outputs less tars than the other types of gasifiers. Both cocurrent and countercurrent gasifiers are moving packed-bed gasifiers. A practical limitation of employing a packed bed is that the feed material traveling through the gasifier often bridges before reaching the reaction zones. This usually requires the gasifier to be shut down and the bridge manually broken, increasing both downtime and operating cost of these gasifiers.

[07] Ideally, all of the tars in a cocurrent gasifier are cracked within the gasifier. However, in reality, channeling within the bed, heat losses, and cooler wall temperatures

within the gasifier allow some tars (pyrolysis gases) to pass through the relatively narrow, high-temperature combustion zone uncracked. Moisture in the feed will also adversely affect the tar output of the gasifier, since moisture acts as a heat sink and will reduce the overall temperature within the gasifier. Both the temperature and size of the combustion zone and reduction zones in packed-bed gasifiers are dictated by the feed and operating conditions, such as moisture content and air input. This limits the moisture content in most feeds to below 15% for good, low-tar gasification conditions. To ensure enough heat is produced for the cracking and reduction reactions, complete oxidation of a larger fraction of fuel is required. This reduces the efficiency of the gasifier and increases nitrogen dilution of the resultant synthesis gas.

[08] Advantages of cocurrent gasifiers include that they are relatively simple to design and construct, low cost, and output the least tars of all the gasifier types. Disadvantages include that they still produce enough tars to foul downstream systems, require low moisture feed to operate, and have a tendency to bridge within the gasifier, depending on feed material. These disadvantages currently outweigh the advantages and have prevented wide-scale adoption of this technology in commercial applications.

## SUMMARY OF THE INVENTION

[09] An apparatus of the invention is provided for gasifying carbonaceous feedstock to produce a low-tar, high-energy synthesis gas, the apparatus including a gasification reactor having a gasification zone, and a space at least partially surrounding the

gasification zone, wherein the gasification zone is maintained at a temperature above 800°C by providing heat to the space.

[10] Another embodiment of the invention provides a method of gasifying carbonaceous feedstock to produce a low-tar, high-energy synthesis gas using a gasification reactor having a gasification zone, the method including forming a space around the gasification zone, and providing heat to the space to maintain a desired temperature in the gasification zone.

[11] Another embodiment of the invention provides a method of reducing solid waste that is capable of generating toxic emissions in synthetic gas produced by a gasification reactor having a gasification zone, the method including gasifying the solid waste in the gasification zone of the gasification reactor, oxidizing synthetic gas produced by the gasification reactor using a combustor to decompose toxic emissions in the synthetic gas, and using the combustor to convert chemical energy from synthesis gas to thermal energy to provide heat to the gasification reactor.

[12] Other features and advantages of the present invention will be apparent from the accompanying drawings and from the detailed description that follows below.

## BRIEF DESCRIPTION OF THE DRAWINGS

[13] The present invention is illustrated by way of example and not limitation in the figures of the accompanying drawings, in which like references indicate similar elements and in which:

[14] FIGS. 1A and 1B are plots showing the effect of equivalence ratio (ER) on the adiabatic flame temperature and char conversion for wood with various moisture contents.

[15] FIGS. 2A-2D are plots showing the variation in carbon conversion with reactor temperature as a function of equivalence ratio at various biomass moisture levels.

[16] FIGS. 3A and 3B are plots showing the higher heating value of synthesis gas as a function of equivalence ratio for wood at constant enthalpy and pressure condition (FIG. 3A) and constant temperature and pressure condition (FIG. 3B).

[17] FIG. 4 is a plot showing the effect of moisture on the gasification efficiency at different equivalence ratios when a reactor is operated at an isothermal temperature of 1000°C.

[18] FIG. 5 is a process flow diagram illustrating one example of a gasification system of the present invention.

[19] FIG. 6 is a process flow diagram illustrating another example of a gasification system of the present invention.

[20] FIG. 7 is a process flow diagram illustrating another example of a gasification system of the present invention.

[21] FIG. 8 is a process flow diagram illustrating another example of a gasification system of the present invention.

[22] FIG. 9 is a process flow diagram illustrating an example of a gasification system and integrated fuel cell of the present invention.

[23] FIG. 10 is a process flow diagram illustrating another example of a gasification system of the present invention used as a solid waste reduction system.

## DETAILED DESCRIPTION

[24] The present invention overcomes the disadvantages in the prior art described above by maintaining a wide high-temperature heating zone along the length of a gasifier (described in detail below). The wide high-temperature heating zone is maintained by circulating or flowing hot combustible gases through an annular space around the hot zone of the reactor. This creates a quasi-isothermal temperature zone large enough to ensure much longer residence times of gases in the reaction zone of the reactor, particularly reduction zone. In one example, the minimum temperature is 800°C, but

preferably greater than 900°C. The minimum residence time is dictated by the feed, temperature, and moisture conditions within the gasifier and is essentially the residence time necessary to achieve near-total destruction of tars and conversion of char. The long temperature zone prevents channeling of pyrolysis gases and eliminates cold spots below 800°C. The hot space around the reactor minimizes heat losses. The result is that carbon and tar conversion is near complete and results in a near-equilibrium gas composition at the temperature of the hot zone. Bridging within the gasifier is much reduced because the much longer reaction zone inside the gasifier continuously decreases the bed particle sizes, allowing any bridges formed within this zone to collapse and continue to flow.

[25] Generally, in one example of a gasification system of the present invention, carbonaceous feedstock is subject to gasification in a gasification reactor to provide synthesis gas. A portion of the energy of the synthesis gas upon exiting the gasification reactor is used to heat a space around the gasification zone of the gasifier through circulation of hot gases. Sufficient heat is provided in the gasification reactor to maintain an isothermal or quasi-isothermal temperature condition above approximately 800°C in the gasification zone. In this example, the length of the gasification zone is long enough to ensure adequate gas residence time in the gasification zone for near complete tar cracking and carbon conversion. The length of the gasification zone depends on factors such as feed type, isothermal temperature, and the gasifier radius. In one example, the combustion products used to heat the gasification reactor are kept separate from the syngas generated within the gasification reactor.

[26] The portion of the output syngas used to heat the gasification zone of the reactor may be combusted before or after a secondary energy converter, such as a fuel cell, gas turbine, stand alone boiler system and/or coupled with steam turbine, a Fischer–Tropsch reactor, an internal combustion engine, etc., depending on the effluent temperature characteristics of the secondary energy converter. In the example of a secondary energy converter where the output effluent temperature is below approximately 800°C, and there is insufficient chemical energy within the output effluent to raise the temperature of the effluent above 800°C, a portion of the syngas used to heat the gasification reactor can be diverted to a combustor before the bulk syngas is sent to the secondary energy converter. In the example of a secondary energy converter where the output effluent temperature is above approximately 800°C, or there is sufficient chemical energy within the output effluent to raise the effluent temperature above 800°C, the effluent may be combusted, if necessary, and used to heat the gasification zone of the reactor.

[27] One feature of the present invention is to produce a very low tar synthesis gas to minimize or eliminate the cost of scrubbing and disposing tars downstream of the gasifier. Another feature of the invention is to produce a higher-energy content-synthesis gas without the use of pure oxygen. Another feature of the invention is to allow the practical use of a higher moisture carbonaceous fuel than conventional gasifiers. Another feature of the invention is to reduce or eliminate bridging of the moving packed bed within the reactor.

[28] A gasification system of the present invention provides numerous benefits and advantages. For example, a lower oxidant/fuel ratio will be needed to gasify the fuel. Syngas produced using the present invention will have a higher heating value compared to syngas produced using conventional gasification reactors utilizing the same oxidant and fuel types. Syngas produced using the present invention will also have lower tar levels compared syngas produced using conventional gasification reactors utilizing the same oxidant and fuel types. The operating range of a gasifier of the present invention will extend to higher moisture level fuels compared to conventional gasification reactors. Bridging within a gasifier of the present invention is reduced or eliminated because of the constant reduction in particle size of the bed material within the gasification zone of the gasifier.

[29] The present invention, in one example, relates to a system and method for the generation of very low-tar, high-energy synthesis gas from a large variety of carbonaceous feedstock, including those with higher moisture levels than conventional gasifiers. An exemplary system includes a gasification reactor wherein a portion of the energy of the output syngas of the reactor is used to heat the gasification zone of the reactor via an annular space surrounding the gasification zone of the gasifier, to maintain a temperature condition above approximately 800°C. The maintenance of a long, quasi-uniform high-temperature gasification zone reduces the amount of input air or oxygen, reduces bridging within the gasifier (which reduces operating costs), cracks pyrolysis oils, increases the conversion of char, minimizes heat losses from the bed, and converts moisture within the packed bed into a gasification medium. This results in a very low tar

synthesis gas with less nitrogen dilution and higher energy content than conventional gasifiers.

[30] Following is a more detailed description of examples of the present invention, which, together with the figures, will serve to explain the principles of the invention.

[31] The performance advantages of the invention are best shown in comparing the theoretical gas compositions of conventional gasifiers and a gasifier which is maintained at an isothermal temperature condition, as described in the description. The gas composition for an isothermal gasifier and a conventional gasifier is modeled by calculating the equilibrium compositions at constant temperature and constant enthalpy conditions, respectively. In contrast to an isothermal gasifier, the required heat for a conventional gasifier is obtained by oxidation of fuel in situ, within the reactor. The heat required for an isothermal gasifier can be obtained by oxidizing a portion of the syngas from the gasifier, utilizing waste heat from the system, or a combination thereof. For Figures 1 through 4 (described below), the carbonaceous fuel will be modeled after wood, also denoted as biomass. A gasification system of the present invention, however, can run on a wide variety of carbonaceous feedstock, such as coal, lignite, pet coke, agricultural residues, and other carbonaceous waste.

[32] FIGS. 1A and 1B are plots showing the effect of equivalence ratio (ER) on the adiabatic flame temperature (FIG. 1A) and char conversion (FIG. 1B) for wood with moisture contents ranging from 0% to 50%. FIG. 1A shows the adiabatic flame

temperature (AFT) of a downdraft gasifier as a function of equivalence ratio (ER), defined as the ratio of actual air-to-fuel ratio to stoichiometric air-to-fuel ratio, and biomass moisture content. The plot shown in FIG. 1B depicts the effect of ER on the equilibrium char content for the wood–air reaction at various wood moisture levels. These plots also show the regime of operation for a typical gasifier (Regime I) and the low ER operating regimes (Regimes II and III).

[33] The AFT rises very slowly from 639° to 754°C with increasing ER from 0 to 0.25, beyond which it rises much faster with increasing ER. This break in the curve corresponds to the point at which char or carbon gets completely converted. The chemical energy of the producer gas is highest at this point (ER = 0.25). Beyond this ER, the chemical energy reduces to zero as the ER increases to 1 because of oxidation of CO and $H_2$ in the producer gas. At lower ER, a substantial fraction of unconverted carbon remains in the gasifier, even when operated at high moisture levels. Since the AFT reduces with an increase in the moisture levels, the reaction kinetics, a strong function of temperature, are adversely affected. An ER of 0.25 is the theoretical point at which a conventional air-blown gasifier is expected to produce the best results in terms of achieving a steady-state gas composition close to equilibrium. However, the low AFT at ER = 0.25 (shown in FIG. 1A) reduces the reaction kinetics, making it difficult to sustain gasification reactions. Most conventional downdraft gasifiers are operated at an ER in the range of 0.30–0.37 (Regime I), a value higher than the optimum value, to drive the reaction rates.

[34] A typical downdraft gasifier operating in Regime I will oxidize sufficient fuel to provide the necessary exothermic heat profile to drive the endothermic gasification reactions, primarily the Boudouard reaction and the water-gas reactions (the reaction kinetics and mechanisms for carbon/char gasification are well documented in the literature). These reactions control the operating temperature limits of the gasification reactor. The first reaction rapidly establishes equilibrium at temperatures above 1100°C, while the second reaction becomes significant at temperatures from 1000° to 1100°C. At lower operating temperatures, the reaction kinetics of both the Boudouard reaction and water-gas reactions decrease substantially. This limits both the wood moisture content and the operating ER in achieving self-sustained gasification. FIG. 1 shows that, even under the most optimistic conditions (dry wood and adiabatic enclosure), the minimum ER is 0.30. For biomass with a moisture content of 20%, the minimum ER to reach the lower operating temperature range increases to 0.37. However, if the gasifier temperature is maintained above 800°C by external heating, as provided in the invention, the kinetic limitations of operating at lower ER and higher biomass moisture content can be eliminated.

[35] FIGS. 2A-2D show the effect of various reactor operating temperatures and biomass moisture on the unconverted carbon at different ERs. Both ER and reactor temperature affect the unconverted carbon fraction for a given biomass moisture. In the case of dry wood (FIG. 2A), no reduction of unconverted carbon occurs, regardless of the temperature, when the reactor is operated at an ER lower than 0.2. Increased biomass moisture will decrease the ER (i.e., air input) necessary for complete carbon conversion

at any given temperature. At 20% moisture and a 900°C reactor bed temperature (FIG. 2C), the gasifier can be operated down to ER = 0.05 with complete carbon conversion. At 30% moisture (FIG. 2D), carbon is completely converted if the gasifier is operated at a reactor bed temperature of 800°C or higher. Theoretically, the gasifier can be operated with no air input if the reactor bed temperature is maintained above 800°C for biomass moisture greater than 30%. For biomass moisture greater than 20% and a bed temperature of 900°C, the reactor should be able to operate at an ER as low as 0.05, which, for all practical purposes, can be considered leakage air with the biomass feed. These limits fix the lower reactor operating temperature at 800°C. The upper limit is fixed primarily by material concerns.

[36] FIGS. 3A and 3B compare the dry gas heating value at different ERs and biomass moisture contents from 0% to 50% for conventional gasifiers (modeled by constant enthalpy conditions (FIG. 3A) and an isothermal gasifier (FIG. 3B). Both cases show the heating value of the synthesis gas increasing as the ER decreases. But substantial char is left unconverted at ERs less than 0.20 in the case of the plot shown in FIG. 3A. This means that a conventional gasifier sacrifices reactor efficiency for gas heating value. FIG. 3B shows complete carbon conversion at 1000°C for biomass moisture greater than 30% at all ERs. For lower moisture levels, an ER in Regime II appropriate to the given moisture content will provide complete carbon conversion. For an externally heated reactor, very high energy gas can be produced at complete carbon conversion, increasing both reactor efficiency and gas quality. The direct effect of this is to increase output gas calorific value by 50% as compared to a conventional gasifier.

[37] FIG. 4 shows the effect of moisture on the gasification efficiency at different ERs when the reactor is operated at an isothermal temperature of 1000°C. Here, the classical definition of gasification efficiency or cold-gas efficiency is used (defined as the ratio of output chemical energy of the producer gas (higher heating value) to the input chemical energy content of the feed). The addition of heat to the gasifier is not summed with the input chemical energy of the biomass. The plot shows that the maximum theoretical gasification efficiency (without any reactor heat loss) occurs when ER = 0.2 for a moisture level of 0.0%, ER = 0.15 for a moisture level of 10%, ER < 0.1 for a moisture level of 20%, and an ER = 0.0 for moisture level greater than 30%. The introduction of external heat for the reduction reactions increases the gasification efficiency from 95% for bone-dry wood to 119% for "green" wood. As a comparison, a conventional reactor achieves a maximum cold-gas efficiency of approximately 60%-80% for bone-dry wood. In the case of a gasifier of the present invention, bone-dry wood provides the lowest reactor efficiency at 95%. Additional moisture increases reactor efficiency up to a biomass moisture of 50%. Efficiency greater than 100% is an indication of thermal energy (heat) being transferred to the chemical energy of the producer gas through the endothermic gasification reactions. This would partially or fully offset the system efficiency penalty of diverting a portion of the syngas from the gasifier to heat the gasification zone of the gasifier.

[38] The reactor reaches maximum cold-gas efficiency between 20% and 30% biomass moisture content. This is the minimum biomass moisture needed to completely reduce the char and pyrolysis gases in the absence of air. Excess biomass moisture above this point

does not contribute to increasing the producer gas heating value, since there is no carbon left to convert. It is simply vaporized and exits the gasifier at the same temperature of the producer gases. While the additional moisture does not contribute to the cold-gas heating value of the producer gas, it does recycle some additional heat by the process of vaporization and the specific heat needed to raise the water vapor to temperature. Excess water vapor may also have a beneficial effect in stabilizing the overall system temperature profile and further reducing tar and particulate levels in the gasifier.

[39] To obtain a producer gas with reasonable gasification efficiencies, conventional gasifiers should limit the biomass moisture level to below 20%. This generally requires additional equipment and operational expenditures for drying the biomass before gasification. Regime I is the typical operating range of conventional downdraft gasifiers. The heating value of the producer gas in this region varies between 4–5 MJ/m3 for moisture levels below 30%. Since moisture acts as a thermal sink for energy that would otherwise be used for the endothermic gasification reactions, biomass with moisture levels above 30% produces high $CO_2$ and tar contents for conventional downdraft gasifiers. For the reactor design of the present invention, the external heat converts the moisture into an essential gasification medium, allowing a much wider range of biomass moisture levels. A reactor of the present invention can operate in Regime III, resulting in wet producer gas heating values from 7 to 12 MJ/m3.

[40] A gasification system of the present invention desires adequate heat transfer through the reactor walls to maintain the isothermal temperature condition throughout the

gasifier. If poor heat-transfer characteristics occur in the reactor or if the thermal energy in the annular space around the gasifier is insufficient to maintain the isothermal boundary conditions above 800°C, additional primary air can be added (increased ER) to increase the interstitial temperatures within the char bed. This will produce a heating value penalty in the producer gas output.

[41] FIGS. 5-10 are process flow diagrams of various examples of gasification systems of the present invention. Other examples and combinations of gasification systems are also possible within the spirit and scope of the present invention.

[42] FIG. 5 is a process flow diagram illustrating one example of a gasification system of the present invention. In this example, the synthesis gas is combusted before a secondary converter and used to heat the gasification zone of the reactor above 800°C. FIG. 5 shows a gasification system 10, including a gasification reactor 12 containing a packed bed 14. A gasification zone is formed within the reactor. The reactor 12 is surrounded by an insulated wall 16, that forms an annular space 18 around the gasification zone. For clarity, the reactor 12 and wall 16 are shown in cross-section, to better illustrate the annular space 18 formed between the reactor 12 and the wall 16. FIG. 5 also shows a syngas cleaning subsystem 20, a combustor 22, a secondary energy converter 24, and a pre-heater 26 (described below).

[43] In the figures, various steps and functions are represented by arrows, with reference numerals, which are included in the description in parentheses. In this example,

carbonaceous fuel is fed (30) to the gasification reactor 12 (e.g., an externally heated high-temperature heterogeneous gasification reactor). The carbonaceous fuel is pyrolized into gases and char. The pyrolysis gases then react with the char at high temperatures to convert the char and pyrolysis gases to a synthesis gas consisting primarily of $CO_2$, $H_2$, CO, $CH_4$, and water. If additional heat or oxidant is necessary to enhance the conversion process air, oxygen or water (32) may be added to the reactor 12 along with the carbonaceous feed (30). Unconverted char and ash exits the gasification reactor (34).

[44] Because of the more ideal gasification conditions within the reactor relative to a conventional gasifier, both carbon and pyrolysis gas conversion is increased. The synthesis gas exits (36) the gasification reactor 12 with much lower tar content than conventional gasifiers. The synthesis gas is cleaned by the syngas cleaning subsystem 20, and a portion thereof is diverted (38) to a combustor 22. The combustor 22 combusts the portion of synthesis gas with air or oxygen (40). The air or oxygen (41) can be preheated by the preheater 26 to reduce the amount of synthesis gas that is diverted to the combustor 22. The heated air or oxygen (43) that is not used by the combustor 22 may be used to provide additional oxidant.

[45] The exhaust (42) from the combustor 22 is then circulated through the annular space 18 surrounding the gasification zone of the reactor 12 to externally heat the gasification zone to a temperature above 800°C. The combustor exhaust gases are kept separated from the pyrolysis and char. The exhaust gases will decrease in temperature

through a combination of both heat losses to the surroundings and the endothermic reactions occurring in the gasifier prior to exiting the gasification reactor.

[46] The exhaust gases exiting (44) the gasifier can then be used to preheat the air, oxygen or water being fed to the gasification reactor 12 or combustor 22 or, if desired, used for process heat elsewhere, or exhausted to atmosphere. The portion of syngas (46) from the reactor 12 not used by the combustor 22 to heat the gasification zone is sent to a secondary energy converter 24. The secondary energy converter 24 can be any desired device, for example, a fuel cell, an internal combustion engine, a gas turbine, a Stirling engine, etc.

[47] The process flow diagram of FIG. 6 illustrates another example of a process flow diagram of the present invention. In this example, the effluent temperature from the secondary energy converter 24 is greater than 800°C and is used to heat the gasification zone of the gasification reactor 12 above 800°C, rather than using the combustor 22. In the gasification system shown in FIG. 6, there could be no combustor, or the combustor could be bypassed using any desired control system.

[48] FIG. 6 shows a gasification system 10, including a gasification reactor 12, as described above. FIG. 6 also shows a syngas cleaning subsystem 20, a secondary energy converter 24, and a pre-heater 26. In the example of FIG. 6, all of the synthesis gas exiting (36) the gasification reactor 12 is sent to a secondary converter 24 after the gas is cleaned (46). In this example, the exhaust (42) of the secondary energy converter 24 is

greater than 800°C, and is used directly to maintain the temperature of the gasification zone of the gasification reactor 12 above 800°C. An example of secondary converters that could produce an exhaust temperature greater than 800°C are combustors, high-temperature fuel cells, Stirling engines, etc.

[49] The process flow diagram of FIG. 7 illustrates another example of a process flow diagram of the present invention. In this example, the exhaust (47) of the secondary converter 24 has sufficient chemical energy within it to raise its temperature above 800°C upon combusting to heat the gasification zone of the gasification reactor above 800°C.

[50] FIG. 7 shows a gasification system 10, including a gasification reactor 12, as described above. FIG. 7 also shows a syngas cleaning subsystem 20, a syngas cleaning subsystem 20, a combuster 22, a secondary energy converter 24, and a pre-heater 26. In the example of FIG. 7, all of the synthesis gas exiting (36) the gasification reactor 12 is sent (46) to a secondary energy converter 24, after being cleaned by the syngas cleaning subsystem 20. The exhaust (47) of the secondary converter 24 has sufficient chemical energy to raise the gasification zone of the gasification reactor above 800°C. The exhaust of the secondary energy converter 24 is sent to the combustor 22 and combusted with air or oxygen (40) before being sent (42) to the gasification reactor 12 to heat the gasification zone. Examples of secondary energy converters that may have sufficient chemical energy within their exhaust to raise the temperature of the gasification zone of the gasification reactor above 800°C include fuel cells, combustors operated below stoichiometric conditions, Fischer–Tropsch reactors, etc.

[51] The process flow diagram of FIG. 8 illustrates another example of a gasification system of the present invention. In this example, the effluent temperature of the secondary energy converter is below 800°C and does not have sufficient chemical energy within it to heat the gasification zone of the gasification reactor above 800°C.

[52] FIG. 8 shows a gasification system 10, including a gasification reactor 12, as described above. FIG. 8 also shows a syngas cleaning subsystem 20, a syngas cleaning subsystem 20, a combuster 22, a secondary energy converter 24, and a pre-heater 26. In the example of FIG. 8, a portion of the cleaned synthesis gas is diverted (38) to the combustor 22 and mixed with the exhaust (47) of the secondary energy converter 24, and with air or oxygen (40). The exhaust of the secondary energy converter 24 has sufficient chemical or thermal energy to reduce the amount of synthesis gas diverted to the combustor 22. If the exhaust of the secondary energy converter 24 does not have sufficient oxygen to combust the synthesis gas, then additional air or oxygen is added to completely combust the synthesis gas and exhaust gases. Examples of secondary energy converters that could be operated in this embodiment include combustors, fuel cells, Stirling engines, gas turbines, Fischer–Tropsch reactors, etc.

[53] FIG. 9 illustrates another example of a process flow diagram of the present invention. FIG. 9 depicts a thermally and physically integrated fuel cell-gasification system 10, where a fuel cell is located in the annular heating space 18 around the gasification zone of the gasifier to allow the endothermic gasification reaction of the gasifier to remove excess heat from the exothermic reactions in the fuel cell.

[54] FIG. 9 shows a gasification system 10 where a high-temperature tubular fuel cell 50 is physically located in the annular heating zone 18 of the gasifier 12. In one example, the operating temperature of the fuel cell 50 is above 800°C, and the heat produced by the electrochemical reactions of the fuel cell is transferred directly to the gasification zone of the gasifier. In this embodiment, the endothermic gasification reactions act as a heat sink for the exothermic electrochemical reactions of the fuel cell 50. This reduces parasitic losses in operating the fuel cell 50 by reducing the amount of excess air or oxygen (41) necessary to carry away heat from the reaction zone of the fuel cell. The temperature of the gasification zone and fuel cell reaction zone can be further controlled by the addition of air or oxygen (32) to increase temperature or water to decrease temperature to the gasification reactor 12. In the process diagram of FIG. 9, the tubular fuel cell 50 has its anode on the inside and the cathode on the outside of fuel cell tubes 52. A fuel cell manifold 54 distributes the cleaned syngas (42) to the inside of the fuel cell tubes 52 of the tubular fuel cell 50. Hot cathode-side air or oxygen (45) circulates through the annular section 18 on the cathode side of the fuel cell 50. The opposite fuel cell configuration, where the anode is on the outside of the tube and the cathode on the inside, may also be employed. Both anode and cathode exhaust to a combustor 22 that subsequently preheats the cathode side air. Other fuel cell configurations could also be integrated with the gasification reactor 12. The tubular fuel cell 50 is merely one example.

[55] The process flow diagram of FIG. 10 illustrates another example of a gasification system of the present invention. In this example, solid waste is gasified, and syngas is

partially or fully oxidized in the combustor such that toxic emissions are decomposed. The hot exhaust leaving the system can be used for heat and electricity generation. In the example shown in FIG. 10, a combined gasification reactor 12 and combustor 22 (without syngas cleaning system) is used as a solid waste reduction system. Solid wastes capable of production of toxic emissions in the syngas can be decomposed in the process. In this process, the syngas is fully or partially oxidized in the integrated combustor 22. The heat of reaction (42) is utilized in the solid waste conversion process (within the gasification reactor 12) as well as in decomposing the toxic compounds (organics) in the gas phase.

[56] The high-temperature exhaust (leaving the gasifier heat-transfer zone) (44) is utilized for heating system reactants (via pre-heater 26) and for production of electricity and process steam (via secondary energy converter 24). The partially oxidized hot syngas will contain a fraction of chemical energy that can be utilized in increasing the gas temperature for the above-stated applications.

[57] Low-grade heat can be utilized for space heating. The primary advantage of the process is the effective utilization and destruction of environmentally hazardous solid waste and inertization of inorganics.

[58] In the preceding detailed description, the invention is described with reference to specific exemplary embodiments thereof. Various modifications and changes may be made thereto without departing from the broader spirit and scope of the invention as set

forth in the claims. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

## CLAIMS

What is claimed is:

1. An apparatus for gasifying carbonaceous feedstock to produce a low-tar, high-energy synthesis gas, the apparatus comprising:

a gasification reactor having a gasification zone; and

a space at least partially surrounding the gasification zone, wherein the gasification zone is maintained at a temperature above 800°C by providing heat to the space.

2. The apparatus of claim 1, wherein the space is an annular-shaped space.

3. The apparatus of claim 1, wherein the heat provided to the space to maintain the temperature of the gasification zone is obtained from the chemical energy of the synthesis gas produced by the gasification reactor.

4. The apparatus of claim 1, further comprising a combustor for converting chemical energy from the produced synthesis gas to thermal energy to heat the gasification zone of the gasification reactor.

5. The apparatus of claim 1, further comprising a combustor for converting chemical energy from exhaust of a secondary energy converter to thermal energy to heat the gasification zone of the gasification reactor.

6. The apparatus of claim 1, further comprising a high-temperature fuel cell disposed at least partially within the space surrounding the gasification zone of the gasification reactor, such that the endothermic heat of reaction of the gasification zone is at least partially balanced by the exothermic heat of reaction of the fuel cell.

7. The apparatus of claim 6, wherein the fuel cell further comprises one or more fuel cell tubes at least partially disposed in the space surrounding the gasification zone.

8. A method of gasifying carbonaceous feedstock to produce a low-tar, high-energy synthesis gas using a gasification reactor having a gasification zone, the method comprising:

forming a space around the gasification zone; and

providing heat to the space to maintain a desired temperature in the gasification zone.

9. The method of claim 8, wherein the space formed around the gasification zone is an annular-shaped space.

10. The method of claim 8, wherein heat is provided to the space to maintain a temperature in the gasification zone above 800°C.

11. The method of claim 8, further comprising using a combustor to convert chemical energy from synthesis gas to thermal energy to provide heat to the gasification reactor.

12. The method of claim 8, further comprising using at least some of the synthesis gas to power a secondary energy converter.

13. The method of claim 12, further comprising using a combustor to convert chemical energy from exhaust of the secondary energy converter to thermal energy to provide heat to the gasification reactor.

14. The method of claim 8, further comprising using chemical energy from exhaust of a secondary energy converter to heat the gasification zone above 800°C.

15. The method of claim 8, further comprising:
integrating a high-temperature fuel cell with the gasification reactor;
using the synthesis gas to fuel the high-temperature fuel cell; and
using heat generated by the fuel cell to provide heat to the gasification zone.

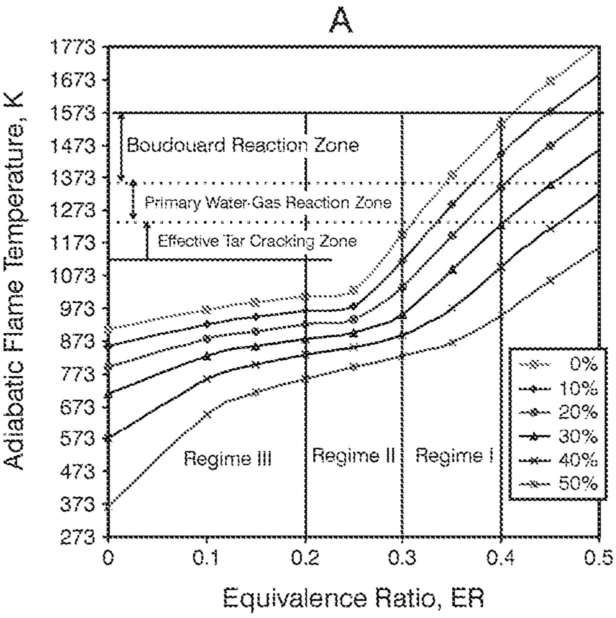
16. The method of claim 15, wherein the fuel cell includes one or more fuel cell tubes at least partially disposed in the space formed around the gasification zone.

17. A method of reducing solid waste that is capable of generating toxic emissions in synthetic gas produced by a gasification reactor having a gasification zone, the method comprising:
gasifying the solid waste in the gasification zone of the gasification reactor;
oxidizing synthetic gas produced by the gasification reactor using a combustor to decompose toxic emissions in the synthetic gas; and

using the combustor to convert chemical energy from synthesis gas to thermal energy to provide heat to the gasification reactor.

18. The method of claim 17, wherein heat from exhaust of the gasification reactor is used by a secondary energy converter.

19. The method of claim 18, wherein heat from exhaust of the gasification reactor is used to generate electricity.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Adiabatic Flame Temperature, K
1773
1673
1573
1473
1373
1273
1173
1073
973
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373
273
Boudouard Reaction Zone
Primary Water-Gas Reaction Zone
Effective Tar Cracking Zone
Regime III
Regime II
Regime I
0%
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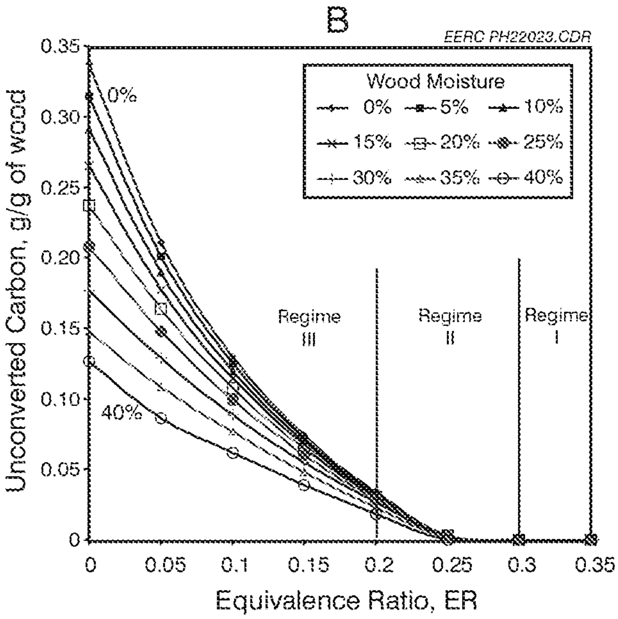
Equivalence Ratio, ER

FIG. 1A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EERC PH22023.CDR
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Wood Moisture
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5%
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40%
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Equivalence Ratio, ER

FIG. 1B

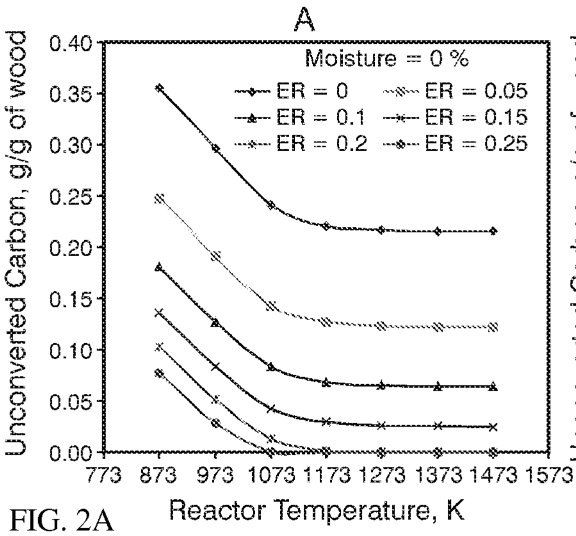


FIG. 2A

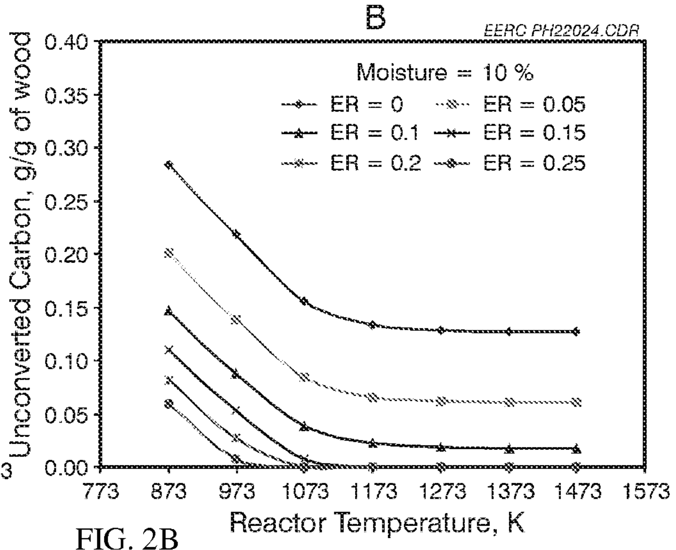


FIG. 2B

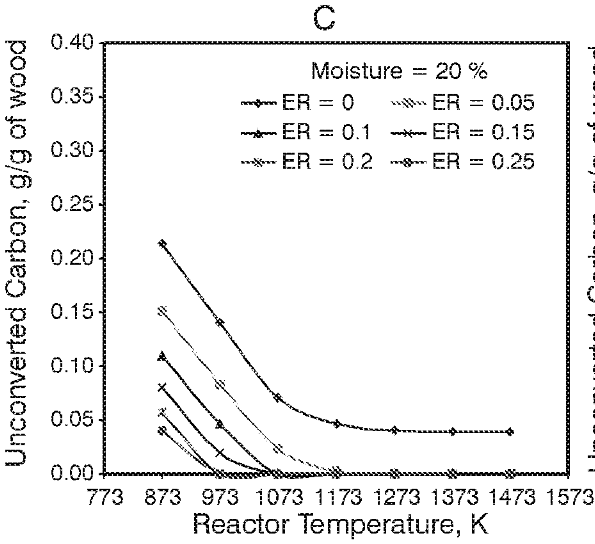


FIG. 2C

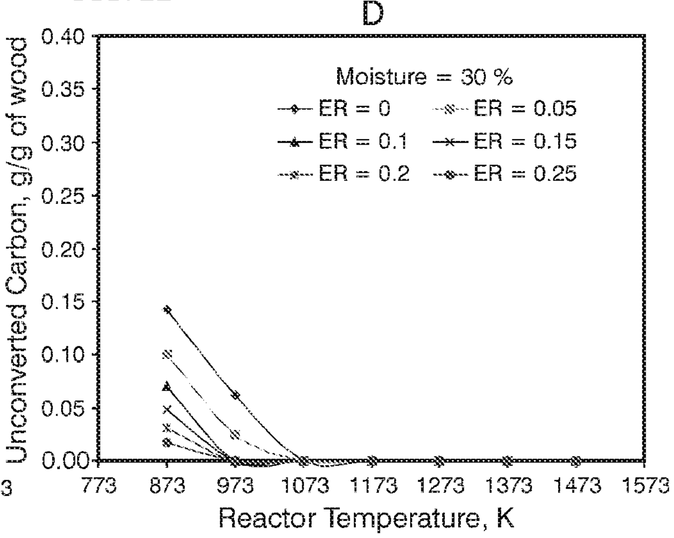


FIG. 2D

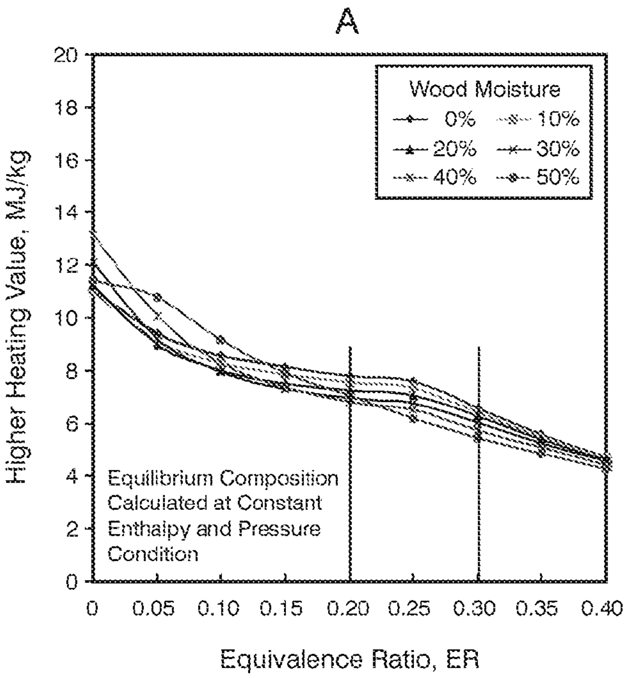


FIG. 3A

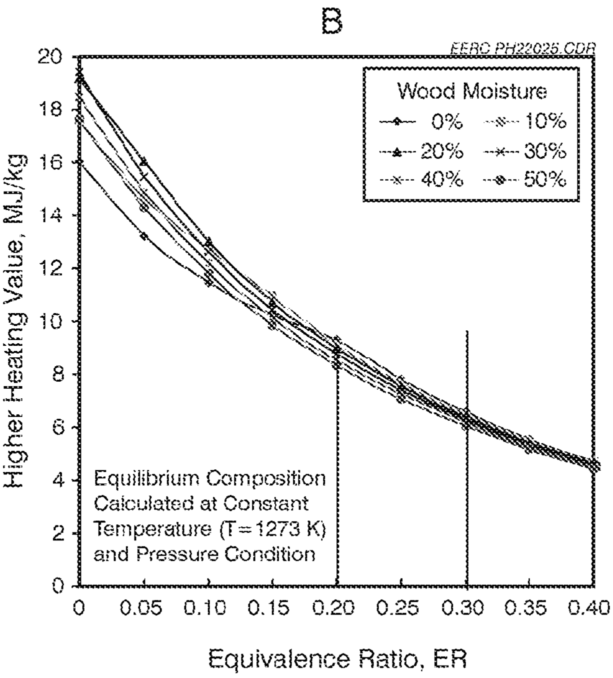


FIG. 3B

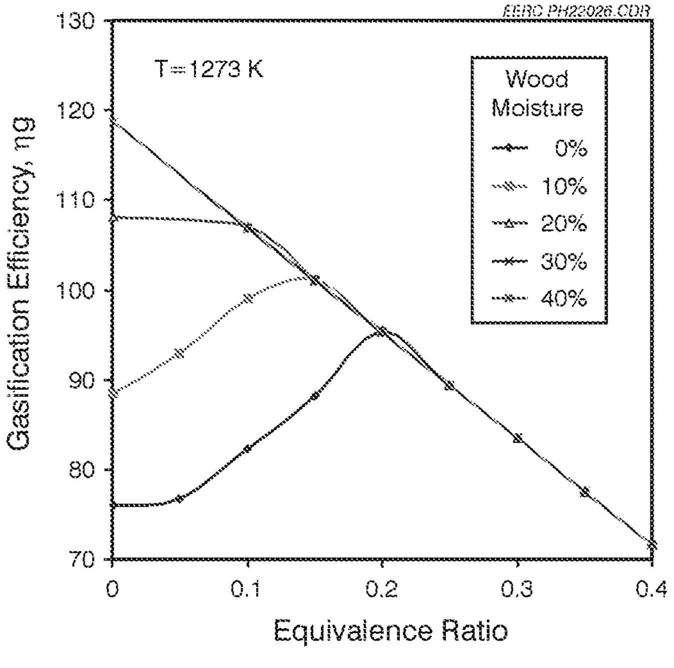
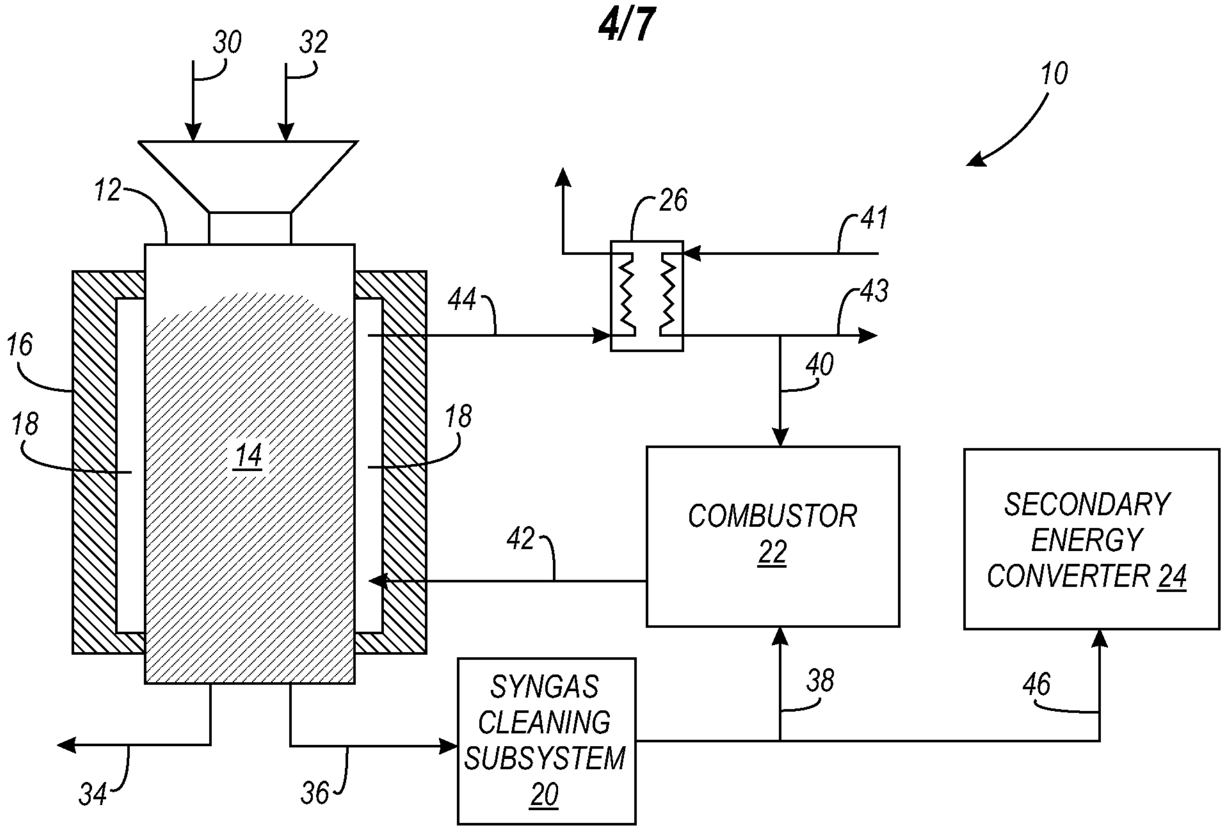


FIG. 4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SYNGAS CLEANING SUBSYSTEM 20
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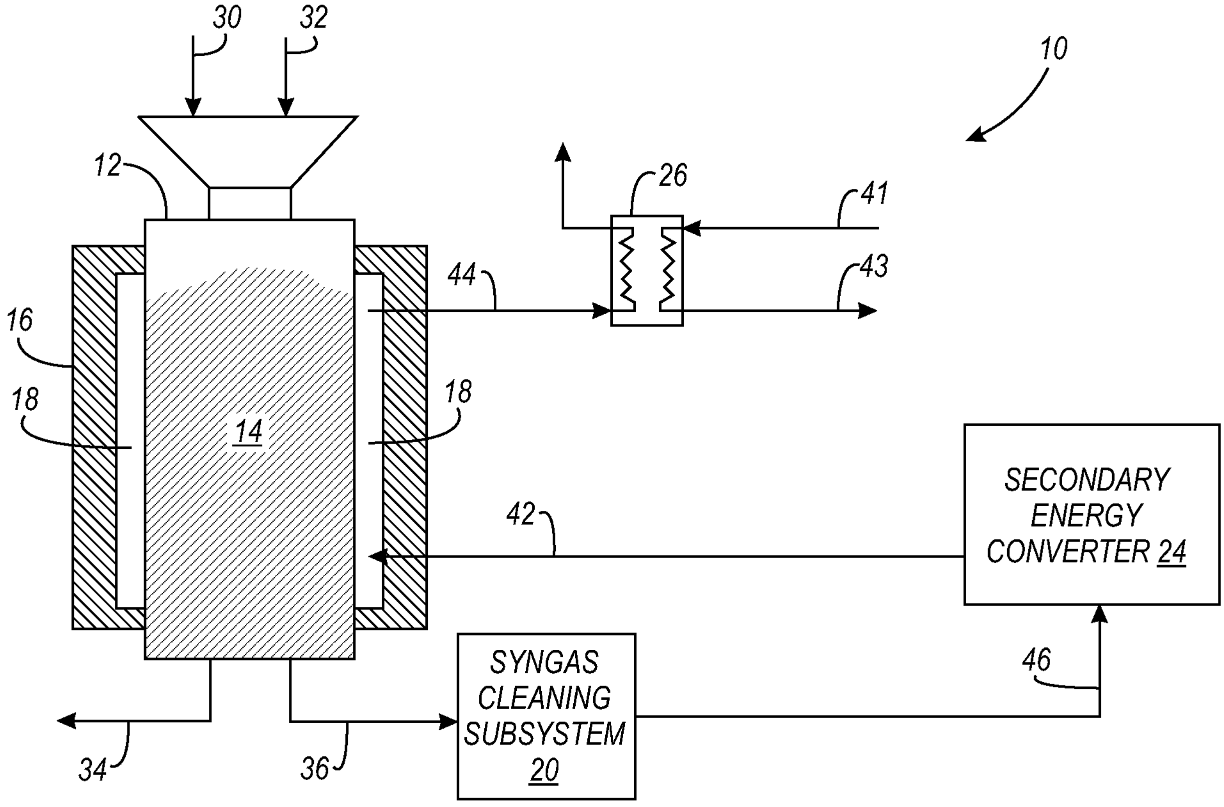
FIG. 5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SYNGAS CLEANING SUBSYSTEM 20
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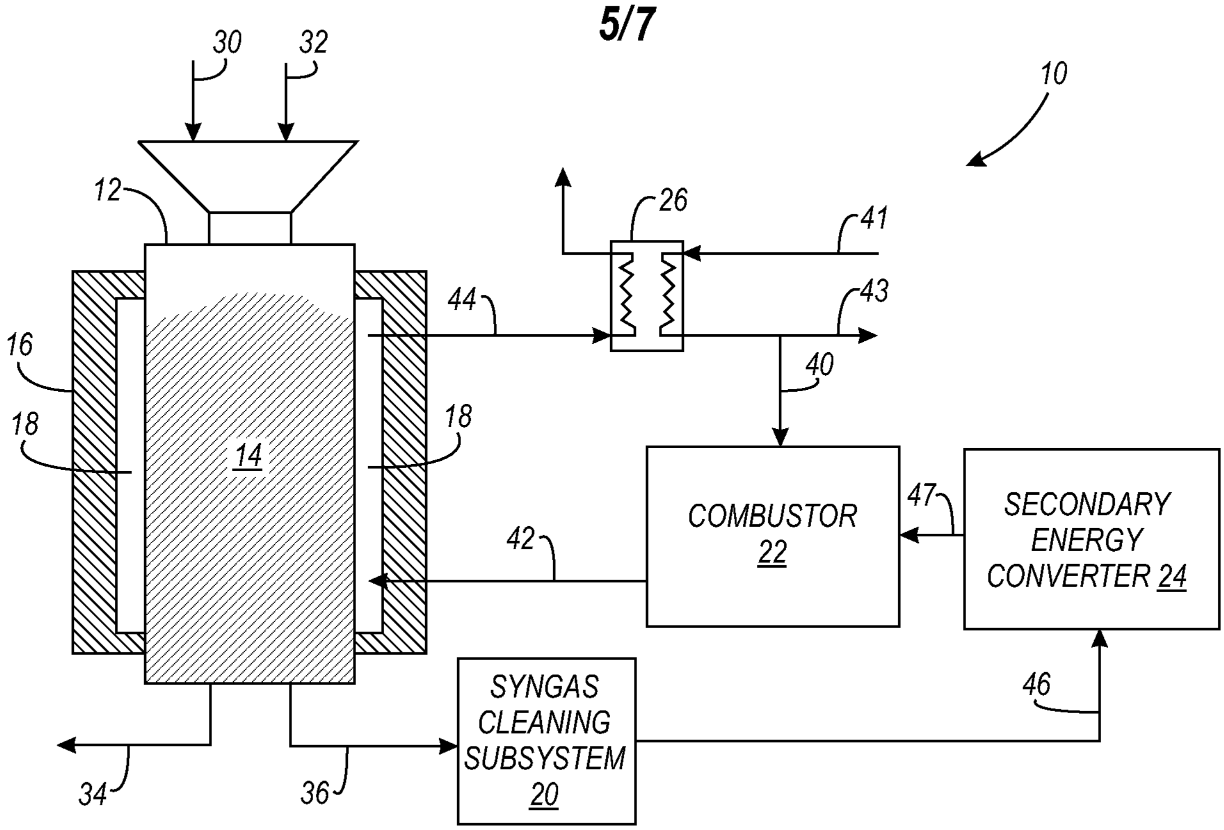
FIG. 6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SYNGAS
CLEANING
SUBSYSTEM
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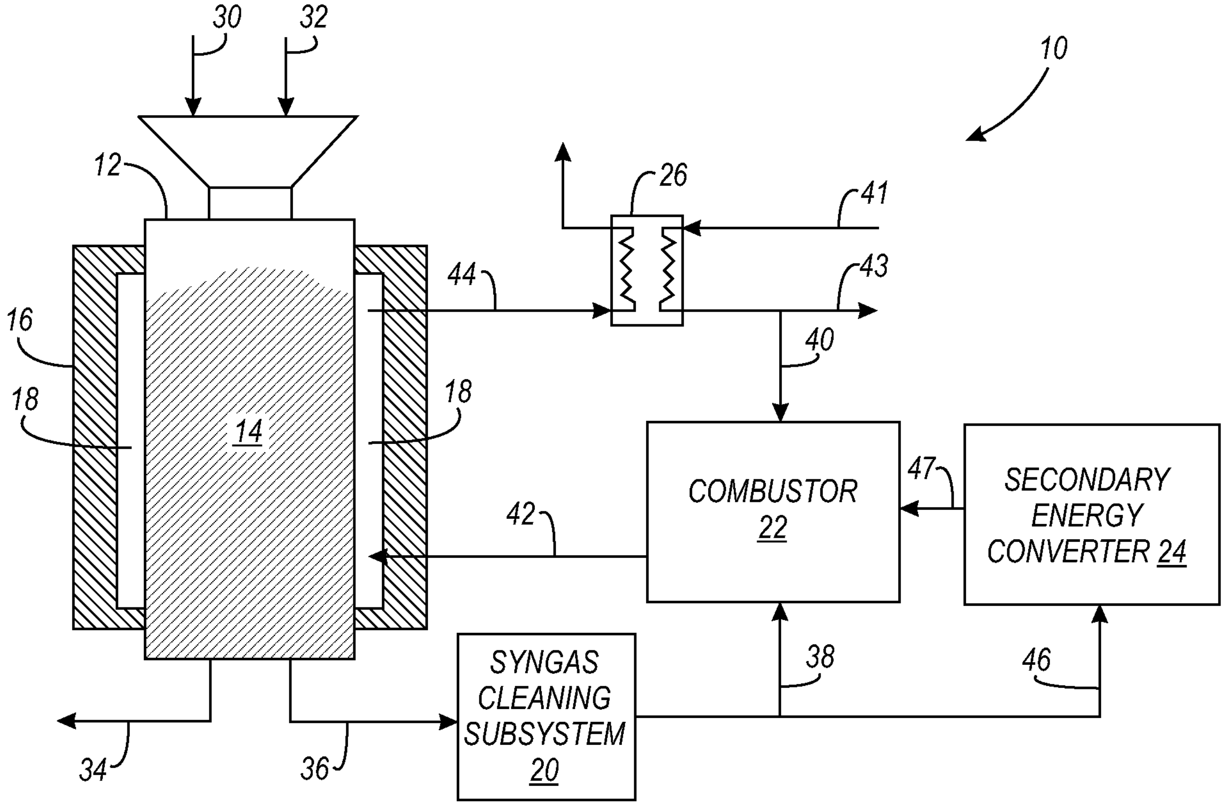
FIG. 7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COMBUSTOR
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SYNGAS
CLEANING
SUBSYSTEM
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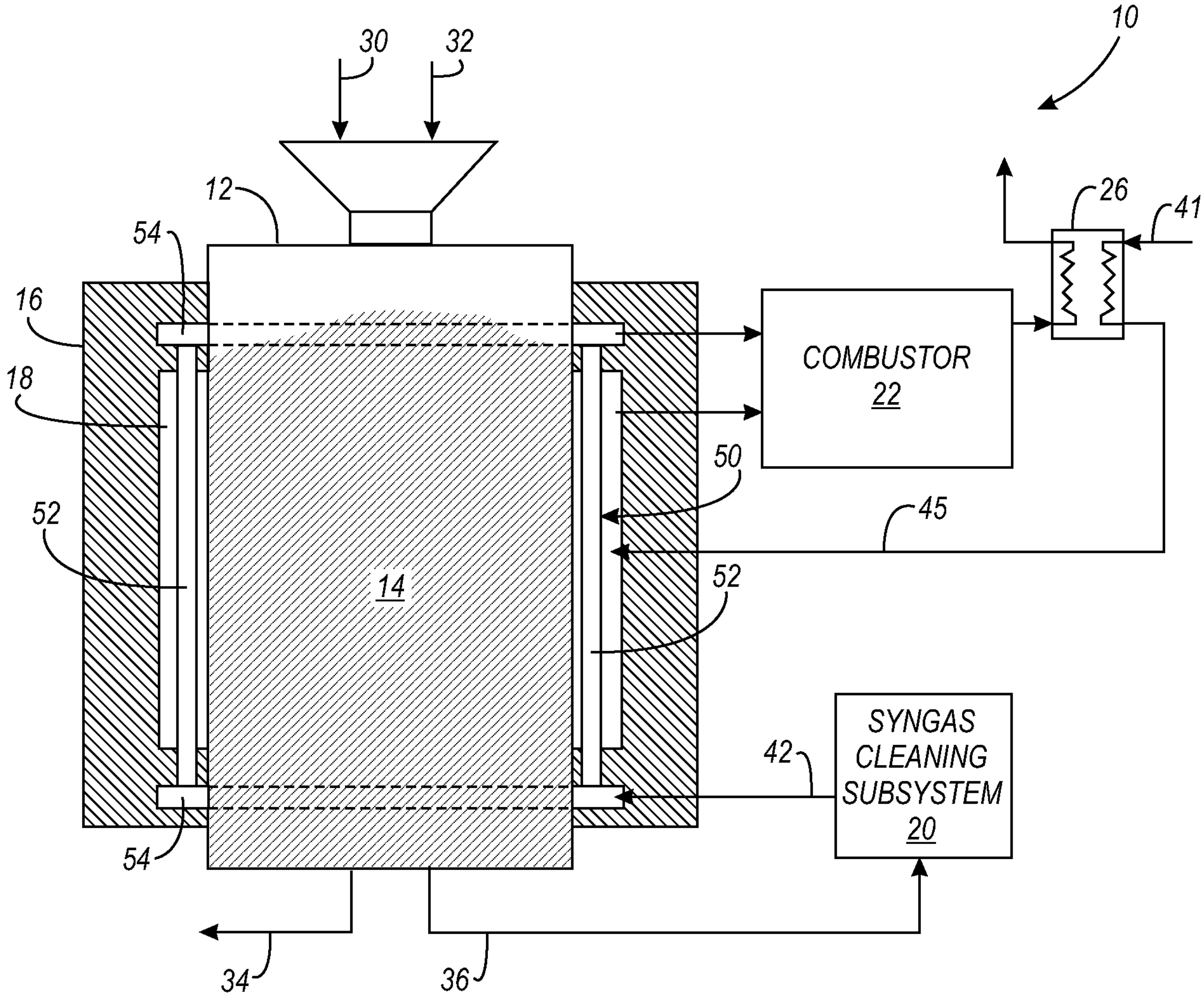
FIG. 8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COMBUSTOR
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SYNGAS
CLEANING
SUBSYSTEM
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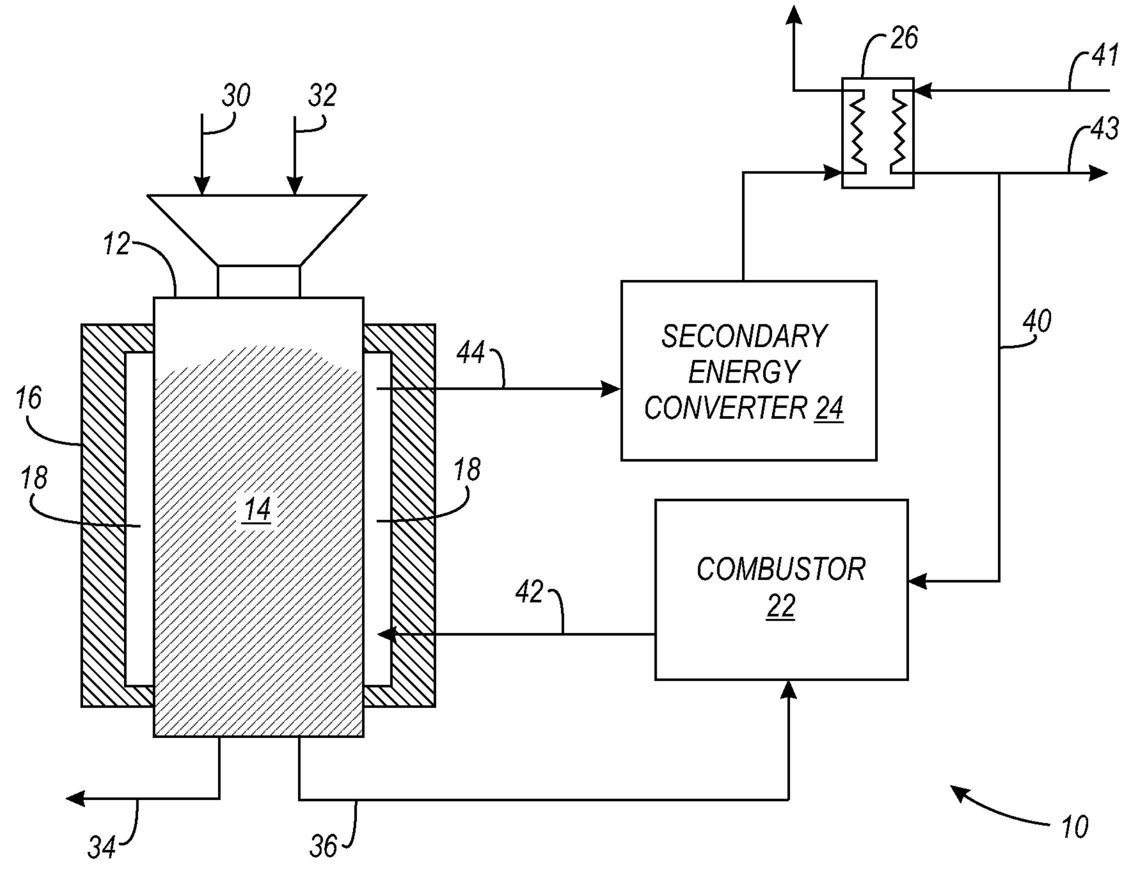
FIG. 9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SECONDARY ENERGY CONVERTER 24
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COMBUSTOR 22
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FIG. 10

# INTERNATIONAL SEARCH REPORT

International application No.
**PCT/US2008/054588**

## A. CLASSIFICATION OF SUBJECT MATTER

*C10J 3/20(2006.01)i*

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 8 C10J 3/20

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

e-KIPASS (KIPO internal) and keywords: gasification, heat source, zone, space, combustor, converter, fuel cell, and similar terms

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

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| Y | | 4, 11, 12, 17 |
| A | | 5-7, 13-16, 18, 19 |
| Y | KR 10-1998-0703226 A (METALLGESELLSCHAFT AKTIENGESELLSCHAFT) 15 OCTOBER 1998<br>See abstract, example, claims 1 and 6, and figure 2 | 4, 11, 17 |
| A | | 1-3, 5-10, 12-16, 18, 19 |
| Y | KR 10-2002-0020931 A (EBARA CORPORATION) 16 MARCH 2002<br>See abstract, claims 1, 5, 9, 11, 19, and 21-23, and figures 1-3 | 12 |
| A | | 1-11, 13-19 |

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

| | |
|---|---|
| * Special categories of cited documents: | "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention |
| "A" document defining the general state of the art which is not considered to be of particular relevance | "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone |
| "E" earlier application or patent but published on or after the international filing date | "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art |
| "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified) | "&" document member of the same patent family |
| "O" document referring to an oral disclosure, use, exhibition or other means | |
| "P" document published prior to the international filing date but later than the priority date claimed | |

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|---|---|
| Date of the actual completion of the international search<br>30 JUNE 2008 (30.06.2008) | Date of mailing of the international search report<br>**30 JUNE 2008 (30.06.2008)** |
| Name and mailing address of the ISA/KR<br>Korean Intellectual Property Office<br>Government Complex-Daejeon, 139 Seonsa-ro, Seo-gu, Daejeon 302-701, Republic of Korea<br>Facsimile No. 82-42-472-7140 | Authorized officer<br>PARK Jin<br>Telephone No. 82-42-481-8274 |

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