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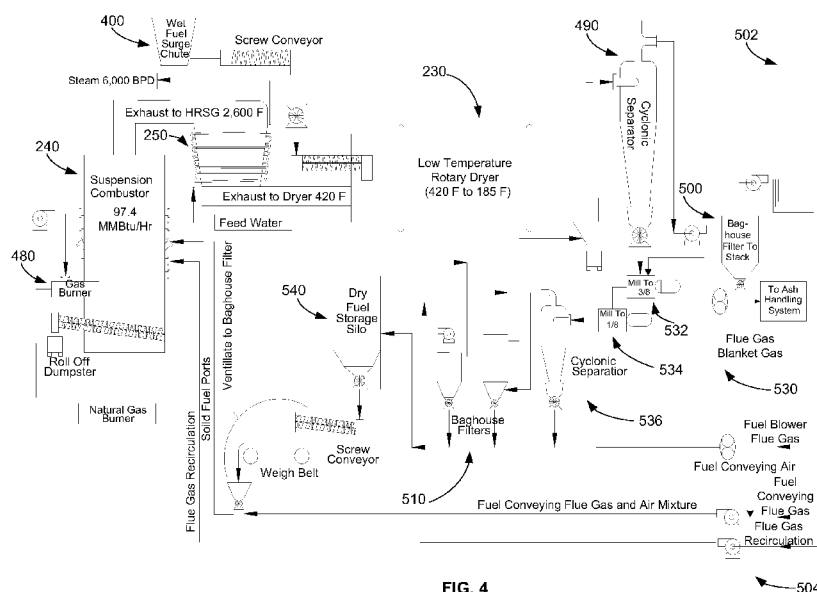


FIG. 4

- (57) Abstract:** A solid biomass-to-energy combustion method includes introducing an oxygen containing gas into a combustion chamber of a suspension furnace to form a flow of gas through the combustion chamber; injecting a particulate solid biomass fuel into the combustion chamber through a port in the furnace wall and into the gas flow, and combusting the particulate solid biomass fuel in the gas flow to form a flame in the gas flow.

BIOMASS-TO-ENERGY COMBUSTION METHOD

FIELD OF THE INVENTION

[01] The field of the invention relates to biomass-to-energy combustion systems and methods. The field of the invention also relates to the preparation and combustion of waste wood and/or diverse biomass fuel to produce energy. More particularly, the present invention relates to a system and a method for producing energy by preparing the waste wood and/or diverse biomass fuel and combusting it in a precisely controlled suspension furnace, reducing the pollutants emitted from such combustion, increasing the heat transfer from combustion to a working fluid, and reducing the fire hazards of fuel preparation.

BACKGROUND OF THE INVENTION

[02] With increasing restrictions on open burning, increasing landfill costs and decreasing availability of landfill and other disposal options, the cost of waste management has increased dramatically across multiple industries during recent years and is expected to increase further. This is a particularly serious problem for those, such as agricultural producers, wood and pulp products producers, municipalities, and electric utility companies, who have large quantities of waste wood and/or diverse biomass for disposal. Much waste wood and diverse biomass, however, has potential fuel value. Likely restrictions on carbon emissions from fossil fuels have made wood and diverse biomass even more attractive fuel sources. If efficiently combusted, waste wood and diverse biomass can provide multiple benefits of reducing air pollution, reducing carbon emissions, alleviating landfill and waste management problems across multiple industries, and producing needed energy. Waste wood and diverse biomass is a relatively low cost fuel and, when properly prepared and efficiently combusted, emits very low levels of all traditional air pollutants, and is carbon neutral.

[03] Waste wood has long been burned in furnaces to produce energy. Traditional methods of converting waste wood to energy including comminuting waste wood to a reduced particle size having a maximum dimension from about one to four inches and burning the particulate wood fuel on grates in stoker furnaces or boilers fluidized bed furnaces/ boilers, or less commonly suspension furnaces/ boilers. Such methods are effective to produce energy from waste wood

but tend to be difficult to control because of the size and moisture content of the particles and variations in size, moisture, type, and quality. As a result of these difficulties, such methods have suffered from high emissions of air pollutants and low thermal efficiency. Making these traditional methods even marginally acceptable from an air emissions standpoint requires the addition of expensive chemical additive-based pollution control equipment, particularly for NO_x. The air emission and thermal efficiency difficulties associated with traditional wood to energy conversion are only compounded when more diverse types of biomass waste such as manures, crop residue, and green waste, are used as fuel.

[04] Nitrogen oxide (NO_x) is arguably the “most regulated” pollutant, with a variety of Federal and State regulatory initiatives aimed at reducing NO_x emissions. NO_x emissions are a concern because they contribute to the formation of acid rain and, either directly or through the creation of ozone, lead to harmful effects on human health.

[05] Regulations and the permitting process refer to Best Available Control Technology and Lowest Available Emissions Rate. Best Available Control Technology (BACT) considers requirements for each source on a case-by-case basis, and includes economic, energy, and environmental considerations. Lowest Available Emissions Rate (LAER) is stricter, rigid, and objective by not allowing economic, energy, or environmental consideration, only considering the most stringent control achieved in practice for the category of source being considered.

[06] For converting biomass into steam and/or electrical power, fluidized bed boilers are the norm for new installations. Fluidized beds combust biomass in the form of larger high moisture content chunks or co-fired with coal. By themselves, fluidized bed boilers produce NO_x in their exhaust gas streams, and the current best practice is to equip them with “end of pipe” clean up, where the exhaust gas is cleaned to remove a fraction of the NO_x. The two techniques for that are Selective Catalytic Reduction (SCR), and Selective Non-Catalytic Reduction (SNCR). SCR injects ammonia into the process and cleans via a catalyst. Some of the ammonia escapes into the atmosphere and the catalyst needs to be disposed of. Due to a number of other technical challenges, SCR applied to biomass is arguably not feasible at this time. SNCR also uses ammonia, but no catalyst. It leaks less ammonia, but is not as effective at removing NO_x. SNCR has successfully been applied in some biomass combustion applications, and is

therefore deemed “feasible” or “achieved in practice”. SNCR still adds considerable capital and operating cost to the project, certainly at least on the order of millions of dollars per year.

[07] The level of NO_x emissions for woody waste biomass combustion currently being approved in the most stringent jurisdictions are 0.075 – 0.1 lb NO_x/MMBtu (combusted). These are achieved by fluidized bed boilers fitted with SNCR. Many plants employing current combustion methods are proving unable to meet these levels, and proposed new rules will even be tighter.

[08] There exist a number of older, particulate fuel suspension furnaces/ boilers that produce electrical energy via the combustion of fossil fuels such as pulverized coal and atomized oil alone or by co-firing with particulate wood waste fuel. Natural gas may also be used in such furnaces in conjunction with the particulate fuel. These suspension furnaces, which include tangentially-fired suspension furnaces and wall-fired suspension furnaces, are still used to some extent by utilities and manufacturing companies such as paper mills, but are relatively inefficient when compared to furnaces or boilers that burn fossil fuels. Moreover, particulate fuel suspension furnaces typically produce higher levels of air pollutants than modern waste wood or fossil fuel reactors. Today, particulate fuel suspension furnaces are typically used only in times of peak energy demand to supplement the primary electrical power system. Attempts have been made to more economically produce energy with suspension furnaces by burning wood in such furnaces along with fossil fuels, but those attempts have not been successful in replacing over 50% by weight, 40% by caloric value, with wood. Because waste wood and diverse biomass is inexpensive and available in large quantities, particulate fuel furnaces could produce energy more economically and with less air pollution if waste wood and/or diverse biomass could be combusted at high enough rates with lower levels of air pollution. Thus, combusting wood and/or diverse biomass in particulate fuel suspension boilers optimized for lower air pollutants and higher thermal efficiency would increase the usefulness of such boilers and add to their value.

[09] Prior attempts to burn wood in fossil fuel suspension furnaces or boilers include co-firing waste wood particles with pulverized coal by mixing the waste wood particles with the coal at the coal pile and introducing the combined material into the furnace or boiler through the coal pulverizers. This method can be used

with combined fuels that contain less than about 10% by weight of wood particles, but such an amount of wood is ineffective to more economically produce energy with the furnace than by burning solely fossil fuels. By separately comminuting and drying wood particles, as much as 50% by weight can be replaced with waste wood. When greater than about 50% by weight of particulate wood was co-fired with the coal, the wood particles inhibited combustion such that the mixed fuel could not be efficiently combusted. Co-firing prior art includes high temperature combustion gas drying of the biomass fuel. Substantial fire hazards are associated with high temperature combustion gas drying and with inorganic contact during wood comminution, so much as to inhibit wider use of particulate wood fuel. Combustion of broader categories of biomass such as manures, non-wood and diverse biomass crop residue, and green waste, in particulate suspension furnaces or boilers required substantially greater than 60% of caloric value from fossil fuel.

[10] The increasing cost of fossil fuels and decreasing availability of disposal options for waste biomass have made the use of biomass as fuel for steam or process heat more attractive. Biomass-to-energy applications usually require utilizing a variety of fuels due to supply seasonality and need to manage supply risk. Traditional stoker and fluidized bed furnaces or boilers are better suited to waste wood than other forms of waste biomass such as manures, crop residue, and green waste. Less common suspension boilers are better suited to manures, crop residue, and green waste fuel, but even these furnaces often require physical reconfigurations to accommodate a change in biomass feedstock.

[11] Therefore, there is a need for a waste wood and/or diverse biomass fuel and a method for preparing and combusting such fuel in a suspension furnace or boiler that: a) reduces air pollution, b) reduces drying fire hazards, c) increases thermal efficiency, d) allows a wide variety of diverse biomass fuels to be used, and e) requires minimal or no fossil fuel co-firing.

[12] Combustion control methods successfully employed in some fossil fuel-fired applications to minimize air emissions are currently not employed or employed with little effect in biomass fuel-fired applications. These air emissions minimization techniques include low excess air, flue gas recirculation, lean oxygen combustion and staged combustion. They are of most value in minimizing NO_x emissions, but CO and PM emissions benefit from these techniques as well.

Using these techniques requires: 1) a dry fuel with small and consistent size characteristics (if solid), 2) a method for emulating the conditions which create success in fossil fuel applications, and 3) precise combustion process control across a range of fuel and other conditions. Without precise fuel and air control, both in quality of fuel and in mass of fuel and air, air emissions minimization techniques cannot be employed.

[13] In the past, biomass has been sized and dried with the intent of improving combustion, but not to specifications resulting in reduced emissions. This is borne out by the current best available emissions results for biomass combustion which are 2.5-3 times results projected by this method and only achieved by adding expensive “end of pipe” pollution control techniques like SCR and SNCR which are described above.

[14] Counterintuitively, using dry fuel with small and consistent size characteristics reduces, instead of increases, air emission species of NO_x, CO, and PM. This is an unexpected result and counterintuitive because historically NO_x air emissions were controlled in combustion processes by adding water to the combustion stream to control combustion temperature whereas in the present method water is removed (i.e., particulate biomass fuel is dried to low moisture content) while still reducing NO_x emissions. Further, smaller mean particle size increases surface area, which should cause the combustion reaction to speed up and burn hotter as occurs with coal and oil combustion (i.e., finely atomized coal and oil particles cause combustion reactions to speed up and burn hotter) and create greater NO_x emissions in the process. However, in the present method, the smaller mean particle size decreases NO_x emissions. Sizing and drying has been done in past to facilitate combustion, but not to reduce air emissions, which is counterintuitive/unexpected as described above.

[15] A root cause for the difficulty all biomass furnaces or boilers have in accommodating changing biomass fuel slates is the inconsistent feed moisture and size of most biomass fuels. Given that biomass fuel moisture can require from 4% to 12% of the overall fuel supply to dehydrate to a combustible condition and that dryer costs are capacity sensitive, dryers are not typically oversized. Moreover, at moisture levels above 20%, comminution below 0.5 in is problematic due to plugging of equipment. As a result, current practice is to design biomass combustion systems for the specific moisture and size of an expected feedstock,

leaving no allowance for significant variation in biomass moisture or size. Therefore, there is a need for a particulate biomass fuel and a method for making such fuel that accommodates wide variation in biomass feedstock moisture and size such that waste wood, manures, crop residue, and green wastes, among other fuels, can all produce a consistent particulate biomass fuel product and be efficiently combusted.

[16] Drying the fuel is a key step both for comminution and for combustion efficiency and emissions performance.. A few common practices are: 1) spread the material out in wind rows, 2) process the material through a rotary dryer. Wind rows are typically used only for waste wood and their efficacy is highly dependent on weather conditions. In addition, wind rows are often considered an eyesore and an aesthetic nuisance. Rotary dryers are used with many types of biomass. Typical practice is to divert a portion, 4% to 16% of the total biomass, of the more finely sized material to a furnace to heat gas which is supplied to the dryer at 1200 F to 1800 F. Combustion in the furnace occurs at 100% to 200% excess air and combustion is neither efficient nor well controlled. The high levels of excess air do serve two purposes however: 1) to cool the combustion gas to something close to the maximum allowed for the dryer, 2) to negate the need for precise control of the fuel and air. Unfortunately, with high excess air and no combustion process control, NO_x, CO and PM emissions are extremely high. In addition, the resulting high temperatures entering the dryer result in very high VOC emissions from the drying particulate biomass, and in combination with high available oxygen levels present a significant fire hazard in and after the dryer. Since in many historical cases the biomass fuel was free, and new installations fell outside the New Source Review rules of the jurisdiction, there was no economic incentive to minimize air emissions or improve thermal efficiency. In fact, the only incentive was equipment preservation which was addressed through extensive fire suppression systems. Although biomass fuel has become more attractive in both supply and demand, jurisdictions where air emissions are not problematic, unwillingness to ignore inherent fire hazards, and significant fuel consumption, have all limited industry's ability to take advantage of biomass as steam or process heat fuel due to the method of preparing and combusting biomass.

[17] Therefore, there is a need for a method to make particulate biomass fuel without an aesthetic nuisance, without high air emissions, without an inherently high fire hazard, and without diverting fuel energy to drying.

[18] With high excess air and no combustion process control driving air emissions to the very high or extremely high range, any positive or negative effect from moisture or particle size is masked. With fossil fuels, both moisture and particle size impact air emissions, but there is no history of how these parameters effect particulate biomass air emissions. Intuitively, higher fuel moisture should decrease air emissions. With particle size, the optimum size intuitively is medium, not too large or small. Prior art has focused on identifying specific particle size distributions that are not too large and not too small, that work well with higher moisture wood waste combusted with no combustion process control. By focusing on 20% moisture wood waste, prior art has ignored the broader biomass supply as well as the effects of moisture and of particle size at other than 20% moisture levels with wood waste in terms of air emissions as well as thermal efficiency. Therefore, there is a need to be able to isolate the effects of moisture and particle size with a wide variation in biomass feedstock on air emissions and thermal efficiency through more precise combustion process control and lower excess air so that optimal moistures and particle sizes are identified and employed. \

[19] VOC compounds emitted from drying particulate biomass have vapor points in the 300 F to 500 F range. With rotary dryers typically using 1200 F to 1400 F gas as a drying medium, both by design and as a result of poorly controlled combustion, most if not all of the biomass VOC compounds are released during the drying process. Therefore, there is a need for a cooler drying medium to reduce VOC emissions from drying biomass for use as steam or process heat fuel.

[20] The issues previously cited for biomass combustion which lead to very high uncontrolled air emissions also contribute to very poor thermal efficiency. Fuel moisture in the 20% range and fuel particles larger than 0.5 in, depress efficiencies by at least 4% due to evaporating the moisture content alone. Additionally, higher amounts of excess air is also required due to both moisture and particle size, further depressing efficiency. Biomass fuel drying using biomass fuel at high gas temperatures consumes an additional 8% to 12% of the total fuel supply further decreasing process efficiency. For a given heat transfer device, the

higher amounts of excess air typically employed in combusting biomass results in an additional efficiency loss in addition to the losses incurred from moderate moisture, particle size, and fuel drying.

[21] In addition to these thermal efficiency losses which are present on day one of operation, there are losses over time due to fouling of the heat transfer surfaces from ash in the biomass fuel. Stoker and fluidized bed furnaces or boilers utilize combustion gas velocities in an average 20 feet per second range with many even lower velocity gas passages. At those gas velocities, biomass ash particles will settle on any surface, especially a horizontal surface, further reducing heat transfer and increasing the potential for corrosion. Horizontal heat transfer tubes with gas up flow are common in superheaters, economizers, and other heat transfer sections found in stoker and fluidized bed boilers. Overall, the thermal efficiency penalty from all the causes cited above is between 20% and 30%. Even if biomass fuel is free, an increasingly uncommon occurrence, the thermal efficiency penalty requires a design capacity increase of between 25% and 43%, a significant capital expense. By focusing on 20% wood waste moisture levels, prior art has ignored the broader biomass supply plus the effects of moisture as well as size at other than 20% moisture levels in terms of air emissions as well as thermal efficiency.

[22] Therefore, there is the need for a method to dry and communicate and combust biomass fuel that: a) utilizes low temperature waste heat for drying, b) employs precise fuel and air control to minimize excess air, and c) maintains high down flow or horizontal flow velocity in heat transfer sections.

SUMMARY OF THE INVENTION

[23] To overcome the above problems and others, an aspect of the invention involves a solid biomass-to-energy combustion and high quality steam generation method with a process target of 0.025 - 0.040 lb NO_x/MMBtu, approximately 1/3 to 1/2 of the theoretically best available NO_x emissions today. The method improves efficiency in the process itself and avoids the expense of end-of-pipe clean up.

[24] The solid biomass-to-energy combustion and high quality steam generation method involves biomass receiving, storage and preparation, a heat train including biomass drying, combustion, heat recovery steam generation and

particulate pollution control. The process also includes water conditioning, which is provided by a steam customer in a “repowering” case.

[25] A few of the elements of the solid biomass-to-energy combustion and high quality steam generation method include:

[26] Drying the biomass using waste heat; in other processes, the biomass fuel is combusted wet or biomass fuel is diverted to produce hot air to dry the biomass fuel, in either case resulting in reduced heat transfer to the steam production as significant part of the energy is used to evaporate the moisture in the biomass during the combustion process or to dry the fuel.

[27] Biomass dryer temperature; the dryer dries the biomass at significantly lower temperatures than other technologies resulting in minimal volatile organic compound (VOC) emissions.

[28] Combusting uniformly sized, dry biomass fuel particles in a suspension combustor; delivering high energy heat transfer and low uncontrolled air emissions, while using multiple diverse fuels.

[29] Air-fuel ratio control; the method enables the combustion process to operate at much lower levels of excess air than has been achieved with other biomass combustion technologies, and other suspension combustor technology.

[30] Flue gas recirculation; flue gas recirculation optimizes combustion and reduces air emission species; includes, how much flue gas is recirculated, where the recirculation connections are, and how it is controlled.

[31] HRSG gas flow direction and velocities minimize ash deposition in the HRSG, improving sustained heat transfer efficiency, reducing maintenance and improving process reliability.

[32] The waste biomass is likely to contain 30% to 65% moisture on a wet basis (w.b.). Prior to its use as fuel, the biomass is screened and uniformly sized, dried to approximately 5% moisture, and then milled again to reduce the size of the particles to 1/8 inch or less.

[33] The dry fuel is pneumatically blown into a combustion chamber through strategically configured port or ports. Combustion air is injected into the combustion chamber along with recirculated flue gas. The combustion unit includes an auxiliary fossil fuel fired burner that heats the combustion chamber refractory during start-up, prior to the injection of solid fuel.

[34] Hot exhaust gas (as high as 2,600 °F) from the combustion chamber is directed to a heat recovery steam generating unit (HRSG) and then to a rotary dryer. The rotary dryer is designed to operate with a gas inlet temperature of about 420 °F and a gas discharge temperature of about 185 °F. The gas discharged from the dryer proceeds to a cyclonic gas-solid separator, then to a baghouse filter, and finally to a dispersion stack.

[35] A solid biomass-to-energy combustion and high quality steam generation system or heat train system implements the solid biomass-to-energy combustion and high quality steam generation method. The heat train system is highly integrated and is designed to operate as a stand-alone biomass fueled steam generator. The heat train system has a thermal efficiency ranging from 80% to 85% (compared to a thermal efficiency ranging from 65% to 70% for existing biomass power plants).

[36] The heat train system includes equipment that can be broadly grouped into five operational units designed to accomplish the following tasks:

1. Rotary dryer utilizing low temperature exhaust gas from the HRSG (420 °F to 185 °F) to reduce wet fuel moisture to approximately 5%. The heat train system includes a cyclone for fuel separation with dry fuel routed to milling equipment and exhaust gas routed to a baghouse filter and dispersion stack.
2. Milling equipment for reducing the size of the dry wood particles to 1/8 inch or less and equipment required for conveying properly sized fuel to the combustor.
3. Solid fuel fired suspension combustor with auxiliary fossil fuel fired burner used during start-up to heat the combustion chamber refractory. Gas from the combustor is routed to the heat recovery steam generation unit (HRSG) and dryer.
4. Heat recovery steam generator (HRSG) in which heat is transferred to water creating steam.
5. Intermediate and final exhaust gas system handling system consisting of baghouse filters for control of particulate matter and semi-volatile organic compounds.

[37] Another aspect of the invention involves a particulate waste wood and diverse biomass fuel comprising wood and diverse biomass particles with about 5% water by weight and having a particle size distribution suitable for combustion of the particulate wood and diverse biomass fuel in a suspension furnace. A method for making the particulate wood and diverse biomass fuel includes size

reduction of waste wood and diverse biomass and drying the size reduced waste wood and diverse biomass to obtain the desired particle size distribution and water content. A method for producing energy comprises injecting the particulate wood and diverse biomass fuel into the combustion chamber of a particulate fuel suspension furnace that has been previously raised to the autoignition temperature using a separately injected fossil fuel. The particulate wood and diverse biomass fuel is combusted in the combustion chamber in a gas flow through the combustion chamber to form a flame in the gas flow. The wood and diverse biomass particles are substantially completely combusted within the combustion chamber while suspended in the gas flow and are not combusted at the furnace wall. The method of producing energy is particularly suited for suspension furnaces.

[38] A further aspect of the invention involves a particulate wood and diverse biomass fuel comprising particles of wood and diverse biomass with less than about 5% water by weight, the particles of wood and diverse biomass having a particle size distribution such that substantially 100% by weight of the wood and diverse biomass particles will pass through a sieve having 0.125 in diameter holes. The terms “substantially 100%” are used because, for example, some of the particles may get caught up in or along a perimeter of the holes of the sieve by surface attraction forces.

[39] Another aspect of the invention involves a method for making a particulate wood and diverse biomass fuel comprising the step of size reducing waste wood and diverse biomass to form wood and diverse biomass particles having a particle size distribution such that substantially 100% by weight of the wood and diverse biomass particles will pass through a sieve having 0.125 in diameter holes.

[40] One or more implementations of the aspect of the invention described immediately above includes one or more of the following: the step of size reduction comprises the steps of: in a first screening step, screening the wood and diverse biomass particles to separate wood and diverse biomass particles having a maximum dimension less than 1.0 (or about 1.0) inch from a first remaining portion having a maximum dimension of at least 1.0 (or about 1.0) inch; in a first size reduction step, size reducing the first remaining waste wood and diverse biomass portion in a high speed rotating hammermill shredder to produce wood and diverse biomass particles having a maximum dimension of less than 1.0

(or about 1.0) inch; in a second size reduction step, size reduction of all the less than 1.0 (or about 1.0) inch wood and diverse biomass particles in a mill to reduce the wood and diverse biomass particles to wood and diverse biomass particles having a maximum dimension less than about 0.125 inch; the method includes separating non-wood and diverse biomass products from the wood and diverse biomass particles in an air separator; and magnetically separating ferrous metal particles from the size reduced wood and diverse biomass, both steps of separating being conducted before or between the first size reduction step and the first screening step; and/or the method includes the steps of feeding the wood and diverse biomass particles having a maximum dimension less than 1.0 (or about 1.0) inch through a rotary dryer for drying the wood and diverse biomass particles to a moisture content of less than about 5% water by weight.

[41] An additional aspect of the invention involves a method for producing energy comprising the steps of: introducing an oxygen containing gas into a combustion chamber of a suspension furnace to form a flow of gas through the combustion chamber, the combustion chamber being defined by a furnace wall; injecting a fossil fuel into the combustion chamber through a first port in the furnace wall and into the gas flow; injecting a particulate wood and diverse biomass fuel into the combustion chamber through a second port in the furnace wall and into the gas flow, the second port being separate from the first port such that the particulate wood and diverse biomass is injected into the combustion chamber separately from the fossil fuel; and combusting the fossil fuel and the particulate wood and diverse biomass fuel in the gas flow to form a flame in the gas flow, the particulate wood and diverse biomass fuel comprising less than about 5% water by weight and having a particle size distribution such that substantially 100% by weight of the wood and diverse biomass particles will pass through a sieve having 0.125 inch diameter holes, so that the wood and diverse biomass particles are substantially completely combusted within the combustion chamber while suspended in the gas flow and are not combusted at the furnace wall.

[42] One or more implementations of the aspect of the invention described immediately above includes one or more of the following: the furnace is a tangentially-fired fossil fuel suspension furnace; the oxygen-containing gas is introduced tangentially into the combustion chamber so that the gas flow through

the furnace has a vortex; the fossil fuel is introduced tangentially into the combustion chamber and into the vortex of the gas flow; the particulate wood and diverse biomass fuel is introduced tangentially into the combustion chamber and into the vortex of the gas flow; and the fossil fuel and the wood and diverse biomass particles are substantially completely combusted within the combustion chamber while suspended in the vortex of the gas flow; the furnace is a tangentially-fired pulverized coal suspension furnace and the fossil fuel is pulverized coal; the method includes the steps of tangentially injecting natural gas into the combustion chamber through a third port in the furnace and into the vortex of the gas flow, and combusting the natural gas in the vortex of the gas flow; the furnace is a wall-fired fossil fuel suspension furnace; the furnace is a wall-fired pulverized coal suspension furnace and the fossil fuel is pulverized coal; the furnace is a pulverized coal suspension furnace and the fossil fuel is pulverized coal; the fossil fuel is atomized oil; the furnace forms part of a boiler and the furnace wall includes boiler tubes; the boiler is a utility grade boiler; the method includes the steps of injecting natural gas into the combustion chamber through a third port in the furnace and into the gas flow, and combusting the natural gas in the gas flow; the first port is upstream of the third port and the second port is between the first port and the third port.; the second port is upstream of the third port and the first port is between the second port and the third port; the first port is upstream of the second port; the second port is upstream of the first port; the method includes the step of pneumatically conveying the particulate wood and diverse biomass fuel through a conduit to the second port; the method includes the step of conveying the particulate wood and diverse biomass fuel to the conduit with an auger; and/or the particulate wood and diverse biomass fuel is injected in an amount such that the particulate wood and diverse biomass fuel contributes 100% of the energy produced by the furnace.

[43] A further aspect of the invention involves a method for producing energy comprising the steps of: introducing an oxygen containing gas into a combustion chamber of a fossil fuel suspension furnace to form a flow of gas through the combustion chamber, the combustion chamber being defined by a furnace wall; injecting a fossil fuel into the combustion chamber through a first set of ports in the furnace wall and into the gas flow, the first set of ports being spaced about the combustion chamber; injecting a particulate wood and diverse biomass fuel into

the combustion chamber through a set of second ports in the furnace wall and into the gas flow, the second set of ports being separate from the first set of ports such that the particulate wood and diverse biomass is injected into the combustion chamber separately from the fossil fuel, the second set of ports also being spaced about the combustion chamber; and combusting the fossil fuel and the particulate wood and diverse biomass fuel in the gas flow to form a flame in the gas flow, the particulate wood and diverse biomass fuel comprising less than about 5% water by weight and having a particle size distribution such that substantially 100% by weight of the wood and diverse biomass particles will pass through a sieve having 0.125 inch diameter holes, so that the wood and diverse biomass particles are substantially completely combusted within the combustion chamber while suspended in the gas flow and are not combusted at the furnace wall.

[44] One or more implementations of the aspect of the invention described immediately above includes one or more of the following: the furnace is a tangentially-fired fossil fuel suspension furnace; the oxygen-containing gas is introduced tangentially into the combustion chamber so that the gas flow through the furnace has a vortex; the fossil fuel is introduced tangentially into the combustion chamber and into the vortex of the gas flow; the particulate wood and diverse biomass fuel is introduced tangentially into the combustion chamber and into the vortex of the gas flow; and the fossil fuel and the wood and diverse biomass particles are substantially completely combusted within the combustion chamber while suspended in the vortex of the gas flow; and/or the furnace is a wall-fired fossil fuel suspension furnace.

[45] Additional aspect(s) of the invention involves a particulate wood and diverse biomass fuel, a method for making that fuel with a wide variety of biomass materials and with a significantly reduced fire hazard, a method for producing energy by combusting the particulate wood and diverse biomass fuel that results in significant reductions in current state-of-the-art air pollution emissions, and a method for increasing the heat transfer from particulate fuel combustion to a working fluid. The particulate wood and diverse biomass fuel may be 100% single-fired or co-fired with fossil fuel in a particulate fuel suspension furnace to consistently produce energy in an economical manner and with very low levels of all traditional air pollutants. The particulate wood and diverse biomass may be burned along with fossil fuel in a particulate fuel suspension furnace in quantities

up to an amount at which the particulate wood and diverse biomass contributes 100% of the total energy produced by the furnace. In addition, because the particulate wood and diverse biomass fuel of the present invention has desirable flow characteristics and is introduced into the furnace separately from the fossil fuel, the amount of particulate wood and diverse biomass fuel combusted in the furnace can be tightly controlled. As is explained further below, due to the nature of the particulate wood and diverse biomass fuel, including the particle size distribution of the particulate wood and diverse biomass fuel, energy can be reliably and economically produced by single-firing or by co-firing the particulate wood and diverse biomass fuel and fossil fuel in a particulate fuel suspension furnace.

[46] Another aspect of the invention involves particulate wood and diverse biomass fuel including particles of wood and diverse biomass of less than 5% water by weight. The particles of wood and diverse biomass have a particle size distribution such that substantially 100% by weight of the wood and diverse biomass particles will pass through a sieve having 0.125 inch diameter holes.

[47] A further aspect of the invention involves a method of making the particulate wood and diverse biomass fuel, comprising: size reducing waste wood and diverse biomass to form particles having the above-described particle size distribution. More particularly, the method of making the particulate wood and diverse biomass fuel comprises three size reduction steps, one screening step, and one drying step. In a first size reduction step, waste wood and diverse biomass is size reduced in a low speed rotating tub grinder to produce wood and diverse biomass particles having a maximum dimension of about 16 inch. In a first screening step, the wood and diverse biomass particles are screened to separate wood and diverse biomass particles having a maximum dimension of less than 1.0 (or about 1.0) inch from a first remaining portion of wood and diverse biomass particles having a maximum dimension of at least 1.0 (or about 1.0) inch. In the second size reduction step, the first remaining portion of the wood and diverse biomass particles is size reduced in a second mill to reduce the first remaining portion of wood and diverse biomass particles to wood and diverse biomass particles having a maximum dimension of less than 1.0 (or about 1.0) inch. In the first drying step, all the wood and diverse biomass particles now having a maximum dimension of less than 1.0 (or about 1.0) inch and a maximum moisture

of less than about 65% are dried to reduce wood and diverse biomass particles' moisture level to less than about 5%. In the third size reduction step, the wood and diverse biomass particles are size reduced in a third mill to particles having a maximum dimension less than about 0.125 inch.

[48] A still further aspect of the invention involves a method of making particulate wood and diverse biomass fuel including separating non-wood and diverse biomass products from the wood and diverse biomass particles with an air separator and magnetically separating other ferrous metal particles from the size reduced wood and diverse biomass between the first size reduction of the immediate preceding step and the first screening step. The method includes drying the particles of wood and diverse biomass to a moisture content of less than about 5% by weight of water by passing the wood and diverse biomass particles having a maximum dimension of less than 1.0 (or about 1.0) inch through a rotary dryer using the waste heat from the heat recovery steam generator or boiler as the drying medium.

[49] An additional aspect of the invention involves producing energy by combusting the above-described particulate wood and diverse biomass fuel in a suspension furnace. An oxygen-containing gas, such as air, is introduced into a combustion chamber of a suspension furnace through a first port to form a flow of gas through the combustion chamber. The particulate wood and diverse biomass fuel is injected into the combustion chamber through a second port in the furnace wall and into the gas flow. Flue gas is injected into the combustion chamber through a third port in the furnace wall and into the gas flow. A fossil fuel, such as pulverized coal or atomized oil, or distillate, or a natural gas may be injected into the combustion chamber through a fourth port in the furnace wall and into the gas flow. The second port is separate from the fourth port such that the particulate wood and diverse biomass is injected into the combustion chamber separately from any fossil fuel. The particulate wood and diverse biomass fuel has a reduced water content and a particle size distribution such that the wood and diverse biomass particles are substantially completely combusted within the combustion chamber while suspended in the gas flow and are not combusted at the furnace wall. Because the particulate wood and diverse biomass fuel passes through a sieve having 0.125 inch diameter holes, the particles of wood and diverse biomass are of such a size that, when injected into the vortex of the gas flow, the

particles are substantially completely combusted within the combustion chamber of the furnace while suspended in the gas flow.

[50] One or more implementations of the aspects of the invention described above includes one or more of the following: no supplemental fossil fuel is used; furnace ports are located 180 degrees opposite in a tangential particulate fuel suspension furnace with products approximately evenly split between similar ports; the first and third ports are additionally split vertically to locate both above and below the second port and additionally configured to be adjustable in the horizontal plane; and/or the gas conveyance for the particulate wood and diverse biomass fuel is an oxygen lean gas such as that produced by mixing flue gas with air.

[51] Further aspects of the invention involve a particulate biomass fuel, a method for making that fuel with a wide variety of biomass materials and with a significantly reduced fire hazard, a method for producing economically attractive energy by combusting the particulate biomass fuel that results in significant reductions in prior art air pollution emissions, and a method for increasing the heat transfer from particulate biomass combustion to a working fluid.

[52] An additional aspect of the invention involves a particulate biomass fuel that can be single fired in a particulate fuel suspension furnace to consistently produce energy in an economical manner and with remarkably low levels of NO_x and other emissions. Moreover, because the particulate biomass fuel has extremely consistent product properties, including desirable flow characteristics, the precise amount of particulate biomass fuel combusted in the furnace can be tightly controlled. As is explained further below, due to the complimentary and accretive effects of the particulate biomass fuel, the method of making the fuel, the application of precise and thoughtful process control and design, as well as other synergies, reliable and economically attractive energy can be produced with remarkably low air emissions.

[53] Another aspect of the invention involves a particulate biomass fuel comprising particles of biomass less than about 5% water by weight. The particles of biomass have a particle size distribution such that substantially 100% by weight of the biomass particles will pass through a sieve having 0.125 inch diameter holes.

[54] A further aspect of the invention involves a method of making the particulate biomass fuel including shredding waste biomass to form biomass particles having the above-described particle size distribution. More particularly, the method of making the particulate biomass fuel comprises three shredding steps, one screening step, and one drying step. In a first shredding step, waste biomass is shredded in a horizontally forced fed, low speed rotating tub grinder to produce biomass particles having a maximum dimension of about 16 in. In a first screening step, the biomass particles are screened to separate biomass particles having a maximum dimension of less than 1.0 (or about 1.0) inch from a first remaining portion of biomass particles having a maximum dimension of at least 1.0 (or about 1.0) inch. In the second shredding step, the first remaining portion of the biomass particles is shredded in a second mill to reduce the first remaining portion of biomass particles to biomass particles having a maximum dimension of less than 1.0 (or about 1.0) inch. In the first drying step, all the biomass particles now having a maximum dimension of less than 1.0 (or about 1.0) inch and maximum moisture of less than about 65% are dried to reduce biomass particles' moisture to less than about 5%. In the third shredding step, the biomass particles are shredded in a third mill to reduce the biomass particles to less than about 0.125 inch.

[55] A further aspect of the invention involves a method of making the particulate biomass fuel including separating non-biomass products from the biomass particles with an air separator and magnetically separating other ferrous metal particles from the shredded biomass between the first shredding step and the first screening step. It is also desirable that the first drying step be done by diverting all of the exhaust gas from the heat recovery steam generator or boiler to a rotary dryer containing all the undried biomass particles. It is further desirable that in the third shredding step, the biomass particles are drafted through the mill with cleaned dryer humidified combustion exhaust gas having an oxygen content of less than about 6%.

[56] A still further aspect of the invention involves producing energy by combusting the above-described particulate biomass fuel in a particulate fuel suspension furnace. An oxygen-containing gas, such as air, is introduced into a combustion chamber of a particulate fuel suspension furnace to form a flow of gas through the combustion chamber. The particulate biomass fuel is injected into the

combustion chamber through a second port in the furnace wall and into the gas flow. Flue gas, cleaned dryer humidified combustion exhaust gas, is injected into the combustion chamber through a third port in the furnace wall and into the gas flow.

[57] Another aspect of the invention involves a method of preparing solid biomass fuel for a solid biomass-to-energy combustion system. The method includes providing solid biomass fuel; reducing the solid biomass fuel into solid biomass particles having a particle size distribution such that substantially 100% by weight of the solid biomass particles pass through a sieve having 0.125 inch diameter holes.

[58] One or more implementations of the aspect of the invention described immediately above include one or more of the following: reducing the solid biomass fuel comprises a first screening step including screening the solid biomass fuel to separate solid biomass fuel particles having a maximum dimension equal to and less than 1.0 inch from first remaining solid biomass fuel particles having a maximum dimension greater than 1.0 inch; a first size reduction step including size reducing the first remaining solid biomass fuel particles in a high speed rotating hammermill shredder to produce solid biomass fuel particles having a maximum dimension equal to and less than 1.0 inch; a second size reduction step including size reducing all the equal to and less than 1.0 inch solid biomass fuel particles in a mill to reduce the solid biomass fuel particles to solid biomass fuel particles having a maximum dimension less than 0.125 inch; the method further comprising separating the solid biomass fuel particles into primarily solid biomass fuel particles and primarily solid non-biomass fuel particles; and magnetically separating ferrous metal particles from the primarily solid biomass fuel particles, wherein both separating steps being conducted at least one of before and between the first size reduction step and the first screening step; the method further comprising: feeding the solid biomass fuel particles having a maximum dimension less than 1.0 inch through a rotary dryer and drying the solid biomass fuel particles having a maximum dimension less than 1.0 inch to a moisture content of less than 5% water by weight, the method further comprising combusting the solid biomass fuel particles; creating waste heat from combusting the solid biomass fuel particles; introducing the waste heat from combustion into the rotary dryer; and using the waste heat to dry the solid biomass fuel particles

having a maximum dimension less than 1.0 inch to a moisture content of less than 5% water by weight; drying includes drying at a low temperature of 300-500 degrees F the solid biomass fuel particles having a maximum dimension less than 1.0 inch to a moisture content of less than 5% water by weight; and/or the solid biomass fuel is a particulate wood and diverse biomass fuel.

[59] An additional aspect of the invention involves a solid biomass fuel for a solid biomass-to-energy combustion system, comprising: particles of wood and diverse biomass with less than 5% water by weight, the particles of wood and diverse biomass having a particle size distribution such that substantially 100% by weight of the wood and diverse biomass particles pass through a sieve having 0.125 inch diameter holes.

[60] A still further aspect of the invention involves a solid biomass-to-energy combustion method. The method includes introducing an oxygen containing gas into a combustion chamber of a suspension furnace to form a flow of gas through the combustion chamber, the combustion chamber being defined by a furnace wall; injecting a particulate solid biomass fuel into the combustion chamber through a port in the furnace wall and into the gas flow; and combusting the particulate solid biomass fuel in the gas flow to form a flame in the gas flow, the particulate solid biomass fuel comprising less than 5% water by weight and having a particle size distribution such that substantially 100% by weight of the particulate solid biomass fuel pass through a sieve having 0.125 in diameter holes, so that the particulate solid biomass fuel particles are substantially completely combusted within the combustion chamber while suspended in the gas flow and are not combusted at the furnace wall.

[61] One or more implementations of the aspect of the invention described immediately above include one or more of the following: the furnace is a wall-fired fossil fuel suspension furnace; further comprising the step of pneumatically conveying the particulate solid biomass fuel through a conduit to the second port; further comprising the step of conveying the particulate solid biomass fuel to the conduit with an auger; the particulate solid biomass fuel is injected in an amount such that the particulate solid biomass fuel contributes 100% of the energy produced by the furnace; the method produces emissions of 0.025 to 0.040 lb NO_x/MMBtu; the furnace wall includes an additional port, and the method further comprising the steps of injecting flue gas into the combustion chamber through

the additional port in the furnace and into the gas flow; further including recirculating to the combustion chamber more than 0% and no more than 35% of the flue gas from the combustion chamber; further comprising precisely balancing the particulate solid biomass fuel with the oxygen containing gas such that excess air is 10-40%; the furnace wall includes a first port and a second port, and further including injecting a fossil fuel into the combustion chamber through the first port in the furnace wall and into the gas flow; injecting the particulate solid biomass fuel includes injecting the particulate solid biomass fuel into the combustion chamber through the second port in the furnace wall and into the gas flow, the second port being separate from the first port such that the particulate solid biomass fuel is injected into the combustion chamber separately from the fossil fuel; and combusting the particulate solid biomass fuel includes combusting the fossil fuel and the particulate solid biomass fuel in the gas flow to form a flame in the gas flow; the furnace is a tangentially-fired fossil fuel suspension furnace; introducing the oxygen containing gas includes introducing the oxygen-containing gas tangentially into the combustion chamber so that the gas flow through the furnace has a vortex; injecting the fossil fuel includes injecting the fossil fuel tangentially into the combustion chamber and into the vortex of the gas flow; injecting the particulate solid biomass fuel includes injecting the particulate solid biomass fuel tangentially into the combustion chamber and into the vortex of the gas flow; and combusting the fossil fuel and the particulate solid biomass fuel includes substantially completely combusting the fossil fuel and the particulate solid biomass fuel within the combustion chamber while suspended in the vortex of the gas flow; the furnace is a tangentially-fired pulverized coal suspension furnace and the fossil fuel is pulverized coal; the furnace wall includes a third port, and the method further comprising the steps of tangentially injecting natural gas into the combustion chamber through the third port in the furnace and into the vortex of the gas flow, and combusting the natural gas in the vortex of the gas flow; the furnace is a wall-fired pulverized coal suspension furnace and the fossil fuel is pulverized coal; the furnace is a pulverized coal suspension furnace and the fossil fuel is pulverized coal; the fossil fuel is atomized oil or distillate; the furnace forms part of a boiler and the furnace wall includes boiler tubes; the boiler is a utility grade boiler; the furnace wall includes a third port, and the method further comprising the steps of injecting natural gas into the combustion chamber

through the third port in the furnace and into the gas flow, and combusting the natural gas in the gas flow; the first port is upstream of the third port and the second port is between the first port and the third port; the second port is upstream of the third port and the first port is between the second port and the third port; the first port is upstream of the second port; and/or the second port is upstream of the first port.

[62] Another aspect of the invention involves a solid biomass-to-energy combustion method. The method includes introducing an oxygen containing gas into a combustion chamber of a fossil fuel suspension furnace to form a flow of gas through the combustion chamber, the combustion chamber being defined by a furnace wall; injecting a particulate solid biomass fuel into the combustion chamber through a set of ports in the furnace wall and into the gas flow, the set of ports also being spaced about the combustion chamber; and combusting the particulate solid biomass fuel in the gas flow to form a flame in the gas flow, the particulate solid biomass fuel comprising less than 5% water by weight and having a particle size distribution such that substantially 100% by weight of the particulate solid biomass fuel particles pass through a sieve having 0.125 inch diameter holes, so that the particulate solid biomass fuel particles are substantially completely combusted within the combustion chamber while suspended in the gas flow and are not combusted at the furnace wall.

[63] One or more implementations of the aspect of the invention described immediately above include one or more of the following: the furnace is a wall-fired fossil fuel suspension furnace; and/or the furnace is a tangentially-fired fossil fuel suspension furnace; the oxygen-containing gas is introduced tangentially into the combustion chamber so that the gas flow through the furnace has a vortex; the fossil fuel is introduced tangentially into the combustion chamber and into the vortex of the gas flow; the particulate solid biomass fuel is introduced tangentially into the combustion chamber and into the vortex of the gas flow; and the particulate solid biomass fuel particles are substantially completely combusted within the combustion chamber while suspended in the vortex of the gas flow.

[64] Another aspect of the invention involves precisely balancing the particulate biomass fuel with oxygen containing gas such that excess air is no more than 40%, the particulate biomass fuel with a reduced water content and particle size distribution, such that the biomass particles pass through a sieve having 0.125 in

diameter holes but with no more than a limited amount of biomass particles passing a 100 mesh sieve, is substantially completely combusted within the combustion chamber while suspended in the gas flow or injected into the vortex of the gas flow and not combusted at the furnace wall. Counterintuitively, lower moisture, desirably less than or about 5% water by weight, reduces air emission species of NO_x , CO, and PM. This is an unexpected result and counterintuitive because historically NO_x air emissions were controlled in combustion processes by adding water to the combustion stream to control combustion temperature whereas in the present method water is removed (i.e., particulate biomass fuel is dried to low moisture content) while still reducing NO_x emissions. Again counterintuitively, smaller mean particle size further reduces air emissions. This is an unexpected result and counterintuitive because a smaller mean particle size increases surface area, which should cause the combustion reaction to speed up and burn hotter as occurs with coal and oil combustion (i.e., finely atomized coal and oil particles cause combustion reactions to speed up and burn hotter) and create greater NO_x emissions in the process. However, in the present method, the smaller mean particle size decreases NO_x emissions. A significantly larger amount of biomass particles passing a 100 mesh sieve would require lower levels of excess air to avoid damage to the furnace walls near the injection ports.

[65] Accordingly, an object of the present invention is to use particulate biomass fuel with a reduced water content and smaller mean particle size to reduce air emissions. Sizing and drying has been done in past to facilitate combustion, but not to reduce air emissions, which is counterintuitive/unexpected as described above.

[66] Accordingly, an object of the present invention is to provide an improved particulate waste wood and diverse biomass fuel.

[67] Another object of the present invention is to provide an improved method for making particulate waste wood and diverse biomass fuel.

[68] Still another object of the present invention is provide a method for producing energy with particulate waste wood and diverse biomass fuel.

[69] Yet another object of the present invention is to provide a method for more economically producing energy with fossil fuel suspension furnace boilers by co-firing fossil fuel and particulate waste wood and diverse biomass fuel or single-firing particulate waste wood and diverse biomass fuel in the furnace.

[70] Still another object of the present invention is provide a method for producing energy with particulate waste wood and diverse biomass fuel while significantly reducing species of NO_x, CO, and PM, in the combustion product exhaust gas.

[71] Yet another object of the present invention is provide a method for producing energy with particulate waste wood and diverse biomass fuel while significantly reducing species of NO_x, CO, and PM, in the combustion product exhaust gas more economically than alternative air emission specie reduction methods.

[72] Further objects and advantages are apparent to those skilled in the art after a review of the drawings and the detailed description of the preferred embodiments set forth below.

BRIEF DESCRIPTION OF THE DRAWINGS

[73] The details of the present invention, both as to its structure and operation, may be gleaned in part by study of the accompanying drawings, in which like reference numerals refer to like parts, and in which:

[74] FIG. 1 is a block diagram of an exemplary solid biomass-to-energy combustion and high quality steam generation method;

[75] FIG. 2 is a schematic of an exemplary solid biomass-to-energy combustion and high quality steam generation system;

[76] FIG. 3 is a flow chart of an exemplary method of fuel preparation for the solid biomass-to-energy combustion and high quality steam generation method; and

[77] FIG. 4 is a schematic of an exemplary solid biomass-to-energy combustion and high quality steam generation system.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT OF THE INVENTION

[78] With reference to FIGS. 1-4, embodiment(s) of a solid biomass-to-energy combustion and high quality steam generation method 100 and system 110 is described.

[79] With reference to FIG. 1, the solid biomass-to-energy combustion and high quality steam generation method ("method") 100 includes biomass receiving,

storage and preparation 120, a heat train 130 including biomass drying 140, combustion 150, heat recovery steam generation and particulate pollution control (not shown above for simplicity) 160. The process also includes water conditioning 170, appropriate to the final steam product. The method 100 provides a high quality steam supply for industrial and/or electricity generating processes.

Process Stage 1: Receiving, Preparation and Storage

[80] As shown in FIG. 2, at a first process stage (“first stage”), waste biomass delivery is received at material receiving 200 (i.e., biomass unloading and testing stations). Truckloads of waste biomass fuel are received, weighed, and moisture content measured. Although the biomass described here in is generally described as wood biomass, in alternative embodiments, the biomass may be any of wide variety of different forms of biomass such as, but not limited to, crop residue, food processing waste, and manure. At fuel preparation 210 (i.e., biomass screening and separation, wood hogs, hammer mills), dirt, metal, and other non-combustible material are removed and the biomass is ground to a smaller size before being stock piled in storage 220 (i.e., prepared biomass fuel stacking/reclaim (Note: some short term fuel storage occurs after drying and final preparation)). The material handling and preparation equipment and process includes truck unloading stations, conveyors, screens and grates (to filter out undesirable material), wood grinders and hammermills (for sizing), and a stacker-reclaim for bulk storage. All equipment is of standard design and sourced from major manufacturers. Although “fuel preparation 210” as shown as one block in FIG. 2 for simplicity, in actuality, fuel preparation occurs both before storage 220 and after storage 220). As shown by the arrows in FIG. 2, fuel conveyors convey prepared biomass to dryer 230 and combustor 240.

[81] FIG. 3 is a flow chart of an exemplary method 300 of fuel preparation for the solid biomass-to-energy combustion and high quality steam generation method 100. Proper fuel preparation is critical as it increases the overall efficiency and supports meeting stringent local air quality regulations. Fuel preparation starts, at step 310 with offsite biomass collection. Fuel received from agriculturally derived biomass is ground or shredded in large, mobile tub grinders, producing a biomass fuel that is nominally less than 1” in diameter and between 6”

and 16" in length, consists of 30%-65% moisture and is free (after step 350 below) of 3/16" minus grit, sand, and fines.

[82] With reference additionally to FIG. 4, which is a diagram depicting the overall process and equipment integration, at step 320, the biomass fuel is received at wet fuel surge chute 400.

[83] At step 330, a disc scalping screen separates the biomass fuel, with less than 1" fuel diverted for further debris screening, at step 340, over 1" fuel is sent directly to the wood hogs, and over 12" fuel is diverted for additional sizing. The wood hogs size-reduce to 1". The 1" and minus fuel then, at step 350, goes through a de-stoning, grit, and sand removal process. From there, the reject fines, grit, and sand are sent to a truck load-out system and the acceptable 1" minus fuel is, at step 360, dried in rotary drum dryer 230. The dryer 230 is a simple, direct, and highly effective method of drying biomass.

[84] At this point, the fuel is dried to 5% moisture and is fairly consistent in size. Dry and consistent fuel size is not only important to the operation and maintenance of the burner, but it is also important to the effectiveness of the hammer mill. After the fuel has been dried, it is delivered, at step 370, to the hammer mills, which reduces the size of the fuel to 1/8" size or less, the final preparation before, at step 380, combustion in the suspension combustor 240.

Process Stage 2: Heat Train – Drying and Combustion

[85] At a second process stage ("second stage"), the biomass is dried using waste flue gases in a rotary drum dryer ("rotary dryer") 230 (i.e., biomass drying utilizing waste heat from suspension combustor 240) prior to combustion in order to affect an efficient burn and enable a low emissions control. The then dry pulverized biomass is blown into a suspension combustor 240 (i.e., high-efficiency biomass combustion -- biomass energy to thermal energy) where it is efficiently combusted to produce hot gases.

[86] The dry fuel is pneumatically blown into the burner chamber of suspension combustor 240 through strategically oriented port or ports. Combustion air is also injected into the burner chamber 240 along with recirculated flue gas. The suspension combustor 240 will also include an auxiliary fossil fuel fired burner 480 (FIG. 4) which is used to heat the combustion chamber refractory during start-up, prior to the injection of solid fuel.

[87] Hot exhaust gas (as high as 2,600 °F) from the suspension combustor 240 is directed to the heat recovery steam generating unit (HRSG) 250 and then to the rotary dryer 230 at about 420 °F. The rotary dryer 230 is designed to operate with a gas inlet temperature of about 420 °F and a gas discharge temperature of about 185 °F. The gas discharged from the dryer 230 proceeds to a cyclonic gas-solid separator 490, then to a baghouse filter 500 and finally to an exhaust gas stack 502.

[88] The heat train system 130 is highly integrated and is designed to operate as a stand alone biomass fueled steam generator. The heat train system 130 is designed to have a thermal efficiency ranging from 80% to 85%. Existing biomass power plants have typical thermal efficiencies of 65% to 70%.

[89] The heat train system 130 includes equipment that can be broadly grouped into five operational units designed to accomplish the following tasks.

1. Rotary dryer 230 utilizing low temperature exhaust (420 °F to 185 °F) to reduce wet fuel moisture to approximately 5%. This heat train system 130 includes cyclone 490 for fuel separation with dry fuel routed to mill equipment 530 and exhaust gas routed to a baghouse filter 500 and exhaust gas stack 502.
2. Milling equipment 530 for reducing the size of the dry wood particles to 1/8 inch or less and equipment required for conveying properly sized fuel to the suspension combustor 240.
3. Solid fuel fired combustor 240 with auxiliary fossil fuel fired burner 480 used during start-up to heat the combustion chamber refractory. Gas from the suspension combustor 240 is routed to the heat recovery steam generation unit (HRSG) 250 and dryer 230.
4. Heat recovery steam generator (HRSG), in which heat is transferred to water, creating steam
5. Intermediate and final exhaust gas handling system consisting of baghouse filter 500 for control of particulate matter and semi-volatile organic compounds.

[90] The operation of the drying, milling, steam generation and exhaust gas systems is described below.

Low Temperature Biomass Dryer

[91] Biomass fuels typically have high moisture content and woody biomass can consists of up to 65% moisture (w.b.). The method 100 and system 110 of the

present invention avoids the use of wet fuel for the production of energy because it needlessly consumes large amounts of additional fuel since 10% to 20% of the energy is used for evaporation of moisture, adversely effecting combustion.

[92] Evaporation of moisture contained in wet fuel, reduces the adiabatic flame temperature causing incomplete combustion which promotes the formation of carbon monoxide (CO), unburned hydrocarbons, particulates and soot, polyaromatic hydrocarbons, polychlorinated dibenzodioxins, and dibenzofurans.

[93] The method 100 and system 110 of the present invention utilizes fuel drying to greatly improve combustion because drier fuel burns hotter and more vigorously. Using dry fuel in a direct combustion application results in greater efficiency, reduced fuel use, increased steam production, better performance and less ancillary power consumption.

[94] One of the main reasons for these benefits is increased flame temperature which promotes heat transfer and provides for more complete combustion. Better combustion results in fuel savings, and lower emissions of CO, unburned hydrocarbons, soot and fly ash.

[95] With better combustion, excess air can be reduced while ensuring that exhaust gas opacity is maintained at acceptable levels. Operating at lower excess air improves efficiency since it saves energy which would otherwise be lost to flue gas.

[96] With respect to reducing air pollutants, drying fuel prior to combustion is essential. It promotes high thermal efficiency, minimizes fuel use, reduces emissions from transportation of fuel; and reduces emission caused by poor combustion.

[97] Existing biomass facilities typically combust wet fuel at high excess air. Consequently, these facilities have low thermal efficiencies ranging from 65% to 70%. The method 100 and system 110 combust dry fuel (5% MC w.b.) at low excess air and is designed to have a thermal efficiency greater than 80%. Consequently, the method 100 and system 110 consume about 82% of the fuel that would normally be required for an existing biomass to energy facility.

[98] The method 100 and system 110 are operated at comparatively low inlet (420 °F) and outlet (185 °F) dryer temperatures. The operation of the dryer 230 under these low-temperature conditions extends the fiber saturation line and reduce VOC emissions. Operating at lower temperature also reduces VOC

emissions by operating below the vapor pressure of organic compounds contained in wood extractives.

Milling and Storage of Dry Fuel

[99] The combustion unit 240 is designed to burn relatively dry (5% moisture) and homogenously sized fuel. Consequently, after drying the wood particles are milled to reduce the size to 1/8 inch or less.

[100] The particles from the dryer 230 are transferred from the bottom of the fuel cyclone separator 490 to mill equipment 530 using a screw conveyor and a blower system. The size of the particles is reduced in two steps, using two mills, 532, 534. In the first step/mill 532, size of the particles is reduced from 1 inch to 3/8 inch. In the second step/mill 534, the size of the particles is reduced from 3/8 inch to 1/8 inch or less.

[101] After milling, the particles are pneumatically conveyed (blown) to a finished fuel separator 536. The exhaust gas from the filter 536 is routed to a bag house filter 510 and then back to wood dryer 230. The finished fuel discharged from the bottom of the separator 536 is pneumatically conveyed to a finished fuel storage silo 540. Exhaust from the storage silo 540 is routed to a baghouse filter 510 and then back to wood dryer 230.

Combustion of Biomass for Steam Production

[102] Heat required for steam generation is provided by combusting biomass in the combustion unit 240. The combustion unit 240 operates at high temperatures to reduce products of incomplete combustion (PIC), while achieving NO_x emissions of about 20 ppmv (at 3% excess oxygen).

[103] The combustion unit 240 operates at a temperature above 2,200 °F. When solid fuel is blown into the chamber 240 the oxidation of volatile constituents occurs almost instantly and char oxidation occurs within milliseconds. The high temperature promotes clean burning and reduces emissions of carbon monoxide, particulate matter, organic compounds and other products of incomplete combustion (PIC).

[104] The combustion chamber 240 may include multiple injection ports and the unit 240 is designed to operate under near stoichiometric conditions. Fuel is blown into the combustor 240 through one set of ports using a mixture of air and

recirculated flue gas. The mixture results in a relatively low temperature, oxygen deficient, fuel-rich combustion zone which greatly reduces fuel NO_x .

[105] Pulverized biomass is blown into the suspension burner 240, a large cylinder-shaped vessel. The airflow pattern forces the particles through the burner 240 where char oxidation occurs. Very high turbulence is generated in the suspension burner 240 and char oxidation occurs within milliseconds. Combustion intensity in suspension burners is considerably higher than combustion intensity in conventional wood fluidized bed or suspension grate furnaces.

[106] Other strategically located ports are used to inject additional combustion air to ensure complete combustion. External flue gas recirculation is used to minimize formation of thermal NO_x . Compared to EPA uncontrolled conventional solid fuel burner used for wood residue, the method 100 and system 110 achieves an overall NO_x reduction approaching 95%.

[107] Each combustion unit 240 includes a cylindrical reactor equipped with multiple injection ports for introducing fuel, combustion air and recycled flue gas. The unit 240 also includes auxiliary fossil fuel burner 480. The auxiliary fossil fuel burner 480 operates during start-up to raise the combustion chamber temperature prior to the injection of solid fuel.

[108] The hot gaseous combustion products from the combustor 240 are routed to the heat recovery steam generator (HRSG) 250 designed to produce steam (which may be 75% quality as an example). Hot gas circulates vertically downward or horizontally through the HRSG 250. The HRSG 250 is specifically designed to produce high thermal heat transfer from a biomass combusted hot gas. Flue gas discharged by the HRSG 250 is routed to the wood dryer 230. The exhaust gas from the dryer 230 is routed to cyclone gas-solid separator 490, then to baghouse filter 500 and finally to a dispersion stack 502.

[109] As indicated above, the low NO_x combustor 240 includes multiple injection ports for introducing mixtures of fuel, air and recirculated flue gas. The configuration of the injection system and the blending of fuel with combustion air and flue gas enables the control of both temperature and fuel-to-air stoichiometry within the combustion chamber of suspension combustor 240. Fuel NO_x is minimized by maintaining a sub-stoichiometric fuel-to-air ratio in the primary combustion zone. Thermal NO_x is minimized by operating the unit 240 at about 10% excess air ($\approx$ 2% excess oxygen) with up to 35% flue gas recirculation

(FGR). FGR system 504 (recirculates flue gas to the combustion chamber 240) and the configuration of the injection system and the combustion chamber 240 also reduce products of incomplete combustion, such as CO, VOC, PM and soot.

Process Stage 3: Heat Train – Heat Recovery Steam Generation

[110] At third process stage (“third stage”), a heat recovery steam generator (“HRSG”) 250 transfers heat from the hot gases to conditioned feed water (“treated water”) to create process steam. The feed water is treated water that has been conditioned to remove hardness and other minerals so as to minimize heat exchanger corrosion and fouling (i.e., to remove hardness and minimize heat exchanger tube maintenance/replacement expenses). Hot gas produced when the biomass is burned in the suspension combustor 240 is ducted to the HRSG 250. The feed water circulates through heat exchanger tubes imbedded in the HRSG 250, and as the hot gas passes through the HRSG 250 and around these tubes, the heat is transferred through the tubewall to the water, raising its temperature until it turns into steam.

[111] The HRSG 250 provides convective heat transfer and minimal ash build up on the internal surfaces. This maximizes heat transfer efficiency from the biomass combustion hot gas stream and minimizes efficiency loss from ash build up and unit availability while minimizing emissions.

[112] A pollution control system 260 captures ash and particulates from the exhaust flue gas before it is vented to atmosphere. Ash, the primary waste product, may be sold to local companies as either agricultural soil supplement or as an additive to construction fill, concrete, or asphalt.

[113] The solid biomass-to-energy combustion and high quality steam generation method optimizes efficiency of heat transfer to the steam and minimizes emissions, in particular NO_x, a highly regulated emission.

[114] Some of important aspects/elements of the solid biomass-to-energy combustion and high quality steam generation method 100 and system 110 include:

[115] Drying the biomass using waste heat; In other processes, the biomass fuel is combusted wet, which results in reduced heat transfer to the steam production as part of the energy is used to evaporate the moisture in the biomass during the combustion process.

[116] Biomass dryer temperature; dryer dries the biomass at significantly lower temperatures than other technologies resulting in minimal volatile organic compound (VOC) emissions.

[117] Biomass particle sizing and moisture content; the ability to combust small biomass particles enables the suspension combustor to handle optimal fuel conditions thereby delivering high energy transfer with low combustion emissions.

[118] Air-fuel ratio control; system/method enables the combustion process to operate at much lower levels of excess air than other biomass combustion technology and even lower than any other suspension combustor technology has previously been operated.

[119] Flue gas recirculation; system/method involves flue gas recirculation which optimize the combustion and emissions efficiency processes including, how much is recirculated, where the recirculation connections are, and how it is controlled.

[120] HRSG gas flow direction and velocities minimize ash deposition in the HRSG, reducing maintenance, sustaining overall heat transfer, and improving process reliability.

[121] Key benefits/advantages of the method 100 and system 110 are: ultra-low emissions (i.e., dramatically lower levels of undesirable combustion by-products such as mono-nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and particulates, especially NO_x), especially relative to other biomass combustion technologies currently in use; high thermal efficiency benefit over other combustion technologies (10-15%); high reliability and availability robust industrial process and equipment; modular design (i.e., each heat train 130 – including dryer 230, cyclonic combustor 240, HRSG 250, and connecting conveyors, pipes and ducts – is identical); produce particulate wood fuel that reduces NO_x and CO emissions when fired in various furnace types; produce particulate wood fuel that reduces particulate ash exhausting from various furnace types; wood fuel drying method reduces fuel costs using waste heat from combustion in various furnace types; wood fuel drying method reduces VOC emissions using waste heat from combustion in various furnace types; increases heat recovery from wood and/or other solid fuels fired in various furnace types; reduces particulate fouling of heat recovery devices when firing wood and/or other solid fuels in various furnace types; reduces NO_x and CO emissions when firing particulate wood fuel in various furnace types; reduces particulate ash exhausting

from various furnace types; and reduces fire hazards when producing particulate fuels elsewhere described using rotary dryers and comminuting devices.

[122] Compared to what was done in the past, the method 100 and system 110 reduces NO_x and CO emissions by Low Excess Air (10-40% Excess Air (EA) versus 75-100% EA historically), and Flue Gas Recycling (0-25% versus never done historically). Compared to what was done in the past, the method 100 and system 110 reduces VOC by Low Temperature Drying (300-500 degrees F versus 1400 degree F from Stand Alone Dryer), Dryer Exhaust As Combustion Air (0-25% versus not done successfully historically). Compared to what was done in the past, the method 100 and system 110 reduces PM by Complete Combustion (100% versus incomplete historically). Compared to what was done in the past, the method 100 and system 110 minimizes fuel use by Btu Burned/Transfer (approximately 1.21 versus >1.33 historically), Low Temperature Drying (300-500 degrees F versus 1400 degrees F historically), Low Excess Air (10-40% EA versus 75-100% EA historically), High Velocities (approximately 40 ft/s versus approximately 20 ft/s historically), and Tube Bundle Gas Path (Horizontal or Down Flow versus Up Flow Historically).

[123] The above figures may depict exemplary configurations for the invention, which is done to aid in understanding the features and functionality that can be included in the invention. The invention is not restricted to the illustrated architectures or configurations, but can be implemented using a variety of alternative architectures and configurations. Additionally, although the invention is described above in terms of various exemplary embodiments and implementations, it should be understood that the various features and functionality described in one or more of the individual embodiments with which they are described, but instead can be applied, alone or in some combination, to one or more of the other embodiments of the invention, whether or not such embodiments are described and whether or not such features are presented as being a part of a described embodiment. Thus the breadth and scope of the present invention, especially in any following claims, should not be limited by any of the above-described exemplary embodiments.

[124] Terms and phrases used in this document, and variations thereof, unless otherwise expressly stated, should be construed as open ended as opposed to limiting. As examples of the foregoing: the term "including" should be read as

mean “including, without limitation” or the like; the term “example” is used to provide exemplary instances of the item in discussion, not an exhaustive or limiting list thereof; and adjectives such as “conventional,” “traditional,” “standard,” “known” and terms of similar meaning should not be construed as limiting the item described to a given time period or to an item available as of a given time, but instead should be read to encompass conventional, traditional, normal, or standard technologies that may be available or known now or at any time in the future. Likewise, a group of items linked with the conjunction “and” should not be read as requiring that each and every one of those items be present in the grouping, but rather should be read as “and/or” unless expressly stated otherwise. Similarly, a group of items linked with the conjunction “or” should not be read as requiring mutual exclusivity among that group, but rather should also be read as “and/or” unless expressly stated otherwise. Furthermore, although item, elements or components of the disclosure may be described or claimed in the singular, the plural is contemplated to be within the scope thereof unless limitation to the singular is explicitly stated. The presence of broadening words and phrases such as “one or more,” “at least,” “but not limited to” or other like phrases in some instances shall not be read to mean that the narrower case is intended or required in instances where such broadening phrases may be absent.

CLAIMS

We claim:

1. A method of preparing solid biomass fuel for a solid biomass-to-energy combustion system, comprising:

providing solid biomass fuel;

reducing the solid biomass fuel into solid biomass particles having a particle size distribution such that substantially 100% by weight of the solid biomass particles pass through a sieve having 0.125 inch diameter holes.

2. The method of claim 1, wherein reducing the solid biomass fuel comprises

a first screening step including screening the solid biomass fuel to separate solid biomass fuel particles having a maximum dimension equal to and less than 1.0 inch from first remaining solid biomass fuel particles having a maximum dimension greater than 1.0 inch;

a first size reduction step including size reducing the first remaining solid biomass fuel particles in a high speed rotating hammermill shredder to produce solid biomass fuel particles having a maximum dimension equal to and less than 1.0 inch;

a second size reduction step including size reducing all the equal to and less than 1.0 inch solid biomass fuel particles in a mill to reduce the solid biomass fuel particles to solid biomass fuel particles having a maximum dimension less than 0.125 inch.

3. The method of claim 2, further comprising:

separating the solid biomass fuel particles into primarily solid biomass fuel particles and primarily solid non-biomass fuel particles; and

magnetically separating ferrous metal particles from the primarily solid biomass fuel particles,

wherein both separating steps being conducted at least one of before and between the first size reduction step and the first screening step.

4. The method of claim 2, further comprising:

feeding the solid biomass fuel particles having a maximum dimension less than 1.0 inch through a rotary dryer and drying the solid biomass fuel particles having a maximum dimension less than 1.0 inch to a moisture content of less than 5% water by weight.

5. The method of claim 4, further comprising:

combusting the solid biomass fuel particles;

creating waste heat from combusting the solid biomass fuel particles;

introducing the waste heat from combustion into the rotary dryer; and

using the waste heat to dry the solid biomass fuel particles having a maximum dimension less than 1.0 inch to a moisture content of less than 5% water by weight.

6. The method of claim 5, wherein drying includes drying at a low temperature of 300-500 degrees F the solid biomass fuel particles having a maximum dimension less than 1.0 inch to a moisture content of less than 5% water by weight.

7. The method of claim 1, wherein the solid biomass fuel is a particulate wood and diverse biomass fuel.

8. A solid biomass fuel for a solid biomass-to-energy combustion system, comprising: particles of wood and diverse biomass with less than 5% water by weight, the particles of wood and diverse biomass having a particle size distribution such that substantially 100% by weight of the wood and diverse biomass particles pass through a sieve having 0.125 inch diameter holes.

9. A solid biomass-to-energy combustion method, comprising:

introducing an oxygen containing gas into a combustion chamber of a suspension furnace to form a flow of gas through the combustion chamber, the combustion chamber being defined by a furnace wall;

injecting a particulate solid biomass fuel into the combustion chamber through a port in the furnace wall and into the gas flow; and

combusting the particulate solid biomass fuel in the gas flow to form a flame in the gas flow, the particulate solid biomass fuel comprising less than 5% water by weight and having a particle size distribution such that substantially 100% by weight of the particulate solid biomass fuel pass through a sieve having 0.125 in diameter holes, so that the particulate solid biomass fuel particles are substantially completely combusted within the combustion chamber while suspended in the gas flow and are not combusted at the furnace wall.

10. The method of claim 9, wherein the furnace is a wall-fired fossil fuel suspension furnace.

11. The method of claim 9, further comprising the step of pneumatically conveying the particulate solid biomass fuel through a conduit to the second port.

12. The method of claim 11, further comprising the step of conveying the particulate solid biomass fuel to the conduit with an auger.

13. The method of claim 9, wherein the particulate solid biomass fuel is injected in an amount such that the particulate solid biomass fuel contributes 100% of the energy produced by the furnace.

14. The method of claim 9, wherein the method produces emissions of 0.025 to 0.040 lbNO_x/MMBtu.

15. The method of claim 9, wherein the furnace wall includes an additional port, and the method further comprising the steps of injecting flue gas into the

combustion chamber through the additional port in the furnace and into the gas flow.

16. The method of claim 15, further including recirculating to the combustion chamber more than 0% and no more than 35% of the flue gas from the combustion chamber.

17. The method of claim 9, further comprising precisely balancing the particulate solid biomass fuel with the oxygen containing gas such that excess air is 10-40%.

18. The method of claim 9, wherein the furnace wall includes a first port and a second port, and

further including injecting a fossil fuel into the combustion chamber through the first port in the furnace wall and into the gas flow;

injecting the particulate solid biomass fuel includes injecting the particulate solid biomass fuel into the combustion chamber through the second port in the furnace wall and into the gas flow, the second port being separate from the first port such that the particulate solid biomass fuel is injected into the combustion chamber separately from the fossil fuel; and

combusting the particulate solid biomass fuel includes combusting the fossil fuel and the particulate solid biomass fuel in the gas flow to form a flame in the gas flow.

19. The method of claim 18, wherein:

the furnace is a tangentially-fired fossil fuel suspension furnace;

introducing the oxygen containing gas includes introducing the oxygen-containing gas tangentially into the combustion chamber so that the gas flow through the furnace has a vortex;

injecting the fossil fuel includes injecting the fossil fuel tangentially into the combustion chamber and into the vortex of the gas flow;

injecting the particulate solid biomass fuel includes injecting the particulate solid biomass fuel tangentially into the combustion chamber and into the vortex of the gas flow; and

combusting the fossil fuel and the particulate solid biomass fuel includes substantially completely combusting the fossil fuel and the particulate solid biomass fuel within the combustion chamber while suspended in the vortex of the gas flow.

20. The method of claim 19, wherein the furnace is a tangentially-fired pulverized coal suspension furnace and the fossil fuel is pulverized coal.

21. The method of claim 19, wherein the furnace wall includes a third port, and the method further comprising the steps of tangentially injecting natural gas into the combustion chamber through the third port in the furnace and into the vortex of the gas flow, and combusting the natural gas in the vortex of the gas flow.

22. The method of claim 18, wherein the furnace is a wall-fired pulverized coal suspension furnace and the fossil fuel is pulverized coal.

23. The method of claim 18, wherein the furnace is a pulverized coal suspension furnace and the fossil fuel is pulverized coal.

24. The method of claim 18, wherein the fossil fuel is atomized oil or distillate.

25. The method of claim 18, wherein the furnace forms part of a boiler and the furnace wall includes boiler tubes.

26. The method of claim 18, wherein the boiler is a utility grade boiler.

27. The method of claim 18, wherein the furnace wall includes a third port, and the method further comprising the steps of injecting natural gas into the

combustion chamber through the third port in the furnace and into the gas flow, and combusting the natural gas in the gas flow.

28. The method of claim 27, wherein the first port is upstream of the third port and the second port is between the first port and the third port.

29. The method of claim 27, wherein the second port is upstream of the third port and the first port is between the second port and the third port.

30. The method of claim 18, wherein the first port is upstream of the second port.

31. The method of claim 18, wherein the second port is upstream of the first port.

32. A solid biomass-to-energy combustion method, comprising:

introducing an oxygen containing gas into a combustion chamber of a fossil fuel suspension furnace to form a flow of gas through the combustion chamber, the combustion chamber being defined by a furnace wall;

injecting a particulate solid biomass fuel into the combustion chamber through a set of ports in the furnace wall and into the gas flow, the set of ports also being spaced about the combustion chamber; and

combusting the particulate solid biomass fuel in the gas flow to form a flame in the gas flow, the particulate solid biomass fuel comprising less than 5% water by weight and having a particle size distribution such that substantially 100% by weight of the particulate solid biomass fuel particles pass through a sieve having 0.125 inch diameter holes, so that the particulate solid biomass fuel particles are substantially completely combusted within the combustion chamber while suspended in the gas flow and are not combusted at the furnace wall.

33. The method of claim 32, wherein the furnace is a wall-fired fossil fuel suspension furnace.

34. The method of claim 32, wherein:

the furnace is a tangentially-fired fossil fuel suspension furnace;

the oxygen-containing gas is introduced tangentially into the combustion chamber so that the gas flow through the furnace has a vortex;

the fossil fuel is introduced tangentially into the combustion chamber and into the vortex of the gas flow:

the particulate solid biomass fuel is introduced tangentially into the combustion chamber and into the vortex of the gas flow; and

the particulate solid biomass fuel particles are substantially completely combusted within the combustion chamber while suspended in the vortex of the gas flow.

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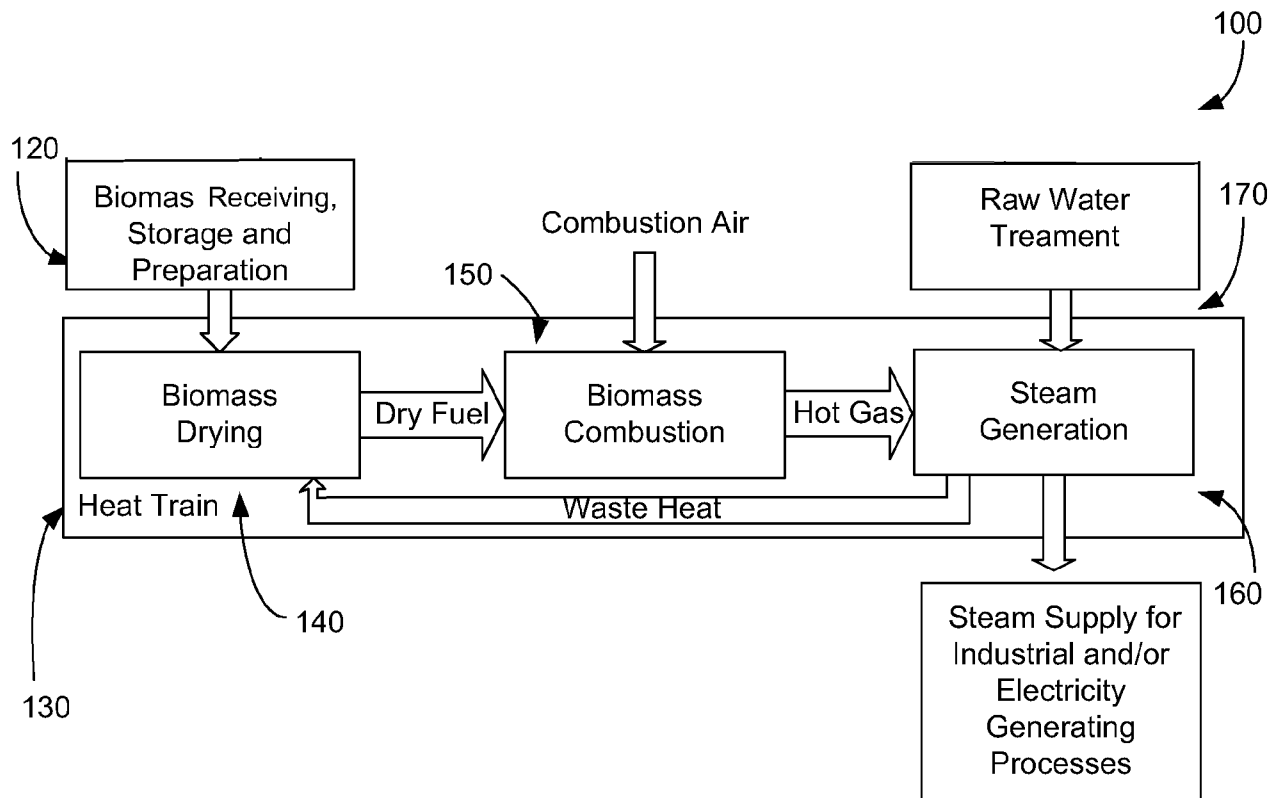


FIG. 1

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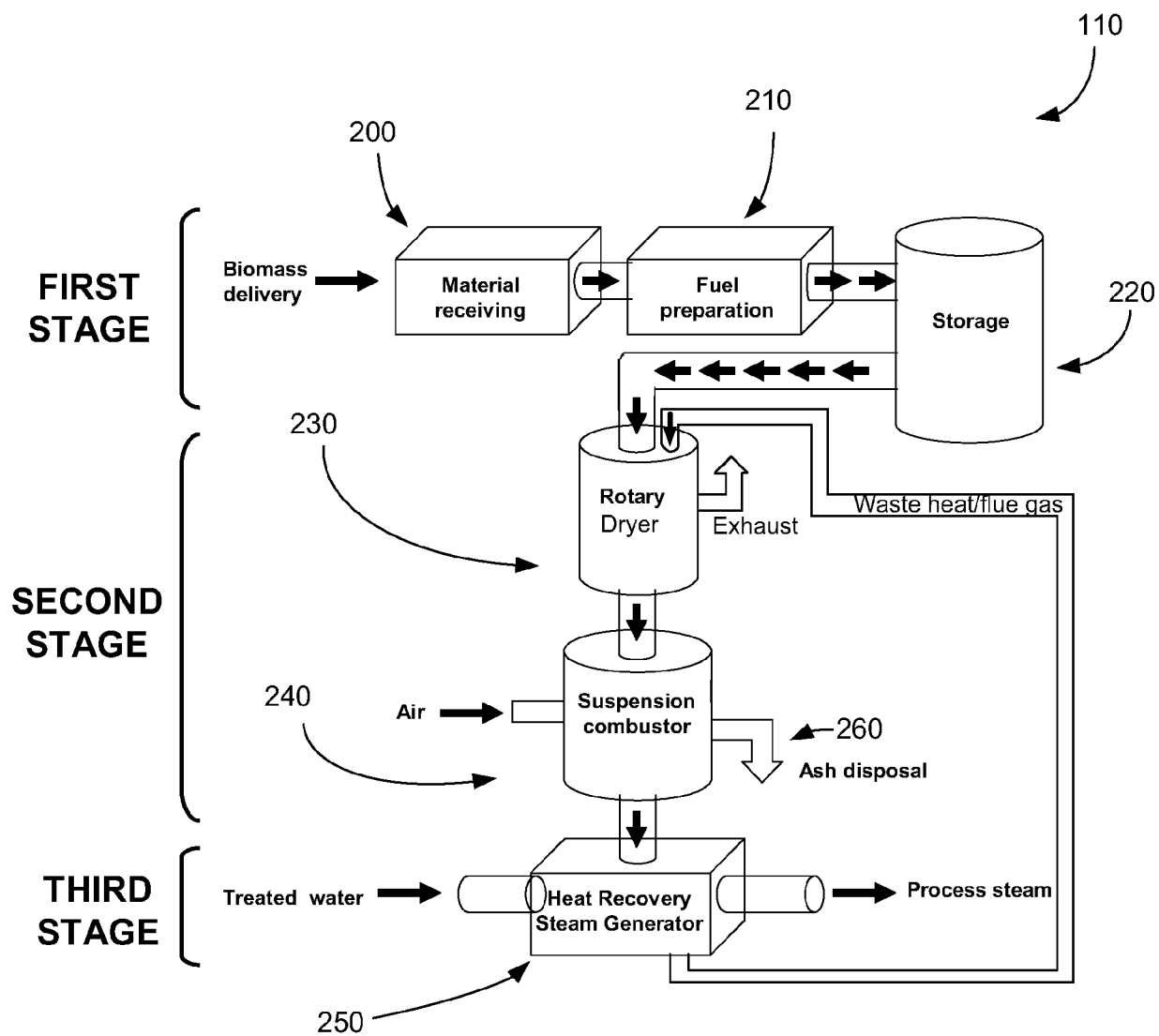


FIG. 2

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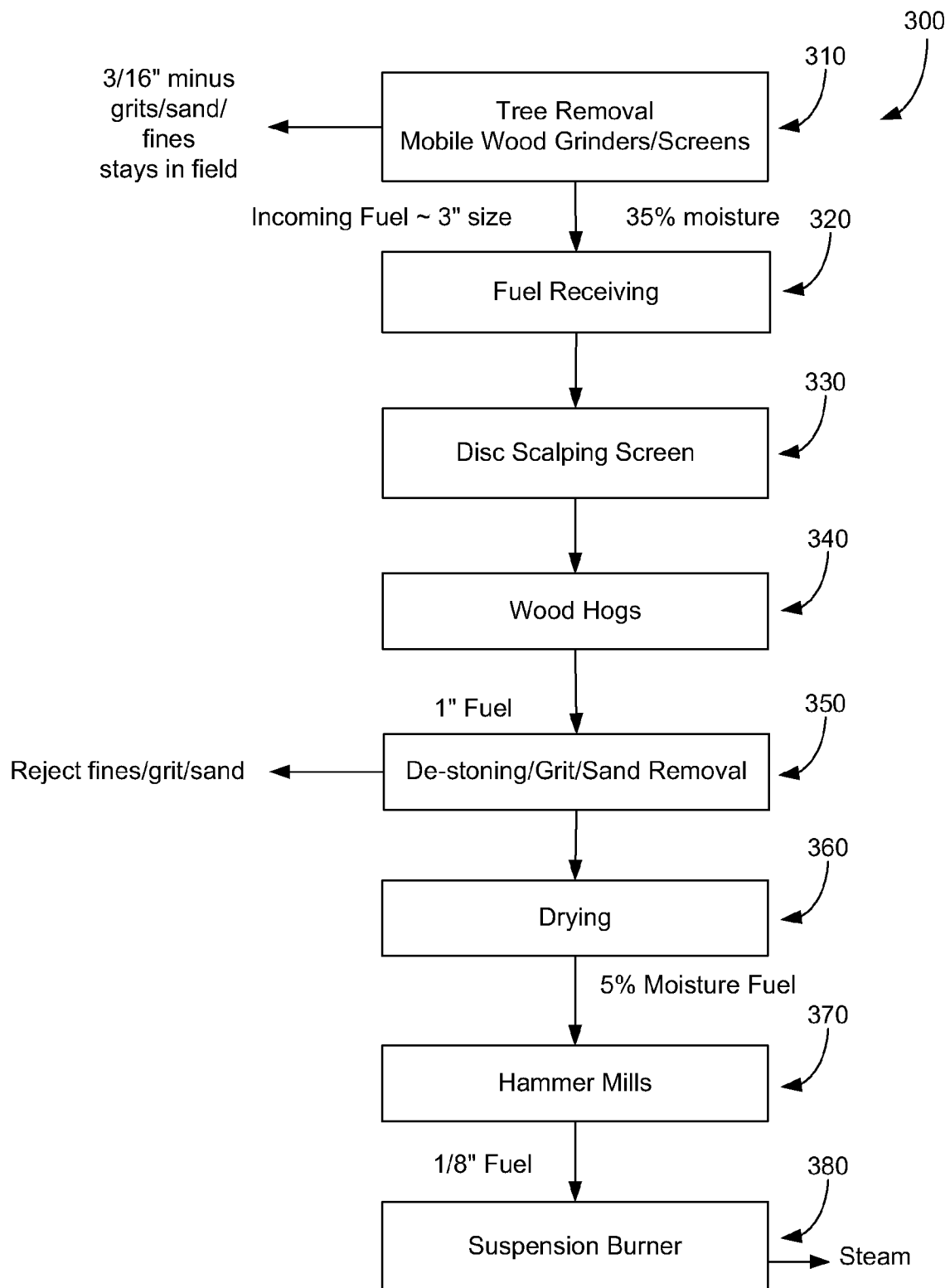


FIG. 3

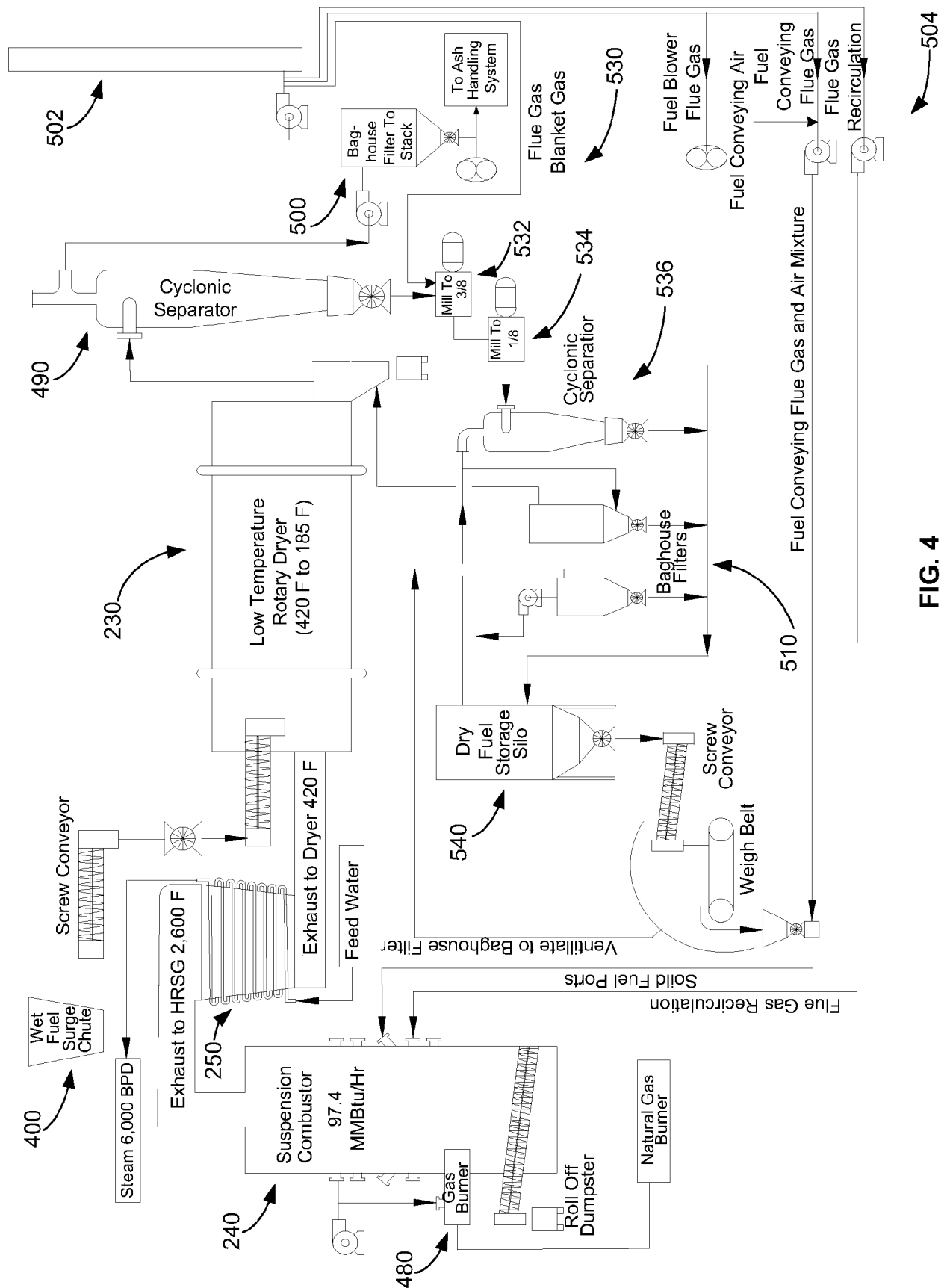


FIG. 4