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(54) **Title**: METHOD AND SYSTEM FOR THE TORREFACTION OF LIGNOCELLULOSIC MATERIAL

(57) **Abstract**: A method for torrefaction of biomass using a torrefaction reactor vessel having stacked trays including: feeding the biomass to an upper inlet of the vessel such that the biomass material is deposited on an upper tray of a vertical stack of trays in the reactor; cascading the biomass down through the trays by passing the biomass through an opening in each of the trays to deposit the biomass on a lower tray; as the biomass moves around each of the stacked trays, heating the biomass material with an oxygen deprived gas; extracting moisture containing gas having passed through the biomass on the upper trays wherein the extraction is immediately below each of the upper trays; as the biomass undergoes torrefaction in the lower trays of the stacked trays, retaining the gas with the biomass until the biomass falls from the stacked trays to a pile of biomass in the reactor vessel; exhausting gases containing organic compounds volatized by the torrefaction of the biomass through a gas outlet on the vessel at an elevation between the stacked trays and the pile of biomass, and discharging torrefied biomass from a lower outlet of the torrefaction reactor vessel.

METHOD AND SYSTEM FOR THE TORREFACTION OF LIGNOCELLULOSIC MATERIAL

RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Patent Application Serial No. 61/537,413 filed on September 21, 2011 and 61/551,932 filed October 27, 2011, respectively, the entirety of which are incorporated by reference.

BACKGROUND OF THE INVENTION

[0002] The present invention generally relates to systems and methods for torrefaction of biomass material, such as wood, other lignocellulosic material, and biomass containing fossil based materials such as plastic fractions and refuse-derived fuel (RDF) (these materials are collectively referred to as "biomass material"). The invention more particularly relates to a pressurized reactor vessel for the torrefaction of biomass material.

[0003] Torrefaction refers to the thermal treatment of biomass, usually in an oxygen deprived atmosphere at relatively low temperatures of 200 degrees Celsius (°C) to 400°C, or 200°C to 350°C, temperatures outside the range used for the process known as pyrolysis. An oxygen deprived atmosphere may have a low percentage of oxygen as compared to the percentage of oxygen in atmospheric air. A torrefaction process is described in U.S. Patent Application Publication US 2011/0041392.Torrefaction converts biomass material to an efficient fuel having increased energy density relative to the input biomass.

Torrefaction removes moisture and volatile components from the biomass material. In torrefaction, the hemicellulose fraction of the biomass material is largely destructed producing moisture and volatile organic compounds (VOCs), while the cellulose fraction is depolymerized to produce a hydrophobic solid combustible fuel product with a higher energy density (on a mass basis) that the unprocessed biomass material. Further, the torrefied biomass material may be suited for grinding.

[0004] Torrefaction changes the chemical structure of the biomass. Torrefied biomass may be burned in coal fired facilities (torrefied wood or biomass has the characteristics that resemble those of low rank coals) and can be compacted to high grade fuel pellets.

[0005] Unpressurized reactor vessels with multiple trays have been used for torrefaction, as is described in U.S. Patent Application Publication 2010/0083530 (the '530 Application). The '530 Application recommends that torrefaction be performed in a reactor vessel operating at atmospheric pressure. In view of this recommendation, the '530 Application teaches that vessels should not be operated at above-atmospheric pressures. See '530 Application, para. 0061.

[0006] Pressurized reactor vessels with multiple trays have been used in pulp mills to delignify pulp by oxidation. Examples of a pulping reactor vessel with multiple trays are disclosed in US patents 3,742,735 ('735 Patent) and 3,660,225 ('225 Patent). Multiple tray vessels allow pulp to cascade through the vertical arrangement trays in the reactor. The trays allow the pulp to cascade in discrete batches down through the vessel. An oxygen rich environment in the pulping reactor promotes delignification and bleaching of the pulp. The '735 Patent and '225 Patent do not suggest using a pulping reactor vessel having an oxygen deprived environment for torrefaction of wood or other biomass material.

BRIEF DESCRIPTION OF THE INVENTION

[0007] The vessel heats biomass on each tray such that the biomass is uniformly heated at each elevation in the vessel. To achieve uniform heating of the material on each tray the flow of oxygen deprived gas may be regulated in a range of 1 to 24 kilograms (kg) of gas per kilogram of dry biomass material being treated on the tray. The flow of the oxygen deprived gas through the trays may be continuous.

[0008] The oxygen deprived gas is a heat transfer media that may add or remove heat from the biomass material for drying and torrefaction. The gas flows through the biomass material and the trays.

[0009] The continuous flow of oxygen deprived gas through the material heats the biomass material, provided that the gas is at a higher temperature than the material. The constant flow of gas may also cool the material where the torrefaction reaction, which is exothermic, causes the material to become hotter than the gas. If the material overheats, the torrefaction reaction may over-react. The continuous flow of gas regulates the temperature of the biomass material in the vessel to be in a range of about the same temperature as the gas, or hotter, such as 20°C to 30°C hotter, than the biomass material.

[0010] The biomass material may have a total retention period in the reactor vessel of 15 to 60 minutes. The retention period in the pressurized reactor vessel may be selected based on the type of biomass material processed in the vessel. For example, the total retention period in the vessel may be 15 to 25 minutes when wood is used as the biomass material.

[0011] To achieve this retention period, the vessel includes a stack of trays through which includes the biomass. The biomass is dried in upper trays, and undergoes torrefaction in lower trays and in a lower chamber of the vessel. The torrefied biomass may be cooled in a lowermost portion of the vessel or in a screw conveyor or other device downstream of the outlet to the vessel.

[0012] The stacked trays effectively form a succession of moving beds for the biomass in a compact vertical pressurized reactor vessel. Each tray may have a pie-segment shaped opening through which biomass material falls to the tray at the next lower elevation in the vessel. The biomass material falls through the opening after traveling around the tray. A scraper may slide the material around the tray toward the opening. The rotational speed of the scraper is selected to provide the desired retention period on each tray. The retention period may be uniform for each of the trays in the vessel. The retention period may be achieved by the selection of number of trays for each of drying and optionally torrefaction and the period necessary to perform each of these processes. Trays may not be needed for cooling or the torrefaction process as these processes may be performed on a pile of the biomass in an open interior chamber of the vessel. Cooling may be performed after discharging the torrefied biomass from the vessel. Alternatively, the trays may be used for the torrefaction or cooling processes within the vessel.

[0013] The torrefaction process volatilizes mainly hemicellulose organic compounds in the biomass material. These compounds become entrained in the hot gases passing through the material and will condense in tar like deposits on cooler surfaces in the torrefaction reactor and in the conduits for the torrefaction gas. To reduce these deposits of organic compounds, the surfaces in the torrefaction reactor and gas exhaust conduits have been minimized. Further, the torrefaction gas is exhausted from regions of the reactor which have high temperatures to minimize the risk of organic compounds condensing on the surfaces of the exhaust conduits. In addition, the reactor and conduits may be insulated, such as with an insulation coating, to assist in maintaining high internal surface temperatures in the reactor and conduits. Further, the trays and inside surfaces of outer walls in the reactor vessel and associated gas conduits may be heated such as with heat traced elements.

[0014] A pressurized vessel configured for subjecting biomass to a torrefaction process has been conceived, the vessel including: a cylindrical vessel wall extending substantially vertically, wherein the vessel wall is may be insulated; an insulated top plate to the vessel wall, forming a pressure seal between the wall and the plate; a rotatable shaft extending vertically down from the top plate, wherein the shaft includes an insulated upper coupling configured to connect to a motor drive system; a plurality of scraper devices each at a different elevation within the vessel and mounted to the shaft; a plurality of tray assemblies wherein each tray assembly is associated with one of the scraper devices such that the scraper device is immediately above a tray of the tray assembly; the tray is perforated, an open mesh or otherwise permeable to gas flow and impermeable to biomass, and each tray includes a discharge opening to transfer biomass from the tray and to a tray of a lower one of the tray assemblies; a chamber of the vessel below the tray assemblies is for subjecting the biomass to a torrefaction reaction; and a bottom discharge port of the vessel through which the torrefied biomass is discharged.

[0015] Alternatively, the vessel may contain a cooling zone in a lower portion of the vessel below the tray assemblies and the chamber for torrefaction. The cooling zone may be configured to retain and cool the torrefied biomass before the biomass is discharged from the torrefaction reactor vessel. A lower zone of the vessel may also serve for passivation of active sites in the biomass by injecting atmospheric air or oxygen (O_2) generated by a nitrogen gas generator. The lower zone for passivation may be below or in place of a cooling zone in the vessel. .

[0016] A method has been conceived for torrefaction of biomass using a pressurized torrefaction reactor vessel having stacked trays including: feeding the biomass to an upper inlet of the vessel such that the biomass material is deposited on an upper tray of a vertical stack of trays in the reactor; as the biomass moves in the vessel on each of the stacked trays, heating and drying the biomass material with an oxygen deprived gas injected into the vessel under a pressure of at least 3 bar gauge (such as 3 to 20 bar gauge, or 3 to 15 bar gauge, or 3 to 5 bar gauge); cascading the biomass down through the trays by passing the biomass through an opening in each of the trays to deposit the biomass on a lower tray; below the lowermost tray, depositing the biomass in a pile of biomass within the vessel; subjecting the biomass to torrefaction in the pile; discharging torrefied biomass from a lower outlet of the torrefaction reactor vessel; removing volatized organic compounds by exhausting gas from the stack of trays; cleaning the exhausted gas to remove the volatized organic compounds, and feeding the cleaned gas to the vessel.

[0017] The oxygen deprived gas may be superheated steam, a gas with substantially less oxygen than in atmospheric air (such as 75% less) or a gas composed of about two percent (2%) or less of oxygen and 98% or more of other gases. The other gases may be a substantial portion of nitrogen with some reaction products from the torrefaction reactor, such reaction produces include carbon monoxide (CO), carbon dioxide (CO_2) and methane (CO_4). The biomass may be pressurized before being fed to the vessel with a pressure transfer device. The trays may be a mesh, screen or have perforations and the heating and drying of the biomass includes passing the gas through the biomass and the trays. A scraper device may rotate to move the biomass material across the tray in an arch-shaped path. Alternatively, the trays may rotate while the scraper device and biomass do not rotate about the vessel. The opening in each tray may be a triangular shaped section extending from the shaft in the vessel to the wall of the vessel.

[0018] The gas may be injected into the stack of trays at multiple elevations wherein the gas is hotter when injected at a lower elevation than the gas injected at an upper elevation. The gases for drying the biomass may be injected at multiple elevations of the vessel, whereas the gases for torrefaction may only be injected at a single elevation of stack of trays such as at the uppermost tray used for torrefaction. At an elevation of the vessel below from which the gas is extracted, the biomass may continue to cascade down through the trays.

[0019] A method for torrefaction of lignocellulosic biomass using a torrefaction reactor vessel having stacked tray assemblies has been conceived comprising: continuously feeding the biomass to an upper inlet to the torrefaction reactor vessel such that the biomass material is deposited on an upper tray assembly of a plurality of tray assemblies stacked vertically within the reactor; as the biomass moves in the vessel while supported by a tray of each tray assembly, heating and drying the biomass material with a gas injected into the vessel, wherein the gas is substantially non-oxidizing of the biomass, under a pressure of at least 3 bar gauge and at least a temperature in a range of 200°C to 400°C (such as 200°C to 300°C or 200°C to 250°C for drying gases and torrefaction gases that are hotter, such as 5°C to 100°C hotter, than the drying gases), and cascading the biomass down through the trays by passing the biomass through an opening in each of the trays to deposit the biomass on the tray of the next lower tray assembly; subjecting the biomass to a torrefaction reaction on the lower tray assembly and in a chamber of the vessel below the trays for drying, and discharging torrefied biomass from a lower outlet of the torrefaction reactor.

[0020] The trays of each of the tray assemblies have a mesh, screen or have perforations, and the heating and drying of the biomass includes passing the gas through the biomass and the trays. In addition, each tray assembly may include a scraper device above the tray and an extraction gas chamber below the tray. The scraper device or tray rotates to move the biomass across the upper surface of the tray.

[0021] The gas injected for torrefaction may be hotter, e.g., by 5°C to 100°C, than the gas injected to the upper tray assemblies which are used for drying the biomass. Further, a cooling zone for the biomass may be below all of the tray assemblies and below the torrefaction chamber of the vessel, such in a discharge portion of the vessel. The cooling gas injected into the cooling zone may be cooler than the gas injected to the cooling tray assemblies, wherein the cooling zone cools the torrefied biomass to below a temperature at which the biomass auto-combusts when exposed to the atmosphere and the cooling tray assemblies cool the torrefied biomass to stop or suppress the torrefaction reaction.

[0022] Gases extracted from the vessel may be circulated back to the vessel by blowers or compressors. The gases to be circulated may pass through a cyclone, condenser or filter to separate particles and condensable byproducts, such as organic compounds, before the gas flows to the compressor or blower. The gases circulated back to the torrefaction tray assemblies or torrefaction chamber may be heated before being injected into the vessel. A portion of the gases extracted from the tray assemblies may be directed to a combustor to generate heat energy to be added to the gases circulated back to the torrefaction tray assemblies. The extracted gases may also be used in other process steps associated with the torrefaction plant or facility.

[0023] A pressurized reactor vessel has been conceived for subjecting biomass to a torrefaction process includes: a cylindrical vessel wall extending substantially vertically, wherein the vessel wall may be insulated; an insulated top plate to the vessel wall, forming a pressure seal between the wall and the plate; inlet nozzles injecting an oxygen deprived gas into the vessel, wherein the gas temperature of the oxygen deprived gas injected through the nozzles at upper elevations in the vessel is lower than the gas temperature of the oxygen deprived gas injected through the inlet nozzles at lower elevations; a rotatable shaft extending vertically down into the vessel from the top plate, wherein the shaft includes an insulated upper coupling configured to connect to a motor drive system; a stack of scrapers and trays extending into the vessel from the top plate, wherein each scraper is fixed to and rotates with the shaft and is immediately above an associated stationary tray, each tray is perforated to allow passage of gas and block passage of biomass and has an opening through which biomass falls; the stack includes a gas extraction chamber at an elevation below one of the trays and above one of the scrapers, wherein the gas extraction chamber receives the gas passing through the one of the trays and includes a gas extraction port to exhaust gas passing through the tray; the stack includes a plurality of lower scrapers and trays which are below the gas extraction chamber and have no gas extraction chamber between the lower scrapers and trays; a torrefaction chamber in the vessel below the stack, wherein the torrefaction chamber is receives a pile of biomass discharged from the stack; a torrefaction gas exhaust outlet on the vessel and at an elevation below the stack and above an upper surface of the pipe of biomass, and a biomass outlet at a lower region of the vessel. Torrefaction gases also may be injected into lower regions of the reactor vessel and specifically directly into the biomass pile in the vessel. Torrefaction gases injected into these lower regions may be at temperatures cooler, e.g., 5°C to 20°C cooler, than in the reactor vessel where gas is injected in the lower portion of the vessel, the lower torrefaction section, the gas temperature of the inert gas injected through the nozzles at a lower elevation in the vessel is lower than the gas temperature of the inert gas injected through the inlet nozzles at upper elevations. Also as an alternative in the reactor vessel, the trays may rotate while the scraper device and biomass do not rotate about the vessel.

[0024] A method has been conceived for torrefaction of biomass using a torrefaction reactor vessel having stacked trays including: feeding the biomass to an upper inlet of the vessel such that the biomass material is deposited on an upper tray of a vertical stack of trays in the reactor; cascading the biomass down through the trays by passing the biomass through an opening in each of the trays to deposit the biomass on a lower tray; as the biomass moves through each of the stacked trays, heating and drying the biomass material with an oxygen deprived gas; extracting moisture containing gas having passed through the biomass on the upper trays wherein the extraction is immediately below each of the upper trays; as the biomass undergoes torrefaction in the lower trays of the stacked trays, retaining the gas with the biomass until the biomass falls from the stacked trays to a pile of biomass in the reactor vessel; exhausting gases containing organic compounds volatized by the torrefaction of the biomass through a gas outlet on the vessel at an elevation between the stacked trays and the pile of biomass, and discharging torrefied biomass from a lower outlet of the torrefaction reactor vessel.

[0025] The torrefaction and optional cooling of the biomass material may occur in a pile of biomass in a lower region of the reactor vessel. To promote torrefaction in the pile, hot oxygen deprived gases may be injected into the vessel at the elevation of the pile such that the gasses rise through the pile to the region of the vessel between the pile and stack of trays. To allow for the torrefaction and optional cooling within the pile of biomass in the reactor vessel, gas nozzles in the wall of the vessel inject the oxygen deprived gas into the pile. The nozzles may be arranged on a center column in the vessel or extend through the sidewall of the vessel. To provide cooling of the biomass materials, a gas well below the torrefaction temperature, such as a gas at 200°C or cooler, is injected through nozzles at the lowermost region of the vessel. This cool gas flows in a direction with the biomass material out the bottom of the vessel.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] FIGURE 1 is a side view of a pressurized torrefaction reactor.

[0027] FIGURE 2 is a perspective view of the top and side of the torrefaction reactor shown in Figure 1.

[0028] FIGURE 3 is a cross-sectional, side view of the torrefaction reactor shown in Figure 1.

[0029] FIGRUE 4 is a perspective view of the top and side of the torrefaction reactor shown in Figure 1, wherein a quarter section of the reactor has been removed to show internal components for illustrative purposes.

[0030] FIGURE 5 is a side view of a stack of tray assemblies, a top plate for the reactor and motor gear box assembly, which are inserted into an upper opening of the reactor shown in Figure 1.

[0031] FIGURE 6 is a top and side view of the stack of tray assemblies shown in Figure 5.

[0032] FIGURE 7 is a perspective view of a spoke wheel scraper component of a tray assembly.

[0033] FIGURE 8 is a perspective view of a top and side of tray plate component of a tray assembly.

[0034] FIGURE 9 is a perspective view of the bottom and side of the tray shown in Figure 8.

[0035] FIGURE 10 is an isolation plate which is a component of the stack of tray assemblies, wherein the plate segments have been remove for illustrative purposes to show the chute and support frame of the isolation plate.

[0036] FIGURE 11 is a side view of the isolation plate shown in Figure 10.

[0037] FIGURE 12 is a top down view of the isolation plate shown in Figure 10.

[0038] FIGURE 13 is a perspective view showing the top and sides of a section of the support frame of the isolation plate shown in figure 10.

[0039] FIGURE 14 is a perspective view showing the bottom and side of a top plate for the torrefaction reactor.

[0040] FIGURE 15 is a cross-sectional view of an insulated coupling between a drive gearbox and a shaft for the stack of tray assemblies.

[0041] FIGURE 16 is a cross-sectional view of a bottom end of the shaft in the stack of tray assemblies.

[0042] FIGURE 17 is a cross-sectional view of a torrefaction reactor showing schematically the gas flows in and out of the reactor.

[0043] FIGURE 18 is a cross-sectional view of an upper portion of the torrefaction reactor and illustrates the drying of biomass in the reactor.

[0044] FIGURE 19 is a top down view of a mesh tray plate illustrated in Figure 18 and used for drying biomass.

[0045] FIGURE 20 is a top down view of an isolation plate illustrated in Figure 18 and having an enlarged portion showing the seal between the reactor and the isolation plate.

[0046] FIGURE 21 is a cross-sectional view of a portion of the torrefaction reactor corresponding to the lower section of the stack of tray assemblies and illustrates the torrefaction process in the stack.

[0047] FIGURE 22 is a top down view of a mesh tray plate illustrated in Figure 21 and having an enlarged portion showing a seal between the tray plate and the reactor.

[0048] FIGURE 23 is a process flowchart illustrating the flow of biomass material and gases through a plant for torrefaction of the biomass.

[0049] FIGURE 24 is a process flowchart illustrating the torrefaction gas processing unit shown in Figure 23.

DETAILED DESCRIPTION OF THE INVENTION

[0050] FIGURES 1 to 4 illustrate an embodiment of a pressurized treatment vessel 10 for receiving, drying, treating by torrefaction, and cooling biomass material from a supply of biomass 12 through an upper inlet 14. The biomass may be wood chips, wood pulp or other comminuted cellulosic material. The biomass is dried, subjected to a torrefaction process and cooled to produce torrefied biomass.

[0051] The biomass may be fully or partially dried in an external dryer 15 before entering the vessel. After passing through the upper inlet, the biomass enters an upper tray in a stack 16 of trays. The trays provide a cascade of moving beds to dry and treat the biomass. The upper trays may be used to dry the biomass. Lower trays may be used to subject the biomass to a torrefaction treatment. An insulating tray may divide the drying trays from each other and the torrefaction trays.

[0052] The upper inlet 14 to the pressurized vessel may be coupled to a continuous feed, pressure isolation device, such as a conventional rotary valve or plug screw feeder, to feed the biomass 12 to the pressurized vessel from a source of biomass at atmospheric pressure. The source of biomass 12 may provide lignocellulose material that has been chipped or cut to have chip dimensions of a length between 10 to 50 millimeters (mm), a width of 10 to 50 mm, and a thickness of 5 to 20 mm. The chip thickness may be in other ranges, such as 20 to 30 mm, 15 to 25 mm, and 3 to 10 mm. These chip dimensions may be most suitable for wood. Other chip dimensions may be suitable depending on the type of wood or the non-wood material being used for the biomass.

[0053] As an alternative, the vessel may be operated with an internal pressure at or near atmospheric pressure. A vessel operating at or near atmospheric pressure may not require the rotary valve or other type of airlock that is needed for pressurized vessels.

[0054] The biomass 12 may be fed to the inlet 14 to the vessel at a temperature of 80°C to 120°C, for example, or higher if a dryer 15 heats the biomass before entering the vessel. If there is no dryer, the biomass material may enter the vessel at ambient temperature. The biomass is heated in the vessel by a pressurized, hot and oxygen starved gas. The gases entering the vessel may be at a temperature in a range of 200°C to 400°C and used to dry the biomass and promote the torrefaction reaction. To promote the torrefaction reaction the gas may particularly be in any of the ranges of 250°C to 400°C, 250°C to 300°C, and 300°C to 380°C. The gas entering to dry the biomass may be cooler than the gas temperature that promotes torrefaction. Gas temperature for drying may be in a range of 200°C to 250°C. The volume of oxygen deprived gas supplied to the vessel may be in ranges of 1 to 8 kilogram (kg), 1 to 12kg or 1 to 24 kg of gas to kg of dry biomass.

[0055] Immediately below the upper inlet 14 in the vessel 10 may be a channel that receives the biomass from the inlet and directs the biomass to the upper tray 18. The biomass falls on the upper tray and is moved in an arc path across the tray until the biomass passes over a leading edge of an opening in the upper tray. The biomass falls through the opening to the next lower tray. The process of moving the biomass over the surface of a tray, falling through an opening in the tray and depositing on the next lower tray is repeated for each tray in the stack of tray assemblies.

[0056] The biomass falls from the stack of tray assemblies and forms a pile in the chamber 20 of the pressurized vessel. While in the pile, the biomass remains an oxygen deprived gas atmosphere and continues its conversion to torrefied biomass. Below the chamber 20, the vessel may converge in a convergence zone 22 in a manner to promote uniform downward flow of the biomass through the chamber and bottom of the vessel, and to a bottom biomass outlet 24 of the vessel.

[0057] A large access or observation port 26 in the wall of the vessel provides access to the pile of biomass in the chamber 20. In addition sensor ports, e.g., temperature and pressure probes may be arranged at various elevations and angular positions throughout the vessel.

[0058] Hot oxygen deprived gas 28 may be injected into the vessel, such as through a top input manifold 30 and through gas injection nozzles 32 arranged at the various elevations of the stack 16 of tray assemblies. A gas extraction port 34 below corresponding injection nozzles 32 allows gases passing through the biomass to be discharged from the stack of trays and vessel.

[0059] In the embodiment shown in Figures 1 to 4, the gas inlets 30, 32 for the oxygen deprived gas are at the top of the vessel and at two elevations corresponding to the tray assemblies for drying the biomass, and the upper tray assembly for the torrefaction process. Similarly, there are three gas extraction ports 34 each below a corresponding as inlet. Two of the gas extraction ports are adjacent the tray assemblies for drying. The third is at an upper region of the chamber 20. The number of gas outlets 34 may be minimized to reduce metallic surface area exposed to gases with organic compounds from the biomass material.

[0060] The oxygen deprived gases flowing to multiple elevations in the vessel may be at temperatures and compositions that vary for different elevations in the stack of trays 16 and chamber 20. For example, the hot oxygen deprived gas introduced to the uppermost elevation of the vessel, e.g., top inlet port 30, may be at a temperature hotter than the temperature of the biomass 12 entering the vessel. The hot oxygen deprived gases introduced through nozzles 32 on the cylindrical wall of the vessel may vary in temperature at different elevations of the vessel. The temperature of the gases may become increasingly hotter at lower elevations of the stack of trays and be slightly above the temperature of the biomass as it moves down through the stack. The biomass increases in temperature as it moves down through the stack of tray assemblies and falls into a pile in the chamber. At the lower elevations of the vessel, the temperature of the gases introduced through the nozzles 32 may be cooler than the biomass in the corresponding elevation of the vessel. The temperature of the gases injected at the different elevations may be selected to create a temperature profile along a vertical direction of the biomass in the vessel. The gases may also be injected through the nozzles 32 to maintain a uniform temperature across a cross-section of the vessel at each elevation of the vessel.

[0061] By injecting the oxygen deprived gas at a temperature slightly above the temperature of the biomass being heated by the gas, the efficiency of heating can be increased as compared to injecting gas at all elevations of the vessel at a single temperature which may be substantially hotter than the incoming biomass to the vessel. Alternatively, the oxygen deprived gases 28 injected for drying and torrefaction may be at substantially similar temperatures and compositions.

[0062] The torrefaction reaction may occur in the lower trays of the stack of trays and in the chamber 20 and optionally just in the chamber 20. A convergence zone 22 at the bottom of the vessel may be configured to promote a uniform downward flow of the biomass material to an outlet 24 of the vessel. The lower chamber 20 may be a hollow region of the pressure reactor vessel below the stack of trays. The lower chamber and convergence zone may span the lower one-half or lower two-thirds of the height of the pressure vessel. The convergence zone 22 may be a DIAMONDBACK® single convergence section sold by the Andritz Group and described in U.S. Patents 5,500,083; 5,617,975 and 5,628,873. The convergence zone alternatively be a straight drop tube and include a multiple screw conveyor or moving grate at the bottom of the zone and at the outlet of the vessel. The convergence zone 22 may be maintained at a cooler temperature than the stack of tray assemblies used for torrefaction and cooler than the temperature of the biomass material in the chamber 20.

[0063] The pressure vessel 10 may have dimensions, such as diameter and height, based on the desired operational conditions, such as the composition of the biomass material and the volumetric rate of biomass to flow through the vessel. In general, for industrial scale units, the pressure vessel may have a height of over 100 feet (30 meters) and a diameter of over 9 feet (2.7 meters). The vessel may have a length to diameter (L/D) ratio in ranges of 5 to 1 (5:1) to 12:1, or 6:1 to 11:1, or 7:1 to 10:1.

[0064] The volume of hot oxygen deprived gas needed for the vessel is dramatically reduced in a pressurized reaction vessel 10 as compared to a vessel operating at atmospheric pressure. Pressurizing the treatment vessel 10 the volume of hot gas needed to heat the biomass is decreased by a factor of two (2) to thirty-five (35) as compared to a vessel at atmospheric pressure. The reduction factor for the vessel depends on the pressure in the vessel.

[0065] Because of the reduced volume of hot gas needed in the pressurized reactor, the volume, size and cost of the vessel 10 may be significantly reduced as compared to a vessel operating at atmospheric pressure. A pressurized vessel in which a hot gas is injected provides effective and economical heat transfer from the gas to the biomass in the vessel.

[0066] The oxygen deprived gas 28 injected to the vessel 10 is a hot, clean gas (as compared to the gas extracted from the torrefaction reaction in the vessel) that is substantially free of organic compounds and other chemicals that may accumulate on the surfaces of the vessel. As the gas passes through the biomass, organic compounds become entrained with the gas and may condense on relatively cool surfaces of the vessel. In view of the potential of condensation, the gas passages downstream of the biomass may be large and substantially free of small passage nozzles and other surfaces that could become clogged if organic compounds condense on the surfaces.

[0067] In the embodiment shown in Figures 1 to 4, the uppermost gas inlet 30 may be a single inlet for drying gas. The nozzles 32 on the side wall of the vessel may be limited to a small number, e.g., two to four, of nozzles that directly inject hot gas through the wall of the vessel.

[0068] The flow of heated gas into, through and from the pressure reaction vessel may be configured to promote the flow of hot, pressurized gases through the tray assemblies in the upper elevations of the vessel where the biomass is being heated to the desired temperature for torrefaction and thereafter cooled. As shown in Figure 1, the hot oxygen deprived gas may be injected into the upper section of the vessel 10 through a top input manifold 86 and gas injection nozzles 34 arranged at the various elevations of the tray assemblies 16, 18 and 20 in the upper portion of the vessel.

[0069] The gases flowing to multiple elevations in the vessel may be at temperatures and compositions that vary for each of the tray assemblies. For example, the hot oxygen deprived gas 28 introduced to the uppermost elevation of the vessel may be at a temperature slightly, e.g., 5°C to 100°C, hotter than the temperature of the dried biomass 12 being fed to the vessel. The hot oxygen deprived gases introduced at succeeding lower elevations of the vessel may be increasingly hotter to be slightly above the temperature of the biomass in the vessel that is proximate to the injected hot gas. By injecting the oxygen deprived gas at a temperature slightly above the biomass being heated by the gas, the efficiency of heating can be increased as compared to injecting gas at a single temperature which may be substantially hotter than the incoming biomass to the vessel. Alternatively, the gases injected for drying and torrefaction may be at substantially similar temperatures and compositions, and the gases for cooling the biomass may be recirculated gases extracted from other cooler elevations in the vessel. For example the exhaust gas from the drying trays will be cooler than that from the torrefaction levels and will be below temperatures required for torrefaction.

[0070] Before the torrefaction reaction occurs in the vessel, the biomass may be dried and heated in an oxygen deprived environment to a temperature of 200°C, or in a range of 180°C to 250°C or 200°C to 300°C. The drying may occur partially or fully in a dryer 15 upstream of the vessel 10 or in the drying tray assemblies in the upper portion of the stack 16. The biomass may be directly heated with an oxygen deprived gas, e.g., super-heated steam, nitrogen or a mixture of both, injected into the top of the vessel or dryer. The drying process may be conducted at a lower temperature than the temperature used to cause torrefaction of the biomass and at a temperature that does not cause the biomass to release large amounts of organic compounds.

[0071] The compounds released in the drying tray assemblies are primarily water and highly volatile (lighter weight) organic compounds. Water condensation does not cause fouling. Similarly, light weight organic compounds tend not to leave tar-like deposits in the vessel and the conduits for the extracted torrefaction gases. The exhaust gases from the drying tray assemblies may be removed from the vessel without resulting in large deposits on the surfaces of the vessel. The water and light organic compounds may be separated from the gas after the gas has been extracted from the vessel or circulated as surplus gas to the torrefaction portion of the vessel.

[0072] The gasses exhausted from the torrefaction process are rich in organic compounds that may condense on surfaces of the vessel or on the biomass material if the surfaces or material cool below the torrefaction temperatures, e.g., 250°C to 200°C or 160°C. These condensed compounds may deposit on surfaces of equipment and conduits in the form of tar like substances which can cause plugging and improper operation of the vessel.

[0073] To prevent or minimize condensation, the vessel, piping, tanks and other equipment having surfaces in contact with the organic rich gas are insulated and heat traced so that cooler surfaces are minimized. Another technique to minimize condensation on surfaces is to minimize surfaces exposed to the organic rich gases. Using an open chamber 20 for some or all of the torrefaction process minimizes the surfaces, especially surfaces of small passages, exposed to gases rich with organic compounds. Eliminating some or all exhaust chambers between the trays for torrefaction also minimizes the surfaces that may receive the tar deposits of organic compounds.

[0074] The gases from the torrefaction of the biomass, which include heavier organic compounds, are extracted from the vessel through the lower gas extraction port(s) 34. After being removed from the vessel, the gasses from torrefaction are cooled to cause a portion of the organic compounds to condense but are maintained at a temperature above the dew-point of water or above a temperature at which lighter organic compounds condense. Upon condensing, the organic compounds form an aerosol, mist or droplets in the gas stream. A cyclone, drop out tank or other separator device separates the condensed organic compounds from the gas stream. Once separated from the organic compounds, these gases pass through a blower or other pressure increasing device, are heated to above the torrefaction temperature and are injected back into the vessel such as at the tray assemblies.

[0075] A circulation flow of condensed liquid organics may be circulated and sprayed into the aerosol laden gas discharging from the condenser, prior to a cyclone separator. This provides a flow of larger droplets of liquid organics which collect some portion of the aerosols and enhance the removal of organics from the gas stream. A condenser may be used to cool the torrefaction gases from the reactor. The condenser may be cooled with a suitable heat exchange fluid. The energy acquired by the heat exchange fluid may be used to re-heat the circulating gases after the heavier organic components have been removed.

[0076] If cooling gases are injected into the convergence zone 22 at the lower region of the vessel, the cooling gases may be cooler than the gases 28 injected for drying and torrefaction. The cooling gases may reduce the temperature of the biomass to below a temperature that causes torrefaction. The cooling gases may be circulated gases extracted from upper elevations in the vessel, such as exhaust gas from the stack of trays 16 or chamber 20.

[0077] The temperature in the convergence zone 22 may be cooler than the temperature needed for torrefaction, such as below 265°C, 240°C or 200°C. The torrefaction temperature will depend on the pressure in the vessel 10 and the composition of the biomass material. The temperature in the convergence zone 22 may be at least 15°C to 40°C lower than the temperature of chamber 20. To control and maintain the temperature in the convergence zone gas may be injected to the chamber 20 through injection nozzle 21 (Figs. 1-4) to provide cooling or heating of the biomass. Cooling or heating gas may be injected into the converging zone through nozzles 23. The injection and extraction of cooling gases may occur at several elevations in the convergence zone 22. The temperature of the cooling gases may be controlled to be at a temperature below that which the biomass material auto-combusts.

[0078] FIGURE 5 is a side view of the stack of trays 16 with cover plate 36 and sleeve 38. FIGURE 6 is a perspective view of the top and side of the stack of trays 16. The stack of trays is vertically aligned and coaxial with the shaft 38 and the circular top plate 36.

[0079] The stack of trays 16 may be supported in the vessel 10 by a center vertical shaft 42 that is rotatably mounted to the cover plate 36 at the top of the vessel. The cover plate 16 may be a flat plate, a hemispherical plate, an elliptical plate or other plate providing a sealable cover to the top of the reactor vessel. The cover plate may have a wide annular flange that bolts, is welded or otherwise fixed to a matching flange on the vertical cylindrical wall to the vessel. A wide flange may assist in the removal and reattachment of the cover plate when the stack of trays 16 is being repaired or replaced.

[0080] Immediately above the cover plate are a gearbox and electric motor assembly 40 that drives the shaft 42 to turn the scrapper or trays of the stack of trays. A vertical sleeve 38 provides a cylindrical housing for the upper end of the shaft and at least a lower portion of the gearbox and motor assembly.

[0081] The stack of trays with shaft may be removed as a stacked unit from the vessel by removing the upper cover plate. A crane may be used to pull out the stack of trays from the vessel. The stack of trays can be cleaned, repaired and otherwise serviced outside of the vessel. The removal of the stack of trays allows easy access to the interior of the vessel for service and cleaning. The crane can be used to insert the stack of trays back into the vessel, attach the cover plate to the top of the tray and attach the motor and gearbox to the upper end of the shaft.

[0082] The shaft 42 extends down through the stack of trays and is supported by a bottom bracket 44. The bottom bracket includes a lower bearing which receives a lower end of the shaft 42. The bottom bracket may include a cylindrical bottom plate 46 that provides a bottom support to the stack of trays and shaft. Metallic straps or bars 47 extend vertically between the bottom plate and the cover plate 36. These straps or bars form an outer cage for the trays and assist in maintaining the alignment of the trays in the stack. The straps or bars may connect to the periphery of each of the non-rotating tray assemblies and isolation plates in the stack. These connections assist in holding the horizontal alignment of the tray assemblies and isolation plates.

[0083] The stack 16 of trays may include tray assemblies each of which includes an annular scraper 48 and a circular tray plate 50. The scraper is coaxial with and fixed to the shaft 42. The scraper rotates with the shaft and moves the biomass in an arched shaped path over the plate immediately below the scraper. The tray plate 50 is coaxial with the shaft and is stationary. Each tray plate 50 has an opening through which biomass falls from the plate down to the next tray plate.

[0084] An isolation plate 52 separates an upper exhaust gas chamber 54 from a lower inlet gas chamber 56. The isolation plate isolates adjacent tray assemblies, and particularly isolates the gas streams in adjacent tray assemblies. The gas chambers, especially the lower chamber may be substantially open and free of structural surfaces. A chute 58 provides a vertical passage for biomass flowing from an upper tray assembly, through an isolation plate and to a lower tray assembly. The chute has sidewalls that separate the biomass falling down through the chute from the gases in the gas chambers 54, 56. A gas extraction port 34 (Figs. 1 to 4) is aligned with the exhaust chamber 54. Similarly, the gas injection nozzles 32 are aligned with the lower inlet gas chamber 56.

[0085] The upper tray assemblies 60 may be used to dry the biomass material. These drying assemblies 60, two of which are shown in Figures 5 and 6, may be each separated by gas chambers 54, 56. Drying causes moisture to be released from the biomass and become entrained with the gases. Having the moisture landed gases enter a gas exhaust chamber 54 below each drying tray plate allows these gases to exhaust through a gas extraction port below each drying tray plate and improves the drying process of the biomass. Further, the biomass tends not to release significant amounts of organic compounds during the drying process provided that the biomass does not reach torrefaction temperatures. With limited amounts of organic compounds, the exhaust gases from the drying tray assemblies 60 tend not to coat the chamber 54 and exhaust port 34 with tar like organic deposits.

[0086] The lower tray assemblies 62 may be used for torrefaction by operating at higher temperatures than the drying tray assemblies 60. Due to the torrefaction process, organic compounds are released by the biomass and become entrained in the gas passing through the biomass. The organic compounds may condense on cooler surfaces and can clog narrow passages and moving parts. Further, a relatively small amount of moisture released into the gases by the biomass in the lower tray assemblies as only a small amount of moisture remains in the biomass after the drying tray assemblies 60. To avoid having organic compounds condense on surfaces and in view of the small amount of moisture being released, the gases pass through two or more of the lower tray assemblies 62 without being extracted immediately below each tray assembly. In the example shown in Figures 5 and 6 the gases pass down through three tray assemblies 62 and are discharged through the bottom plate 46 and into the chamber 20. By eliminating the gas chambers between the lower tray assemblies 62, the surfaces which may be coated with tar are reduced.

[0087] On the tray assemblies, especially the lower tray assemblies 62, where there is a large temperature change between the biomass and the surface of the tray or other surfaces of the vessel, the biomass directly on the surface of the tray and near the biomass entrance for the tray may be relatively cool. To avoid condensation of organic compounds in the biomass at the tray inlet, additional heating may be provided at the tray inlet to avoid condensation. The additional heating may be achieved by baffles directing a portion of the hot inlet gases directly at the inlet section of the tray or other section of the tray or vessel surface where there is a risk of cooler temperatures and condensation.

[0088] The net flow of gas down through the stack 16 is downward and toward the chamber 20. To prevent condensation, aerosol formation and fouling of surfaces in the vessel, the gases from torrefaction are extracted at an elevation in the vessel corresponding to a peak gas temperature in the vessel. This elevation may be in the chamber 20. The lower gas outlet 34 is at the upper region of the chamber 20 and corresponds to the hottest region in the vessel. By extracting gases from the torrefaction process only while the biomass is at its hottest in the vessel or above a threshold temperature, e.g., 280°C, the risk is reduced of excessive tar deposits on the surfaces of the vessel as the gas is exhausted from the vessel. Similarly, by reducing or eliminating the gas chambers between the lower tray assemblies minimizes the surfaces of the tray assemblies and vessel that are exposed to the gases with organic compounds.

[0089] The torrefied biomass material is discharged under pressure from the vessel 10. The biomass material is discharged to a pressure transfer device which reduces the pressure of the material to atmospheric pressure. From the pressure transfer device, the torrefied biomass is moved to other processes such as using a screw conveyor, as is shown in Figure 23.

[0090] The number of tray assemblies in the stack 16 will depend on the design requirements for the vessel, and particularly the retention time desired for drying and for torrefaction. For example, the total number of tray assemblies in the vessel 10 may be in any of the ranges of 3 to 10 and 4 to 6. The proportion of drying tray assemblies may be 20 to 100% or 20% to 50% or 40%, with the remainder and tray assemblies for torrefaction. These ranges are exemplary and do not define limits on the numbers of tray assemblies.

[0091] FIGURE 7 is perspective view of a scraper 48 in each of the tray assemblies 60, 62. The scraper 48, as shown in this embodiment, has a shape similar to a wagon wheel with a center axial collar 64 which slides over and is keyed to the shaft. An annular ring 66 is at the outer periphery of the scraper, and vertical vanes 68 extend generally radially from the collar to the ring. The vanes may be at an angle, e.g., at 5 to 15 degrees, offset from a radial line if desired to promote the movement of the biomass material that fills the pie-shaped chamber 72 between the vanes. A rib 70 may be used for aligning the tray assemblies in the stack, or aligning the stack when being inserted down into the vessel. Further, the rib 70 may dislodge deposits on the straps or bars 47 or other surfaces as the scraper rotates. The height (h) of a scraper is sufficient to ensure that the biomass moves across the tray and may extend substantially the entire gap between plates especially in the lower tray assemblies 62.

[0092] FIGURES 8 and 9 are perspective views of an exemplary tray plate 50. The tray plate includes a substantially circular screen plate 82 which is perforated, a mesh, or otherwise permeable to gas flow and impervious to the biomass material. The plate may be supported by ribs 84 extending radially from a collar 86 and an outer ring 88. The arrangement of ribs, collar and ring provide structural support for the tray plate and minimize the surface area of the plate, especially for the tray plates used for torrefaction. The outer ring 88 may include an arch 90 of the circle that may be slanted radially inwardly in a downward direction. The arch 90 is aligned with a pie-shaped opening 92 and deflects the biomass inwardly and away from the wall of the vessel.

The collar 86 is coaxial with the vertical shaft of the vessel which rotates within the collar. Alternatively the collar may be fixed to the shaft such that the tray plate 50 rotates as the scraper remains stationary.

[0093] The pie shaped opening 92 in the tray plate 50 allows the biomass material on the circular screen plate 82 to pass down to the next tray assembly. The screen plate 50 may also have a pie shaped solid plate 94 which is aligned with the pie-shaped opening in the tray assembly immediately above the solid plate 94 or the biomass inlet chute at the top to the vessel, if the tray is the uppermost tray. The solid plate 94 may have a larger area than the area of the opening 92. The solid plate provides a solid pad to receive the falling biomass material. As the biomass material flows from one plate to a lower plate another it lands on the lower plate at a slightly cooler temperature than temperature of the biomass already moving on the lower tray. The solid plate may include electrical heating elements to assist in heating the biomass. Further, the solid plate prevents the organic rich torrefaction gas falling with the biomass from passing straight through the screen plate and condensing on the tray support structure for the tray.

[0094] The opening 92 in each tray plate is at the furthermost region of the plate with respect to the path of the biomass on the plate. The solid plate 94 is at the start of the path of the biomass on the plate and is aligned with the trailing edge (in the direction of biomass movement) of the opening 92. The alignment of the solid plate and opening ensures that the biomass entering each tray assembly is retained on the tray plate for nearly a full rotational period of the scraper or tray plate.

[0095] Each opening 92 may be vertically staggered such that each opening is over the solid plate of the tray plate immediately below the opening. By aligning the openings 92 over a solid plate, the biomass falls through the opening and onto the solid plate. As the plate or tray turns, the biomass slides from the solid plate, around the entire upper surface of the tray plate in an arc-shaped path to the openings in the plate. Maintaining the biomass on the upper surface of each tray maximizes the retention period of the biomass on tray plate and, thus, allows the biomass to be heated, dried and promotes torrefaction.

[0096] FIGURES 10 to 13 illustrate an isolation plate 52 for the stack of tray assemblies. The isolation plate forms a solid, insulating and substantially impervious horizontal wall within the vessel. The isolation plate 52 may be used to separate the gas chambers 54, 56 within the stack 16 of tray assemblies. The isolation plate 52 may be used to define a bottom wall of an exhaust gas chamber 54 and an upper wall of an inlet gas chamber 56.

[0097] A chute 58 extends through the isolation plate 52 to provide a passage. The chute may be oriented generally vertically and having a cross-sectional shape conforming to the shape of the pie-shaped openings 92 in the tray assemblies immediately above and below the isolation plate 52. The chute may have vertical walls extending entirely around the chute and having a cross-sectional shape conforming to the openings 92 of the plate trays. The walls of the chute confine the biomass to the chute area and prevent the biomass from entering the gas chambers 54, 56. The walls may be solid or meshed to confine the biomass material. Further, the walls may be bracketed, such as with vertical ribs, to provide structural support for the walls.

[0098] The isolation plate 52 may be formed as an assembly of pie-shaped sections 98 each of which has a horizontal plate, support ribs and arch-shaped inner and outer supports. The isolation plate may be solid, such as formed of steel or other metal material. An insulating layer may be applied to the lower or upper surface of the metal plate in the isolation plate. The insulating layer may be alternatively sandwiched between upper and lower metal sheets to form the isolation plate. The pie-shaped sections 98 of the isolation plate may be joined by bracket I-beam strips 100.

[0099] The isolation plate 52 is stationary due to the chute associated with the plate that allows biomass to flow down through the plate. The isolation plate is supported by the vertical strips 47 (Figs. 5 and 6) at the outer periphery of the stack 16 of tray assemblies. The isolation plate is fixed to remain in angular alignment with the trays to ensure that the biomass material falls through the opening in the isolation plate from an upper plate to a lower plate. The isolation plate has a collar 102 formed by the assembly of the chute and pie-shaped sections 98. The collar is coaxial with and surrounds the shaft. Because the isolation plate is stationary, the collar remains stationary as the shaft rotates.

[00100] FIGURE 14 is a perspective view showing the bottom and side of the cover plate 36. The cover plate may be formed of a metal plate with an optional insulating layer. The insulating layer may be sandwiched between metal sheets forming the plate or applied to the outer or inner surface of the metal plate. The upper inlet 14 for the biomass extends through the cover plate 36, opens to the interior of the vessel and is aligned with a solid plate 94 of the uppermost tray assembly. The gas inlet(s) 30 in the cover plate may be relatively small as compared to the inlet 14 for the biomass material.

[00101] A channel 104 may be aligned with the inlet 14 and extend downward from the cover plate. The channel directs biomass material to the uppermost tray assembly and may assist in distributing the biomass in the chambers of the scraper of the uppermost tray assembly. The channel may be a pair of L-shaped walls on opposite sides of the inlet 14. A bearing 106 in a center opening of the cover plate receives the shaft for the stack of tray assemblies. The cylindrical sleeve 38 for the gearbox is coaxial with the center opening with the bearing 106. The sleeve may have a large open area to allow access to the gearbox for service.

[00102] FIGURE 15 is an enlarged cross-sectional view of a coupling 108 between the shaft 42 for the stack of tray assemblies and a drive shaft 110 of the gearbox assembly in the cylindrical sleeve 38 on the top of the cover plate. The coupling 108 is insulated to avoid excessive heat loss from the interior of the vessel through the shaft 42 and to the exterior of the vessel. The coupling includes an insulating disc 112 between the respective ends of the shaft 42 for the stack 16 and the drive shaft 110. The insulating disc 112 is sandwiched between the shafts. The insulated disc 112 may be a lamination of outer steel discs with an insulation layer between the discs.

[00103] The shafts 42, 112 are coupled together by a pair of annular collars 116, an annular flange 114 on each collar is bolted together to ensure that the torsion of the drive shaft 110 turns the shaft 42 of the stack. A ring 118 between the collars 116 maintains an appropriate spacing between the shafts and ensures that the insulating disc 112 is not crushed.

[00104] FIGURE 16 is an enlarged cross-sectional view of the lower end of the shaft 42 for the stack of tray assemblies. The bottom plate 46 supports the stack 16 and provides structural support for a spindle bearing 120 shown in Figure 17. A vertical bracket 121 may provide structural rigidity to the bottom plate and support the shaft 42.

[00105] The collar 64 of each of the scrapers 48 are fixed, e.g., keyed, to the shaft 48 such that the

scrapers rotate with the shaft. A slip ring 122 maintains alignment between the lowermost scrapper 48 and the shaft 48. Between each of the scrapers, the shaft may have a bushing 124 that is adjacent the collar 86 of each of the tray plates 46. The collar forms a bushing to allow its respective tray plate to remain stationary.

[00106] FIGURE 17 is a schematic diagram of the pressurized vessel 10 showing the flow of biomass material, such as wood chips that are shown by a pattern of dots in the vessel. The shaft for the stack of tray assemblies is supported by the spindle bearing 120 that is fixed to the bottom plate 46 by a bracket 121. The scrapers are not shown in Figure 17 for purposes of illustration.

[00107] The two upper tray assemblies 60 are configured for drying of the biomass material. These upper tray assemblies have an upper oxygen deprived gas chamber 56 that is immediately above the scrapers for each of the tray assemblies. The oxygen deprived drying gas 126 for drying enters through gas nozzles 32 that may be arranged to uniformly distribute gases over the scraper and biomass being moved by the scraper. The drying gas 126 may be provided from the same source of gases that provides the oxygen deprived gases 128 for torrefaction, such as is illustrated by gas source 28 in Figure 1. Alternatively, the source of the drying gas 126 may differ from the source of torrefaction gas 128. The temperature of the oxygen deprived drying gas 126 for drying may be raised for the drying gas injected at lower elevations of the upper tray assemblies.

[00108] As the biomass moves over the tray, the oxygen deprived gas flows down through the biomass and the trays of the tray assemblies and into an exhaust chamber 54 below each tray. Isolation plates 52 separate the upper tray assemblies from each other and from the lower tray assemblies 62 that promote torrefaction.

[00109] The lower tray assemblies 62 are configured for torrefaction. These tray assemblies do not have an exhaust gas chamber below each assembly. There may also be a single inlet gas assembly above the uppermost tray assembly 62. Hot torrefaction oxygen deprived gas 128 for torrefaction enters through nozzles 32 above the scrapper for the uppermost one of the lower tray assemblies 62. The hot torrefaction oxygen deprived gas 128 may be at a temperature to promote torrefaction, such as 10 to 30°C hotter than the hottest of the drying gases 126. The hot torrefaction oxygen deprived gas 128 enters the vessel and passes down through all of the lower tray assemblies 62 and through the bottom plate 42 of the stack of tray assemblies. The hot torrefaction oxygen deprived gas 130 is exhausted through an outlet 34 below the stack and above the pile of biomass 132 in the chamber 20 of the vessel 10. The hot torrefaction oxygen deprived gas 130 is exhausted from the hottest region of the vessel. The exhausted torrefaction oxygen deprived gas may be cleaned, heated and as the oxygen deprived drying gas 126 and the hot torrefaction oxygen deprived gas 128.

[00110] Additional hot torrefaction oxygen deprived gas 128 may be injected directly into the chamber 20 and into the pile of biomass. Additional hot torrefaction gas may

be injected through nozzles on or in the convergence zone of the vessel, such as at the mid-point of a convergence. The additional hot torrefaction oxygen deprived gas may flow upward through the biomass in a manner counter-current to the downward movement of the biomass. The counter-current flow may exhaust through the gas outlet 34 and with the torrefaction gas being exhausted from the stack of tray assemblies. Other torrefaction gas may exhaust from or be injected into the vessel through a discharge port 132 at the bottom of the vessel.

[00111] FIGURE 18 is a schematic diagram of the upper portion of the pressurized vessel 10 and particularly the upper tray assemblies 60. The oxygen deprived gas enters the upper inlet 30 through the cover plate at a temperature comparatively cooler than the oxygen deprived gas injected in lower elevations of the vessel. The oxygen deprived gas may be distributed by a baffle 136 that disperses the gas uniformly over the biomass. A gap (G) above the biomass material provides sufficient volume to uniformly distribute the gas. The gap (G) may be a few inches, such as 5 to 8 inches or 150mm to 200mm. The hot oxygen deprived gas flows down through the biomass material (shown by the pattern of dots) and through the meshed or screened tray plate 82 and into the exhaust chamber 54 and out through the single exhaust outlet 34. The exhaust outlet 34 may be positioned adjacent the chute for the isolation tray 52 immediately below the outlet 34. The gas inlet 32 for the next lower tray assembly may also be located adjacent the chute.

[00112] The isolation tray 52 is shown in Figure 18 as a lamination of metal and insulating layers. The tray may include upper and lower layers of steel and a middle layer of a non-metallic insulating layer. Insulating the isolation tray assists with the thermal efficiency in the vessel and allows for substantially large, e.g., greater than 10°C, between adjacent tray assemblies used for drying.

[00113] FIGURE 19 shows a tray plate 82 for an upper tray assembly used to dry biomass material. The tray plate is formed as a mesh. Immediately below the plate 82 are heating elements 138 which are illustrated by dotted radial lines. The heating elements may be electrical resistive elements, conduits with steam or another hot oxygen deprived gas, or other devices that add heat energy to the tray plate, and particularly to the solid plate 94 which receives the cooler, wet biomass as it is deposited on the plate. The heating elements add heat to the tray plate to avoid having deposits of organic compounds and other material on cooler portions of the screen plate. Alternatively, hot gas may be blown on a underside of the tray structure. The rotation direction of the scraper is shown as clockwise.

[00114] FIGURE 20 is a top down view of an isolation tray plate 52. An annular brass or soft glass fiber ring 140 may form a seal between the perimeter of the tray plate 52 and the wall of the vessel. The tray plate 52 may include heating elements to prevent cooling of the plate and thereby prevent condensation of organic and other compounds on the metal surfaces.

[00115] The external wall(s) of the vessel may be insulated, such as by applying an insulating coating to the outer surface of the metal walls 142. The insulation of the walls may extend over the entire outer surface of the vessel. The insulation of the outer wall of the vessel increases the heat efficiency of the vessel and assists in maintaining uniform temperature levels across each elevation of the vessel.

[00116] The enlarged portion shown in Figure 20 illustrates the brass or glass fiber seal 140 between the periphery of the isolation tray plate 52 and the inside surface of the cylindrical metal wall 142 of the torrefaction reactor vessel. The wall 142 may be coated with an insulating material 144, such as a ceramic coating, a glass fiber coating or high-temperature polymer coating.

[00117] FIGURE 21 is a schematic diagram of the upper portion of the pressurized vessel 10 and particularly the lower tray assemblies 62. The scrapers are not shown to better illustrate the gas flow (see arrows) and movement of the biomass material (see pattern of dotted lines). The oxygen deprived gas enters the uppermost tray assembly 62 through, for example, two nozzles 32 arranged at opposite sides of the vessel, e.g., 180 degrees apart. The gas entering the uppermost tray assembly 62 is hot, e.g., above a temperature in a range of 240°C to 300°C to promote torrefaction of the biomass in the tray assemblies 62 and chamber 20. The temperature needed to promote torrefaction is dependent on the biomass material and the pressure in the vessel. The oxygen deprived gas

injected at the uppermost tray assembly 62 may be hotter, e.g., 5°C to 100°C hotter, than the oxygen deprived gases added to the upper tray assemblies 60 used for drying the biomass.

[00118] A gap above the biomass material and scraper on the uppermost tray assembly 62 provides sufficient volume to uniformly distribute the gas. Similar gaps, but possibly shorter, are between the lower surface of the tray plates 82 and the top of the scraper/biomass level in each of the lower tray assemblies 82. The initial gap above the uppermost tray assembly 62 may be a few inches, such as 5 to 8 inches or 125mm to 200mm, and the lower gaps may be 3 to 5 inches. The hot oxygen deprived gas flows down through the biomass material (shown by the pattern of dots) and through the meshed or screened tray plate 82 and directly into the gap immediately above the biomass and scraper on the next lower tray assembly 62.

[00119] The hot gas passes down through each of the lower tray assemblies 62 and out an outlet 34, e.g., a single outlet, which is below the stack of tray assemblies and above the pile of biomass in the chamber 20 of the vessel. The single outlet 34 may be aligned with the elevation of the vessel having the hottest gas, or gases at a temperature substantially hotter than the condensation temperature of the organic compounds in the gas. By extracting the gas while very hot through the outlet 34 the risk is reduced of organic compounds depositing on the surfaces of the vessel and the outlet.

[00120] There may be a single outlet 34 for the gases passing through the biomass material undergoing the torrefaction process. A single outlet minimizes the surfaces of the outlet that are exposed to the exhaust gases with the organic compounds that are volatilized during torrefaction. Minimizing the surfaces of the outlet and associated outlet conduits reduces the surface area which may become clogged with deposits, e.g., organic tar like substances, from the exhaust gas.

[00121] FIGURE 22 is a top down view of a tray plate 82 for a lower tray assembly that is used for torrefaction of the biomass. The tray plate may be a metallic mesh having substantially the same sized mesh openings as the tray plates of the upper tray assemblies. Alternatively, openings of the mesh of the plate may be smaller that the openings in the mesh of the plates in the upper tray assemblies. The tray plate 82 of the lower tray assemblies has the pie-shaped opening 92 and the solid pie-shaped plate 94 below the chute or opening 92 of the next higher isolation plate or tray assembly. The plate 94 is adjacent the opening 92 such that the biomass falls on the plate 94, moves around the entirety of the plate 82 before falling through the opening 92.

[00122] A stationary seal 144, such as an L-shaped vertical wall, may be vertically aligned with the leading edge of the pie-shaped plate 94 and include a flange attached to the interior wall of the vessel. The stationary seal is between the upper edge of the scraper and below the bottom on the next higher tray plate. The seal 144 directs gases flowing with the biomass falling

from the above tray assembly into the biomass and away from the opening in the tray plate.

[00123] FIGURE 23 is a flow diagram of a plant, e.g., factory, for producing torrefied biomass material 151 from biomass material 150. A bucket elevator 152 and drag conveyor 154 may transport the biomass material 150 to a feed bin 156 that provides a continuous feed of biomass material at a flow rate determined by a meter screw at the bottom of the feed bin. A second bucket elevator 158 transports the biomass moving at a uniform flow rate to an inlet rotary valve 160 at the top inlet of a torrefaction reactor 162. The rotary valve may be a high pressure transfer device that transfers the unpressurized biomass material to the pressurized torrefaction reactor 162, without loss of pressure from the vessel. The torrefaction reactor may be a cylindrical pressurized vessel having a height of 30 to 50 meters and a diameter of 3 to 10 meters. These dimensions are exemplary. The actual dimensions of the torrefaction vessel will depend on various factors including the type of biomass material, the desired flow rate of the material and the pressure in the vessel.

[00124] A discharge conveying screw 164 removes the torrefied biomass material from the bottom of the torrefaction reactor at a metered flow rate. A cooling screw 166 conveys the torrefied biomass material while removing heat energy from the material such as by cooling vanes on the outer surface of the screw 166 or cooling water flowing over the outer surface of the screw. Other cooling devices may be used in addition to or

substitution for the cooling screw. These other cooling devices may include a fluid bed cooler.

[00125] The cooled torrefied biomass material passes through a discharge rotary valve 168 which reduces the pressure of the material to an atmospheric pressure and exposes the material to atmospheric air. The torrefied biomass material is cooled before being exposed to air to minimize the risk that the material spontaneously combusts.

[00126] A third bucket elevator 170 and second drag conveyor 172 transports the cooled torrefied biomass material to a storage bin 174. A metering screw discharges the biomass material 151 from the storage bin for further processing or to be used as a combustible fuel.

[00127] Heat or thermal energy 176 for a drying gas processing unit 178 and a torrefied gas processing unit 180 may be provided by steam, combustion or other energy source. The heat energy 176 provides a means to increase the temperatures of the gases that are to be injected into the torrefaction reactor vessel 162. The gas processing unit for the drying gas 178 removes dust and other particles from the circulating drying gases and re-heats the gas to the temperatures needed for drying. The torrefied gas processing unit 180 removes the dust and other particles from the circulating torrefaction gases, removes the heavier organic compounds to allow the recovery of heat, and re-heats the gas to the required temperature for reuse as torrefaction gases.

[00128] The gases circulating through the gas processing units 178 and 180 are at substantially the same pressures as in the torrefaction reactor. The pressurization of the gases may be achieved by adding or relieving the oxygen deprived gases to the reactor or gas processing units.

[00129] The oxygen deprived gases are circulated through the torrefaction reactor in a substantially closed gas loop system. The gases may be used to dry the biomass, apply heat to sustain torrefaction and cool the torrefied biomass. The temperature of the oxygen deprived gas entering a tray may be set to achieve the desired function of the tray. For example, the gas flowing to a top inlet may be cooler than the oxygen deprived gases flowing to the torrefaction tray assemblies.

[00130] The drying gas processing unit 178 provides oxygen deprived heated gases for the drying process occurring in the torrefaction reactor to dry the biomass material. The drying gas may provide a source of oxygen depleted gas such as nitrogen or dry steam. The drying gas from the drying gas processing unit flows to the gas nozzles 32 aligned with the upper tray assemblies in the torrefaction reactor. Exhaust outlets 34 extract the oxygen deprived gas from the torrefaction reactor after the gas has passed through the biomass material to dry the material. The temperature of the drying gas may be in a range of 180°C to 240°C or at other temperatures below the temperature threshold, e.g., 205°C, for causing a torrefaction reaction in the biomass material. The temperature of the drying gas may be coolest at the top inlet and be hotter, e.g., an increase of 5 to 10°C, at

lower gas nozzles 34. The exhausted drying gas may be processed to remove the moisture and other entrained liquids or solids from the gas, reheated and returned for use as a drying gas in the torrefaction reactor.

[00131] The torrefied gas processing unit 180 provides an oxygen deprived gas, which may be the same gas composition as provided by the drying gas processing unit, to the lower regions of the torrefaction reactor where the biomass material undergoes torrefaction. The torrefied gas processing unit 180 supplies an oxygen deprived gas at temperatures above the threshold temperature, e.g., 250°C to 300°C, required to promote a torrefaction reaction. The torrefaction gases are added through nozzles 32 aligned with the uppermost tray assembly configured for torrefaction. Additional inlet nozzles 32 for torrefaction gases may be at the lower region of the vessel. These lower nozzles add hot gases to ensure that the pile of biomass material in the vessel remains at or above a temperature to promote the torrefaction reaction.

[00132] In the embodiment of the torrefaction reactor shown in Figure 23 there is no cooling zone and the torrefaction process may continue as the biomass material flows down to the outlet of the reactor 162. Some cooling gases may flow in a counter-current direction from the cooling screw 162 into the bottom of the reactor 162. Further, the cooling screw 162 may have a small flow of nitrogen gas at its discharge end. The nitrogen gas displaces torrefaction gas containing organic compounds which may be carried with the torrefied biomass material

from the discharge of the reactor and into the cooling screw. The organic compounds in the torrefaction gases, if not removed, might deposit on the cool surfaces of the cooling screw. Additionally, the cooling screw may have an outer water jacket and a water passage through a center of the shaft of the screw. These water jacket and passage transfer heat away from the biomass material and cool the material. Warm water exiting the cooling screw may be circulated to a cooling tower and returned to the cooling screw as cooling water.

[00133] The gases extracted from the torrefaction process may be removed from a single outlet 34 that flows directly and through insulated conduits into the torrefied gas processing unit 180. The extracted gas may include entrained organic compounds that will deposit on surfaces that are cooler than the gas. By flowing the extracted gas directly and quickly into the torrefied gas processing unit, the risk that the organic compounds deposit on conduit surfaces is reduced because the gas remains at a relatively hot temperature during the short passage to the gas processing unit 180. Also from the gas processing unit 180 a stream 181 is sent to a combustor for further processing of the torrefaction gases and particularly the condensed organic compounds removed from the torrefaction gases. A generator 182 of the oxygen deprived gas for the drying gas processing unit 178 and the torrefied gas processing unit 180 may be a nitrogen PSA plant which are conventional and commercially available. These plants may generate sufficient amounts of nitrogen gas to supply the drying and torrefied gas processing units.

[00134] FIGURE 24 is a process flow chart showing an exemplary torrefied gas processing unit 180. The compounds released from the biomass during the torrefaction process include various molecular weight organic components evolved during the torrefaction reaction. These organic components will cause significant fouling of equipment due to tar-like deposits when condensation occurs, particularly in an un-controlled manner. In the torrefied gas processing unit 180 the gases extracted from the torrefaction reactor are reduced in temperature so that heavier organic compounds are condensed but the gas is maintained above the dew point temperature of water and lighter organic compounds. The condensed organic components may be formed into an aerosol, mist or droplets in the gas stream. The gas stream with the condensed organic components flows to one or more drop out tank(s) or cyclone separator(s) 204 where the heavier weight components are separated from the gas stream. The heavier weight components fall to the bottom of the drop out tank(s) or cyclone separator(s) and flow to a collection tank 206. The components 181 from the collection tank 206 may flow to a recovery boiler or other chemical recovery system.

[00135] Torrefaction gas 200 extracted from the torrefaction reactor 162 is cooled in a heat exchanger 202 to cause organic volatile materials in the gas to condense such as into aerosols or droplets. The cooled torrefied gas enters a cyclone separator 204 in which condensed liquid droplets are separated from the gas. Other examples of separators 204 include devices that oxidize the byproducts, catalytically convert the

byproducts, filter the byproducts from the gas flow and flow separators, such as cyclones that use centrifugal forces to separate particles from the gas stream. The separators 204 may be used singularly or in combination in the torrefaction gas processing system 180. The byproducts separated by these components may be further processed by being separated, concentrated or purified into usable products.

[00136] The separated gases flow to a second heat exchanger 212 and the separated droplets flow as a liquid to a condensate tank 206. A portion of the liquid from the condensate tank is sprayed into the gas flowing from the heat exchanger 202 to the separator 204. The liquid droplets sprayed in the gases promote the condensation of gaseous organic compounds from the gas flow. A liquid pump 208 may pressurize the condensed liquid to be sprayed into the gas flow. A droplet spray nozzle 209 breaks the liquid into droplets and sprays them into the gas stream.

[00137] The torrefaction gas flows from the cyclone separator to a second heat exchanger 212 and a third heat exchanger 214 both of which increase the temperature of the gas such as to 250°C to 300°C. The third heat exchanger may receive thermal energy from a gas fired combustor.

[00138] A blower 216 increases the pressure of the torrefaction gas, such as by 0.5 bar gauge, as the gas 218 flows to the torrefaction reactor. The torrefaction gas flows through the torrefaction gas processing unit

180 while pressurized to the pressure in the torrefaction reactor vessel.

[00139] Thermal oil or condensed liquids, such as organic compounds, circulate through the torrefaction gas processing unit, to cool in heat exchanger 202 the torrefaction gas exhausted from the torrefaction reactor and heat the gas in the second heat exchanger 212 after the gas has been cleaned in the separator 204. The thermal oil or condensed liquid is cooled in a heat exchanger 220 by cooling water that flows from 224 and to 226 a cooling tower. The cooled liquid is temporality stored in a fluid tank 222. A liquid pump 210 moves the liquid through the liquid circulation in the torrefaction processing unit 180.

[00140] The gases extracted from the drying portion of the torrefaction reactor, such as from the upper tray assemblies, tend not to have large amounts of higher molecular weight organic compounds. The gases from the drying section include the oxygen deprived gas, steam and water, and volatile, lighter weight, organic compounds which tend not to condense on surfaces in the vessel. The gases extracted from the drying section need not flow through the torrefied gas processing unit 180. The drying gas processing unit 178 may include separators and condensers to remove water from the gas stream, a heat exchanger to increase the temperature of the gas to the temperature(s) desired for the drying portion of the torrefaction and a blower to transfer the drying gas to the reactor.

[00141] The steam produced during drying may be exhausted to a combustor, an exhaust stack or a heat recovery system. The torrefaction gas produced during torrefaction may be burned in a combustor, for instance in combination with the steam from the drying section and the heat produced might be used for instance for pre-drying the biomass.

[00142] While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment, but on the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims.

WHAT IS CLAIMED IS:

1. A torrefaction reactor vessel configured for subjecting biomass to a torrefaction process, the reactor comprising:

inlet nozzles injecting an oxygen deprived gas into the vessel, wherein the gas temperature of the oxygen deprived gas injected through the nozzles at upper elevations in the vessel is lower than the gas temperature of the oxygen deprived gas injected through the inlet nozzles at lower elevations;

a rotatable shaft extending vertically down into the vessel;

a stack of scrapers and trays extending into the vessel from the top plate, wherein each scraper is fixed to and rotates with the shaft and is immediately above an associated stationary tray, each tray is perforated to allow passage of gas and block passage of biomass and has an opening through which biomass falls;

the stack includes a gas extraction chamber at an elevation below one of the trays and above one of the scrapers, wherein the gas extraction chamber receives the gas passing through the one of the trays and includes a gas extraction port to exhaust gas passing through the tray;

the stack includes a plurality of lower scrapers and trays which are below the gas extraction chamber and have no gas extraction chamber between the lower scrapers and trays;

a torrefaction chamber in the vessel and below the stack, wherein the torrefaction chamber holds a pile of biomass discharged from the stack;

a torrefaction gas exhaust outlet on the vessel and at an elevation below the stack and above an upper surface of the pile of biomass, and

a biomass outlet at a lower region of the vessel.

2. The reactor vessel of claim 1 wherein the shaft includes an insulated upper coupling configured to connect to a motor drive system external to the vessel.

3. The reactor vessel of claim 1 or 2 wherein each of the scrapers and trays are strapped together, and the strapped tray assemblies and scraper devices are coaxial with the shaft of the vessel.

4. The reactor vessel of any of claims 1 to 3 wherein each of the trays are coaxial and coextensive with each other, each of the scrapers are coaxial and coextensive with each other, and the trays and scrapers are coaxial.

5. The reactor vessel of any of claims 1 to 4 further comprising an isolation plate below the gas extraction chamber, wherein the isolation plate is coaxial and coextensive with the trays and includes a

walled chute extending through the gas extraction chamber and to the scraper immediately below the isolation plate.

6. The reactor vessel of claim 5 wherein immediately below the isolation plate and above the immediately below scraper is a gas distribution chamber having an inlet nozzle in a wall of the vessel to receive an oxygen deprived drying gas.

7. The reactor vessel in any of claims 1 to 6 wherein the torrefaction gas exhaust outlet is a single outlet through which substantially torrefaction gas exhausts from the vessel except for the gas which flows with biomass through the biomass outlet.

8. The torrefaction vessel as in any of claims 1 to 7 further comprising an oxygen deprived gas inlet nozzle on an outer wall of the vessel and at an elevation below the upper surface of the pile of biomass.

9. A method for torrefaction of biomass using a torrefaction reactor vessel having stacked trays including:

feeding the biomass to an upper inlet of the vessel such that the biomass material is deposited on an upper tray of a vertical stack of trays in the reactor;

cascading the biomass down through the trays by passing the biomass through an opening in each of the trays to deposit the biomass on a lower tray;

as the biomass moves around each of the stacked trays, heating the biomass material with an oxygen deprived gas injected into the vessel;

as the biomass is dried in upper trays of the stacked trays, extracting moisture containing gas having passed through the biomass on the upper trays wherein the extraction is immediately below each of the upper trays;

as the biomass undergoes torrefaction in the lower trays of the stacked trays, retaining the gas with the biomass until the biomass falls from the stacked trays to a pile of biomass in the reactor vessel;

exhausting gases containing organic compounds volatized by the torrefaction of the biomass through a gas outlet on the vessel at an elevation between the stacked trays and the pile of biomass, and

discharging torrefied biomass from a lower outlet of the torrefaction reactor vessel.

10. The method of claim 9 further comprising circulating extracted gas from the vessel, removing the volatized organic compounds from the extracted gas to clean the gas, and feeding the cleaned gas to one or more of the stacked trays.

11. The method of claim 10 wherein the cleaning of the gas includes cooling the gas to condense the organic compounds and separating the condensate from the gas.

12. The method of claims 10 or 11 wherein the feeding of the biomass and the discharge of the torrefied biomass are continuous.

13. The method of any of claims 8 to 12 wherein the oxygen deprived gas includes nitrogen gas.

14. The method of any of claims 8 to 13 further comprising moving the biomass around each tray by a scraper device associated with each tray.

15. The method of any of claims 8 to 14 wherein the oxygen deprived gas is injected under a pressure of at least 3 bar gauge and the interior of the vessel is under the pressure of at least 3 bar gauge.

16. A method for torrefaction of lignocellulosic biomass using a torrefaction reactor having stacked tray assemblies comprising:

continuously feeding the biomass to the torrefaction reactor such that the biomass material is deposited on a first tray assembly of a plurality of tray assemblies stacked vertically within the reactor;

as the biomass cascades down through drying trays in the tray assemblies, heating the biomass material with an oxygen deprived gas injected at a temperature below a threshold torrefaction temperature, wherein the oxygen deprived gas.

extracting from the vessel gases flowing through each of the drying trays before the gas flows to the biomass on a next lower tray;

as the biomass cascades down through torrefaction trays in the tray assemblies, wherein the torrefaction trays are below the drying trays, heating the biomass material with an oxygen deprived gas injected at a temperature above the threshold torrefaction temperature to promote a torrefaction reaction in the biomass on the torrefaction trays;

containing the oxygen deprived gas passing through the torrefaction trays in the vessel as the oxygen deprived gas and biomass pass through a plurality of torrefaction trays, and exhausting the oxygen deprived gas having passed through the torrefaction tray from the vessel, and

discharging torrefied biomass from a lower outlet of the torrefaction reactor.

17. The method of claim 16 wherein the threshold torrefaction temperature is in a range of 230°C to 280°C.

18. The method of claims 16 or 17 further comprising cleaning the exhausted gas by removing volatized organic compounds and feeding the cleaned gas to the vessel.

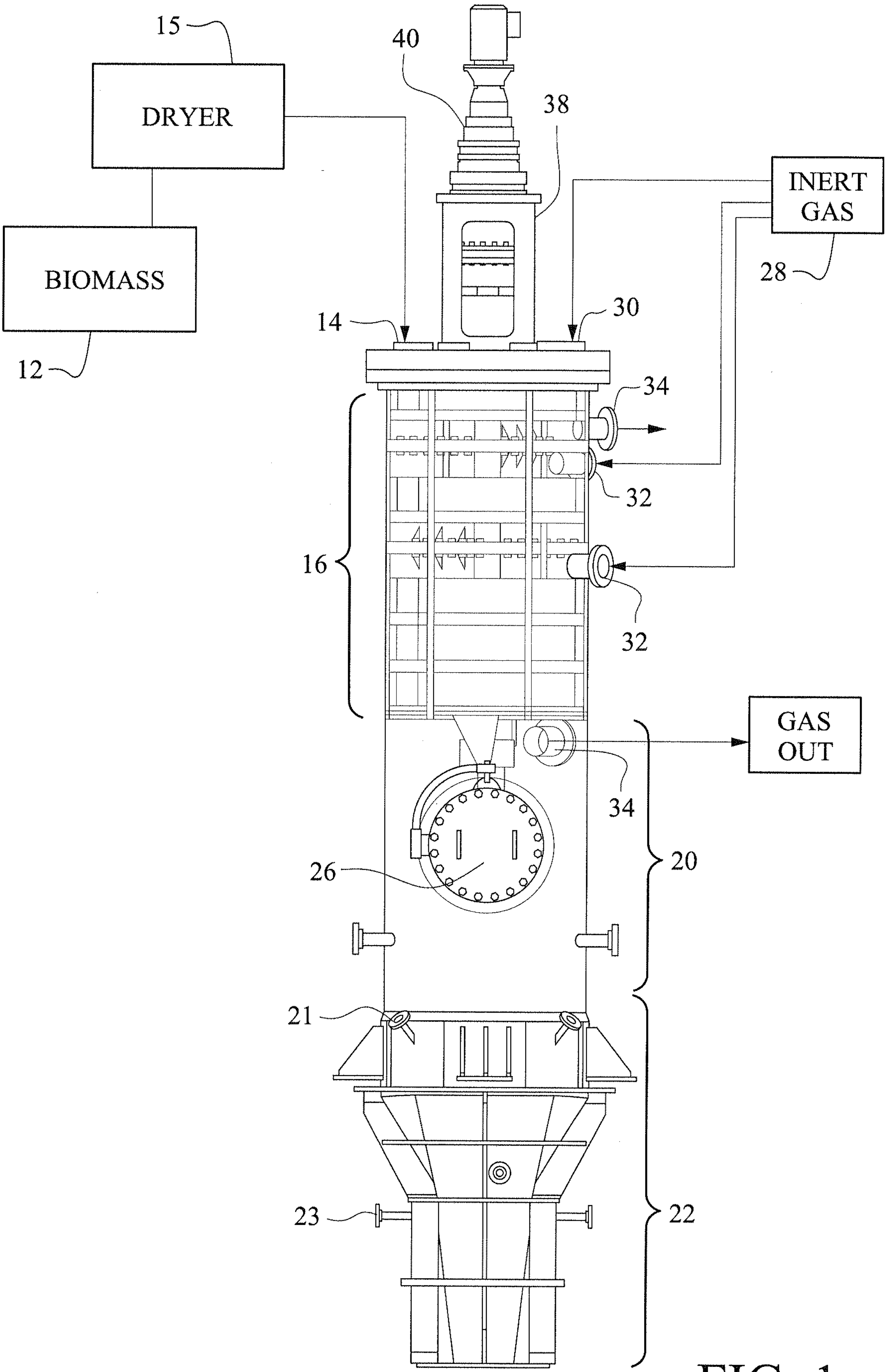
19. The method of claim 18 wherein the cleaning of the gas includes cooling the gas to condense the organic compounds and separating the condensate from the gas.

20. The method of any of claims 16 to 19 wherein the oxygen deprived gas includes a substantial portion of nitrogen gas.

21. The method of any of claims 16 to 20 further comprising moving the biomass around each tray by a scraper device associated with each tray.

22. The method of any of claims 16 to 21 wherein the biomass is retained in the reactor vessel for a period of 15 to 60 minutes.

23. The method of any of claims 16 to 22 wherein the oxygen deprived gas is injected under a pressure of at least 3 bar gauge and the interior of the vessel is under the pressure of at least 3 bar gauge.


15
DRYER
BIOMASS
12
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INERT GAS
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GAS OUT
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22

FIG. 1

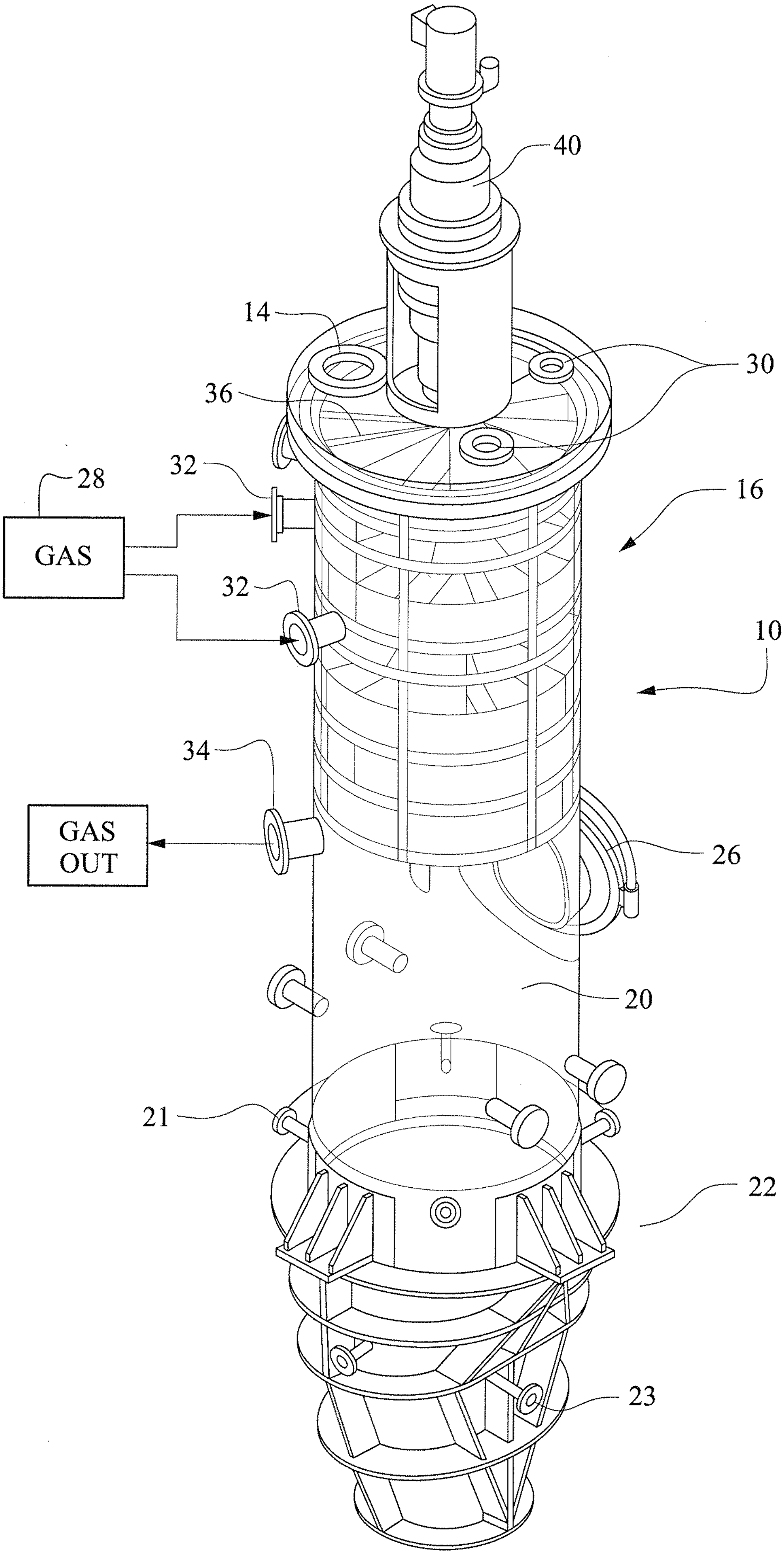


FIG. 2

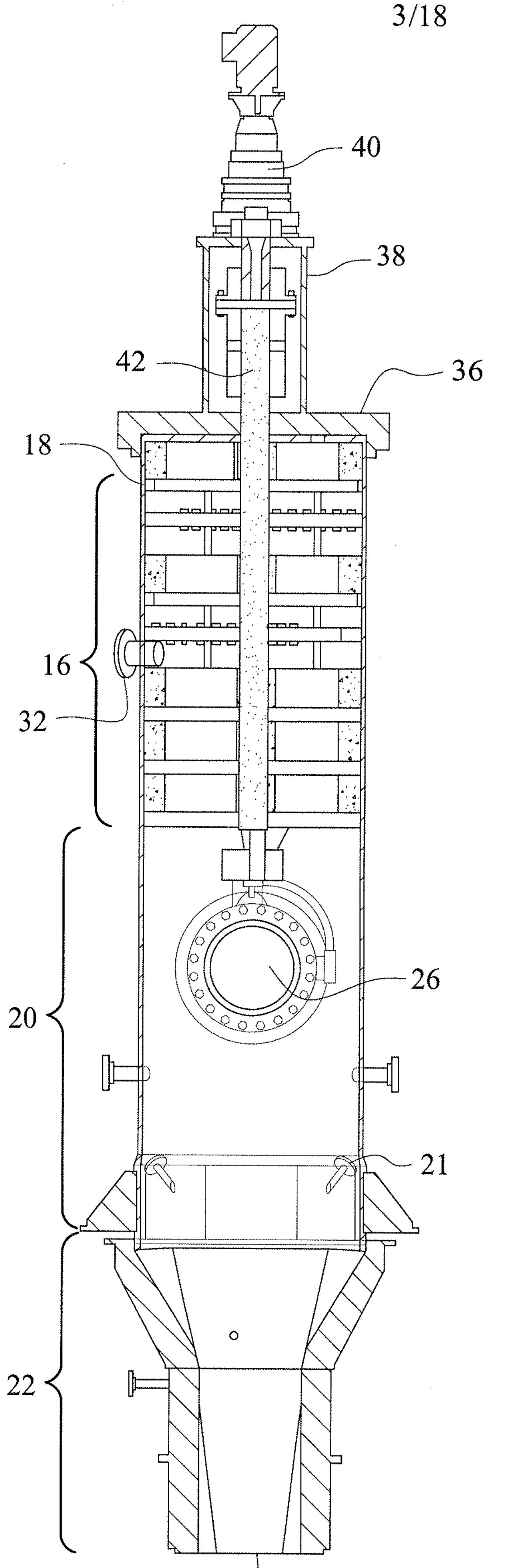


FIG. 3

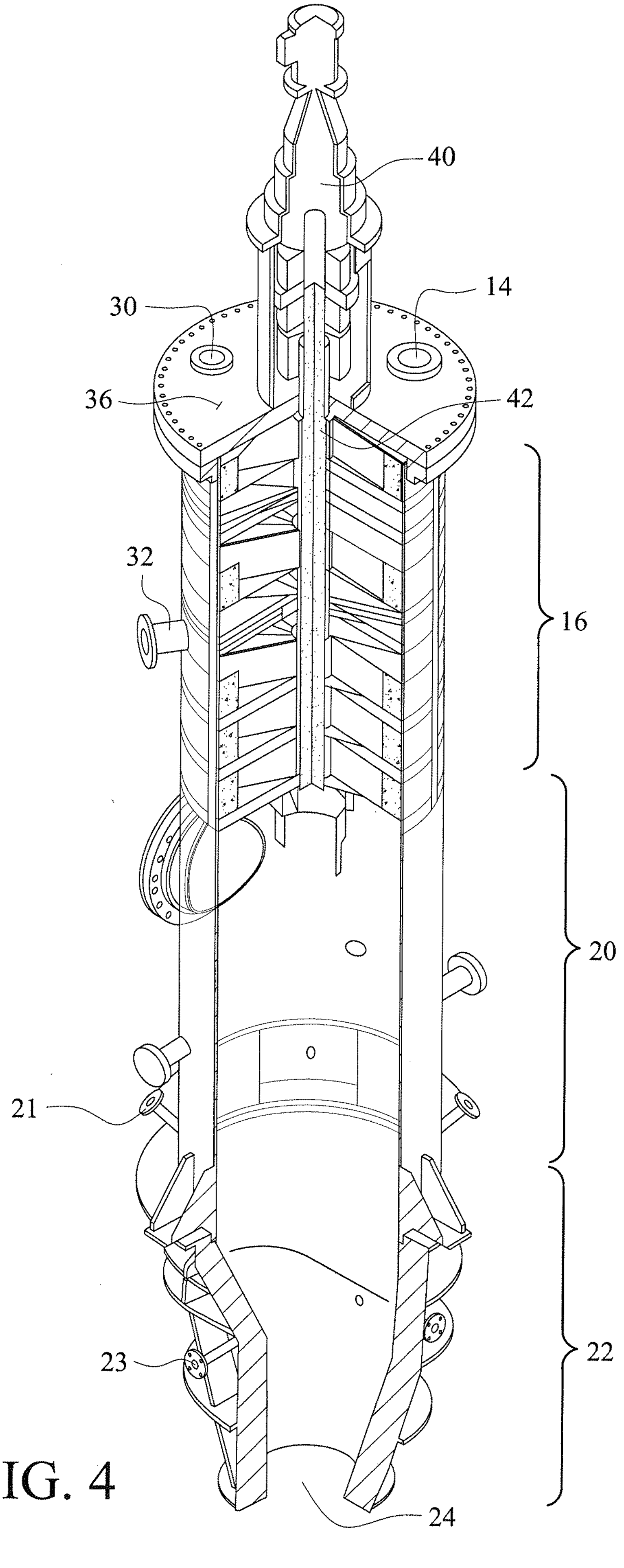
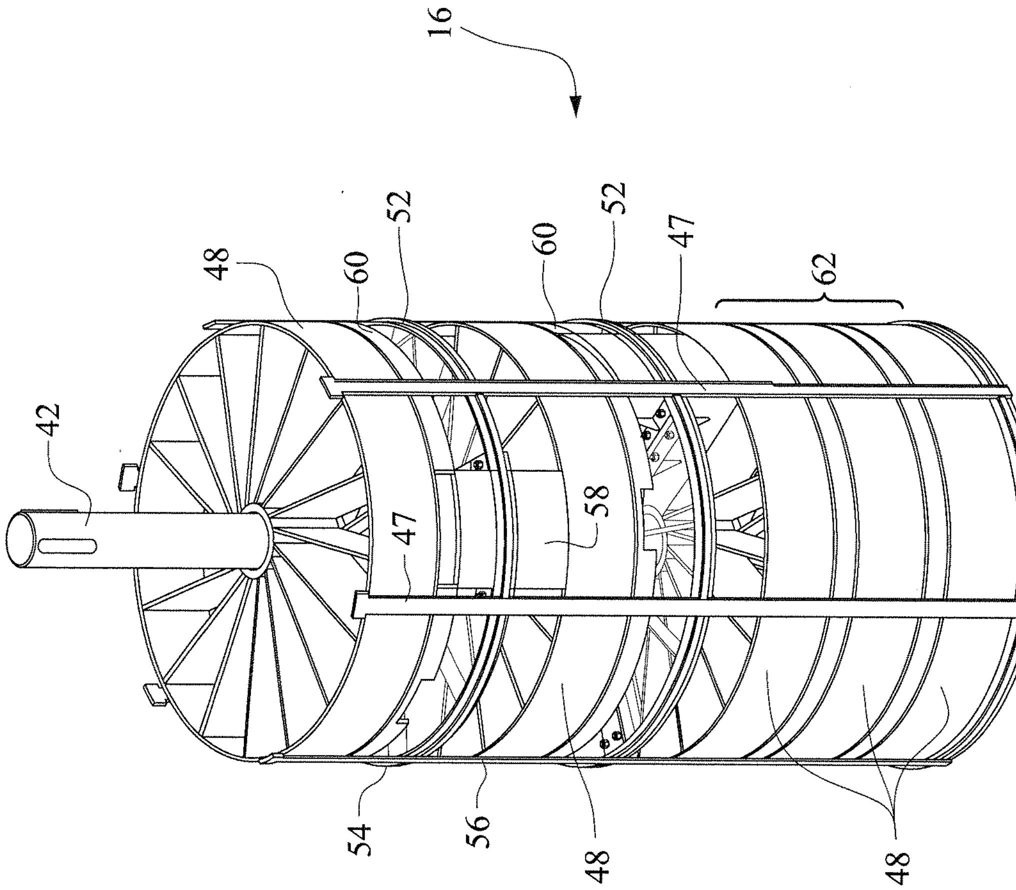


FIG. 4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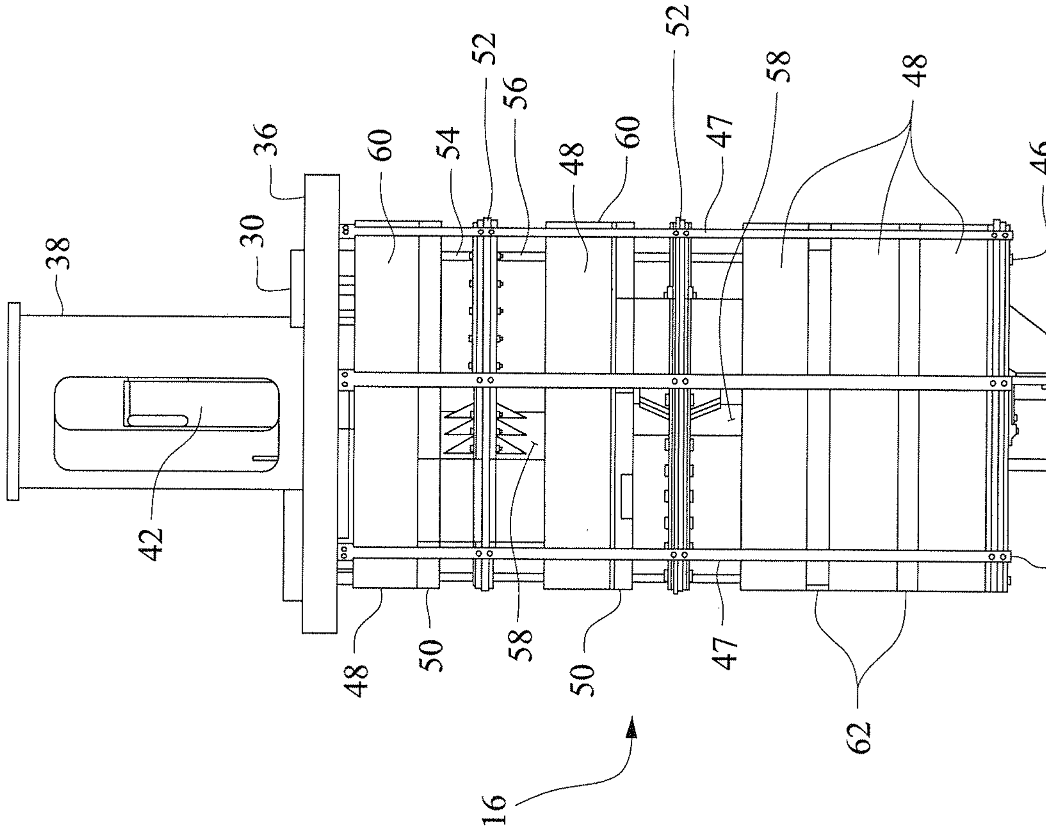
48

FIG. 6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44
16

FIG. 5

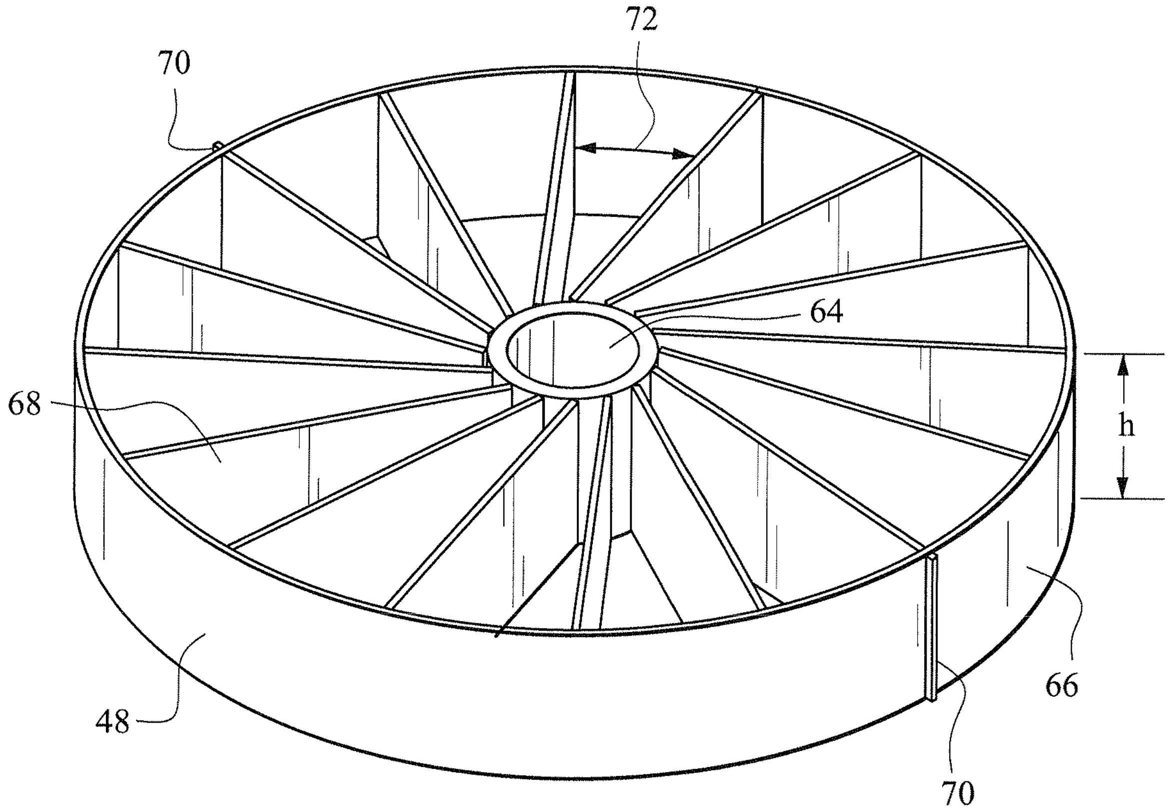


FIG. 7

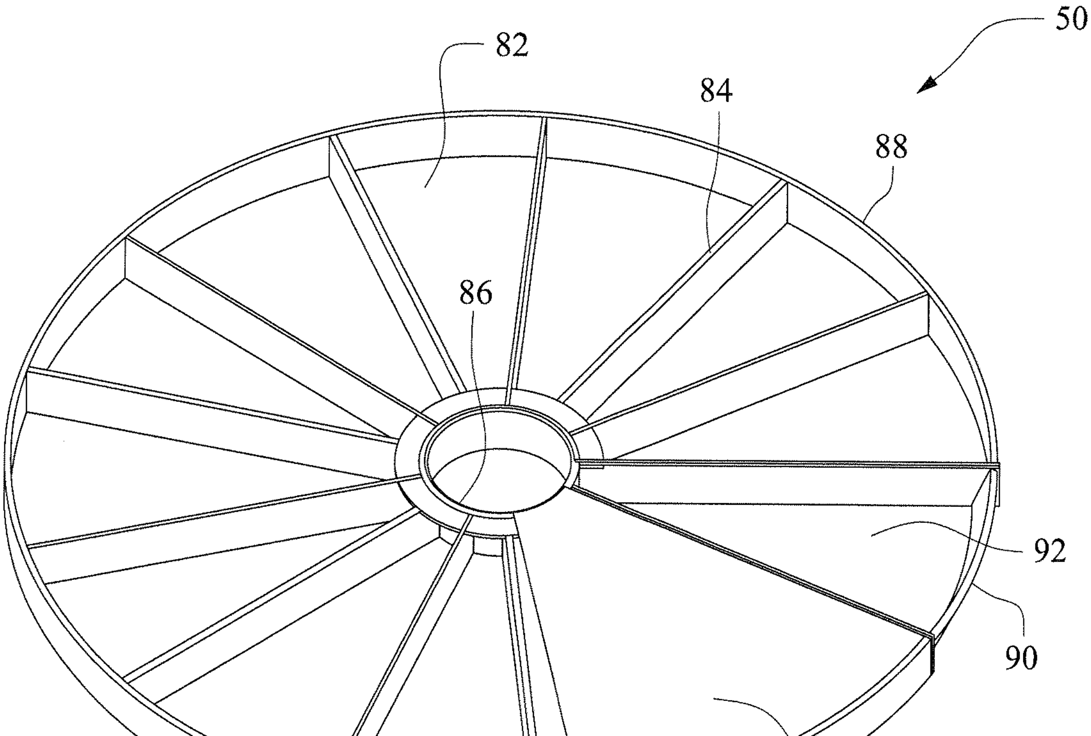


FIG. 8

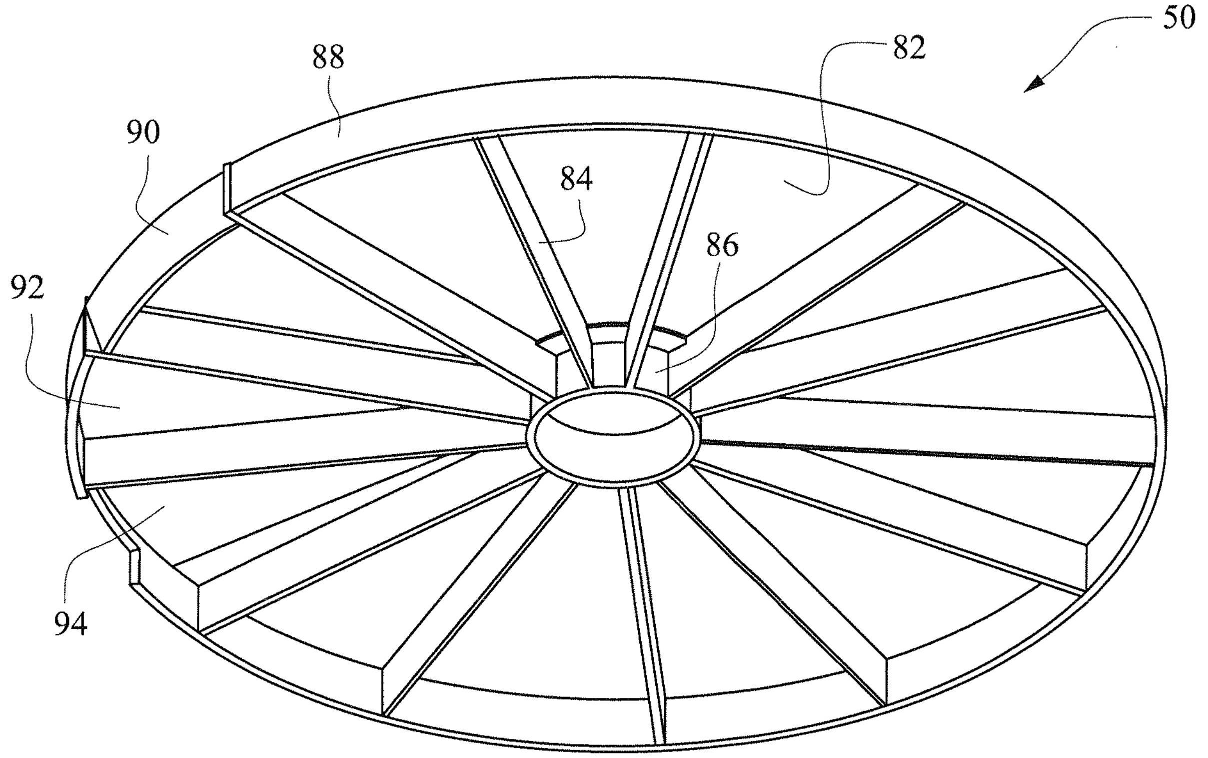


FIG. 9

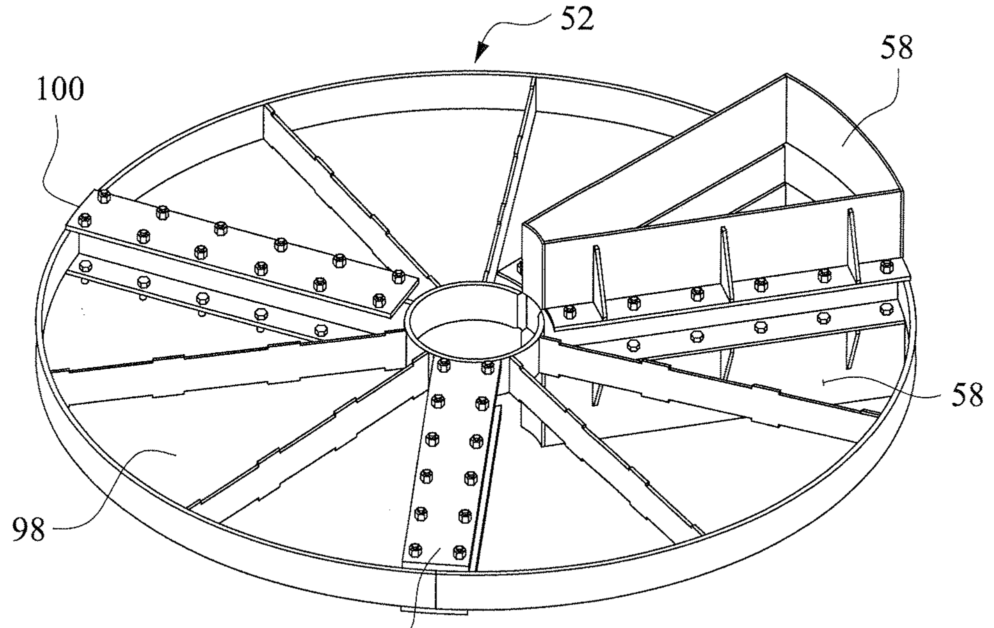


FIG. 10

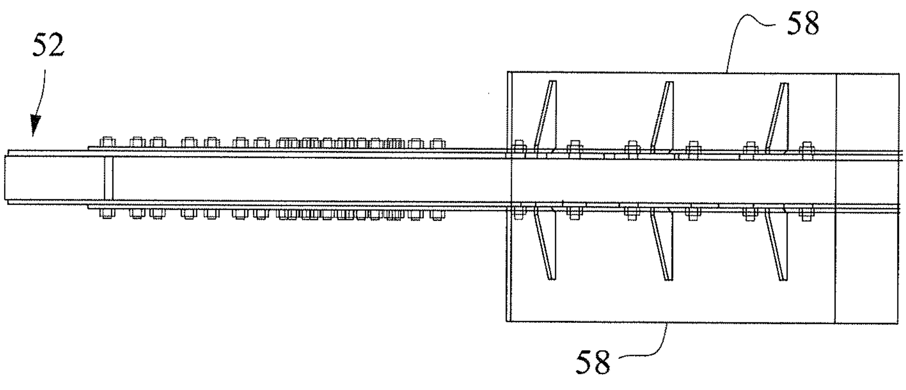


FIG. 11

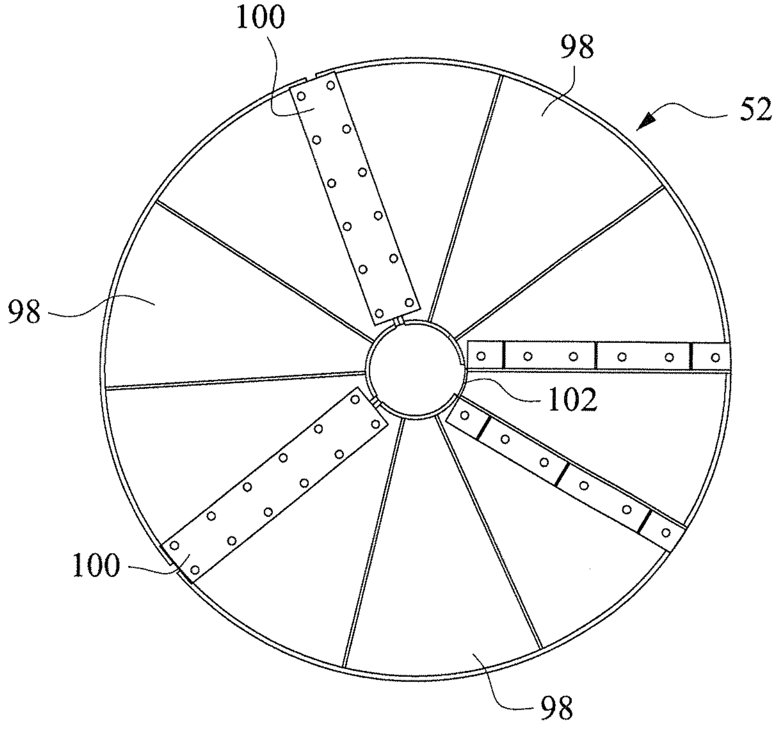


FIG. 12

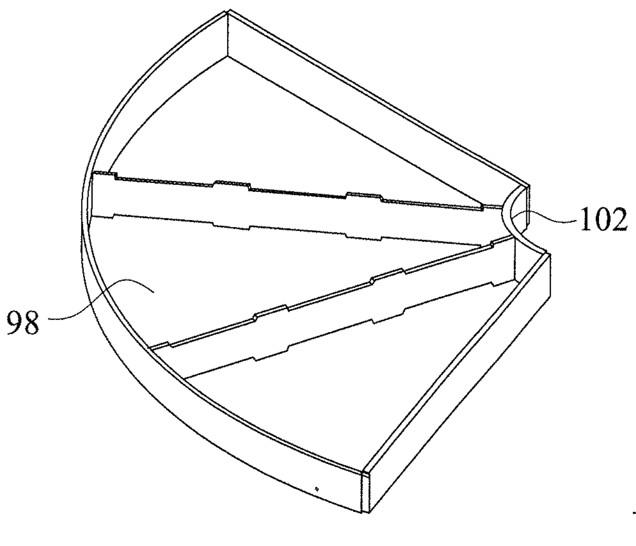


FIG. 13

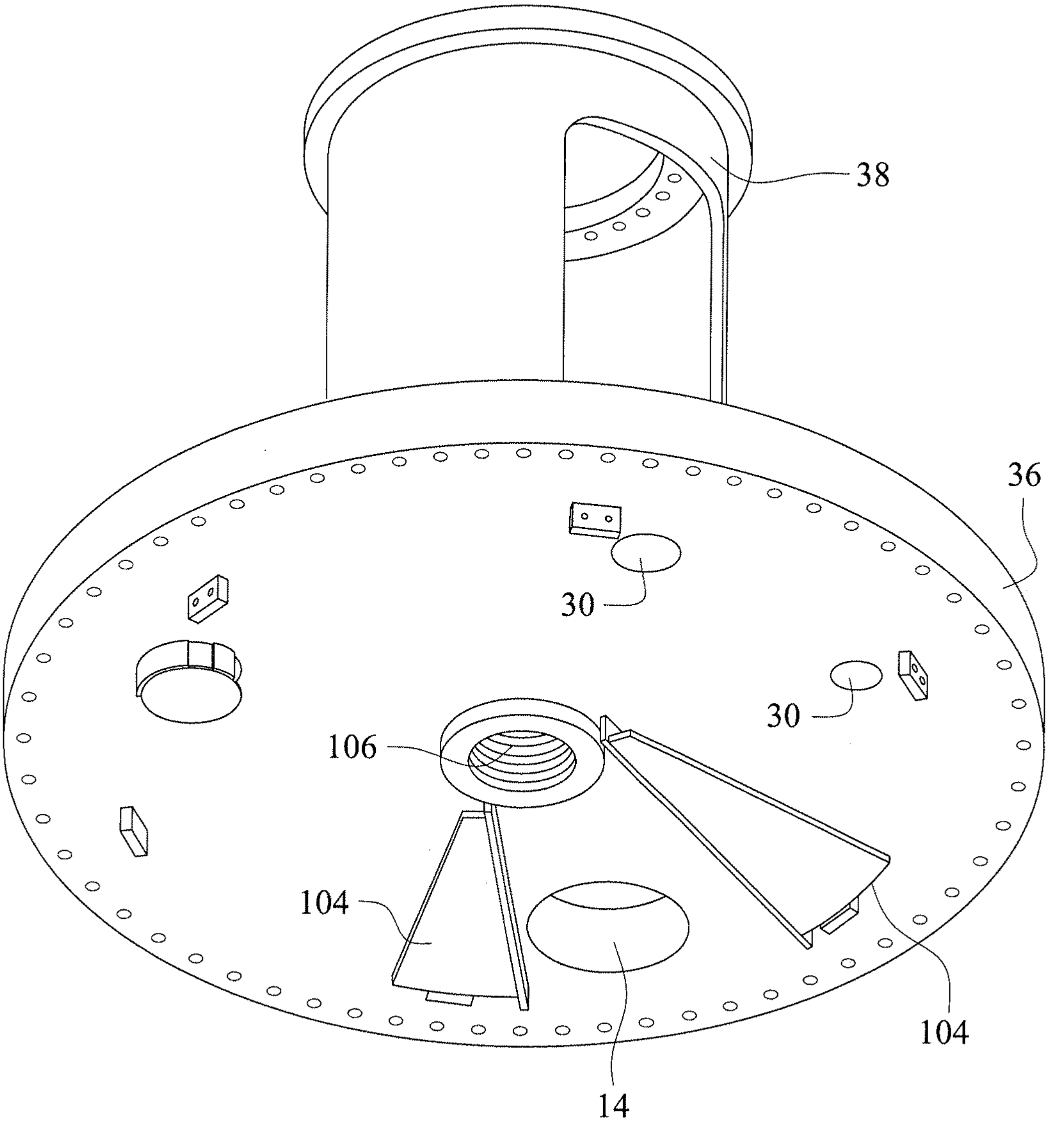


FIG. 14

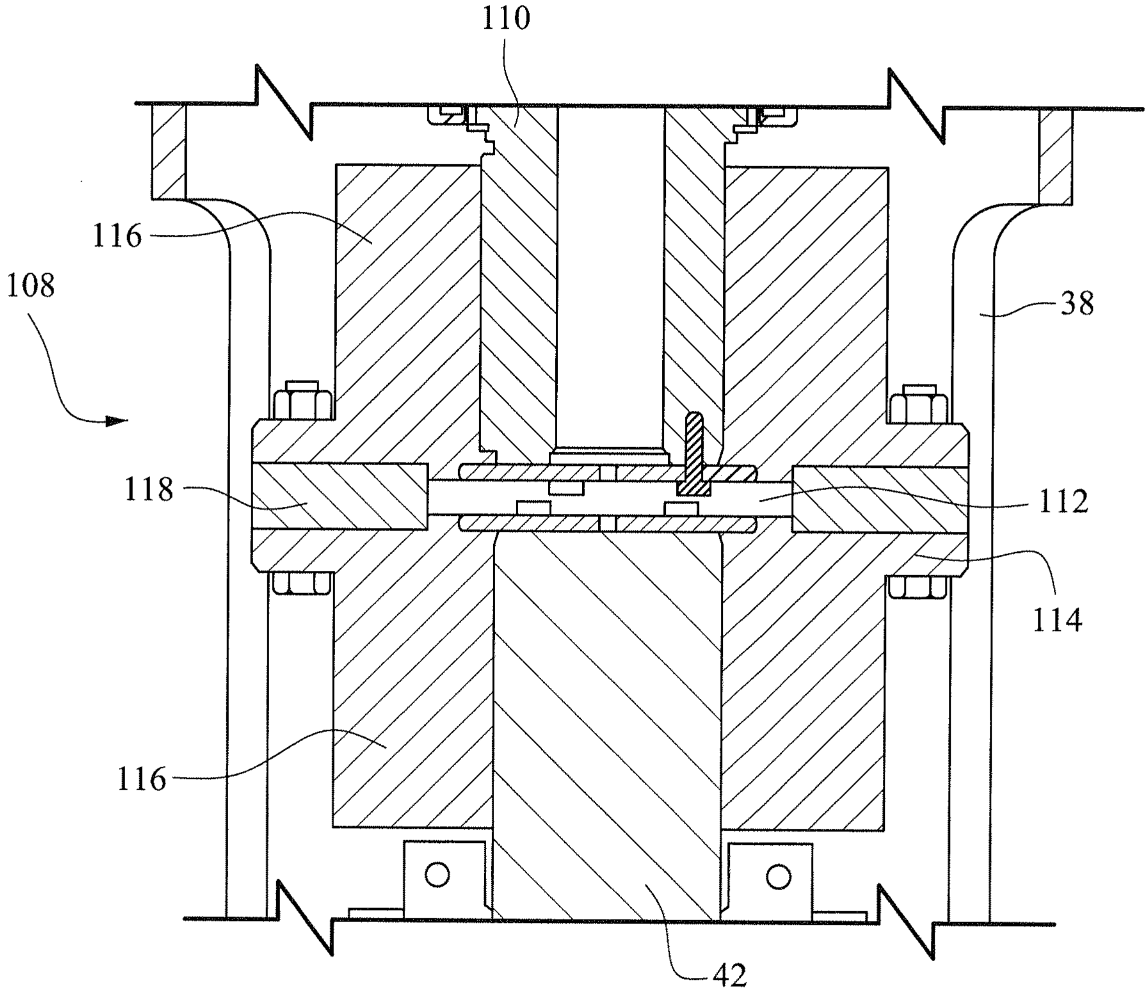


FIG. 15

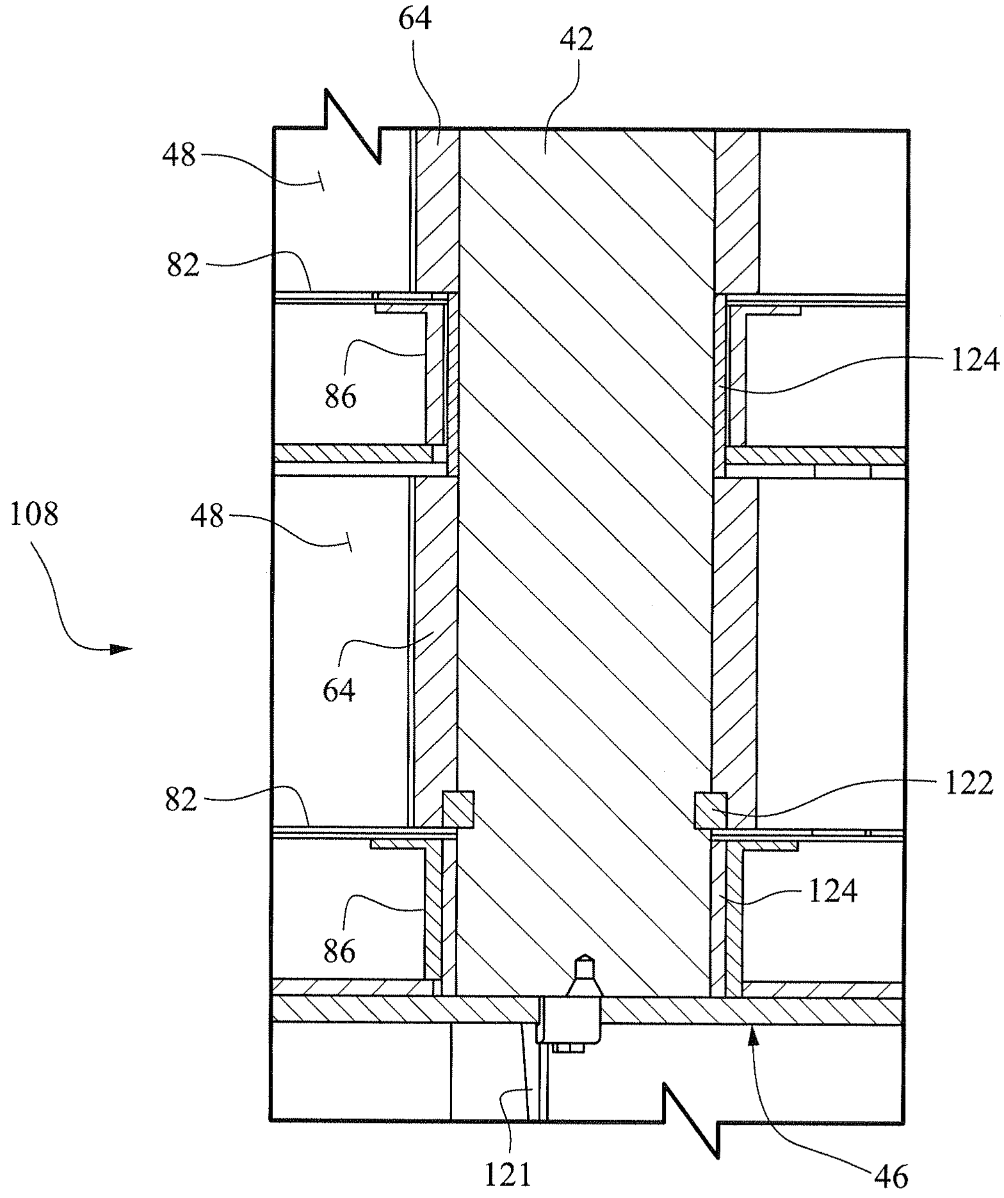


FIG. 16

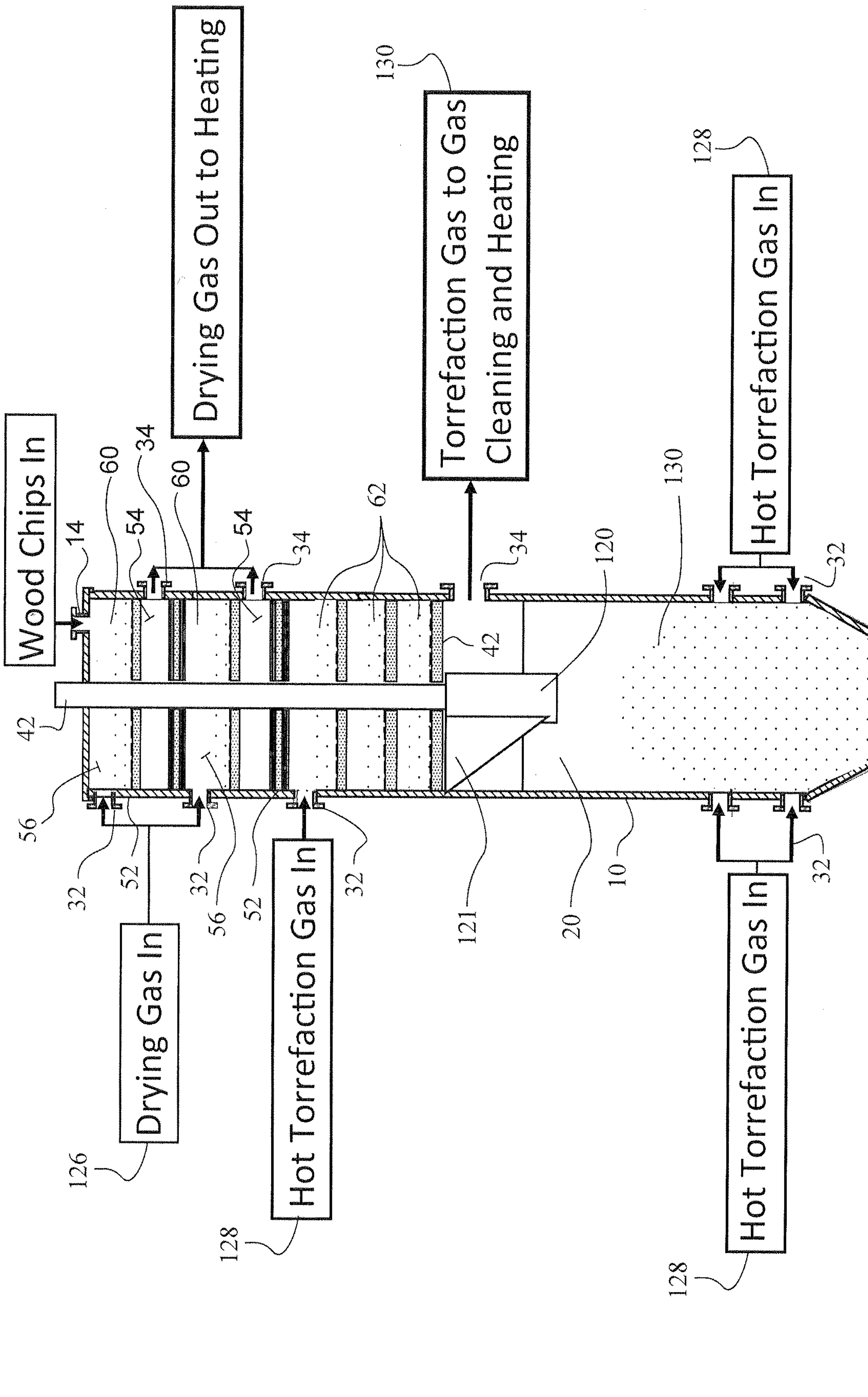

Wood Chips In
Drying Gas Out to Heating
Torrefaction Gas to Gas Cleaning and Heating
Hot Torrefaction Gas In
Drying Gas In
Hot Torrefaction Gas In
Hot Torrefaction Gas In
14
42
56
32
52
60
54
34
62
120
121
20
10
130
132
126
128

FIG. 17

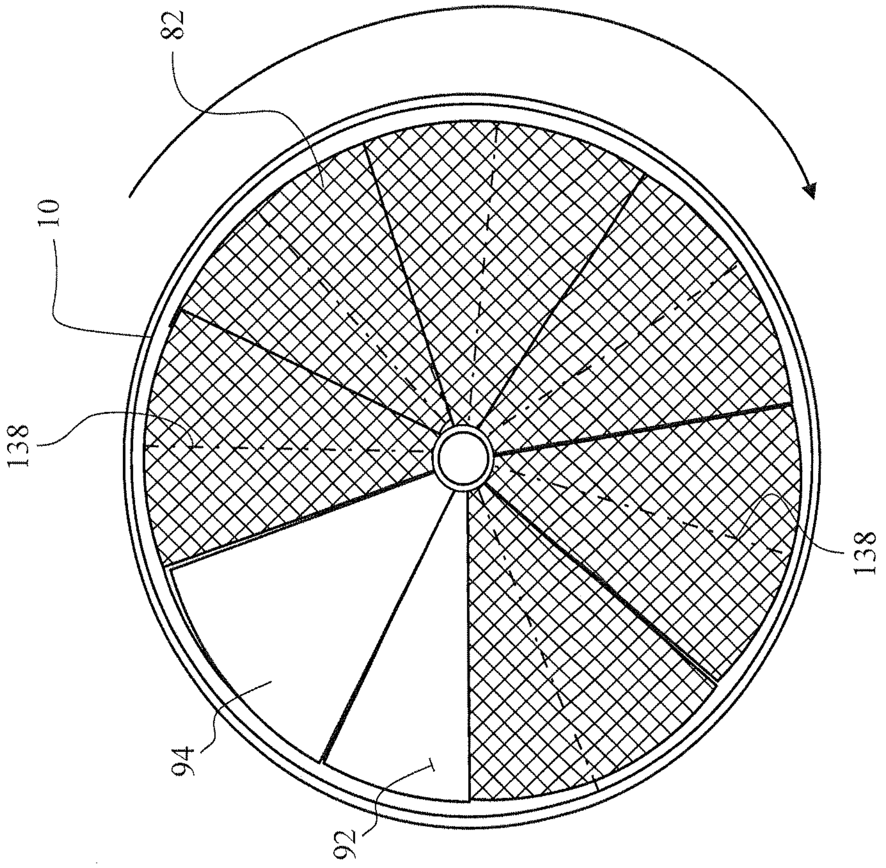
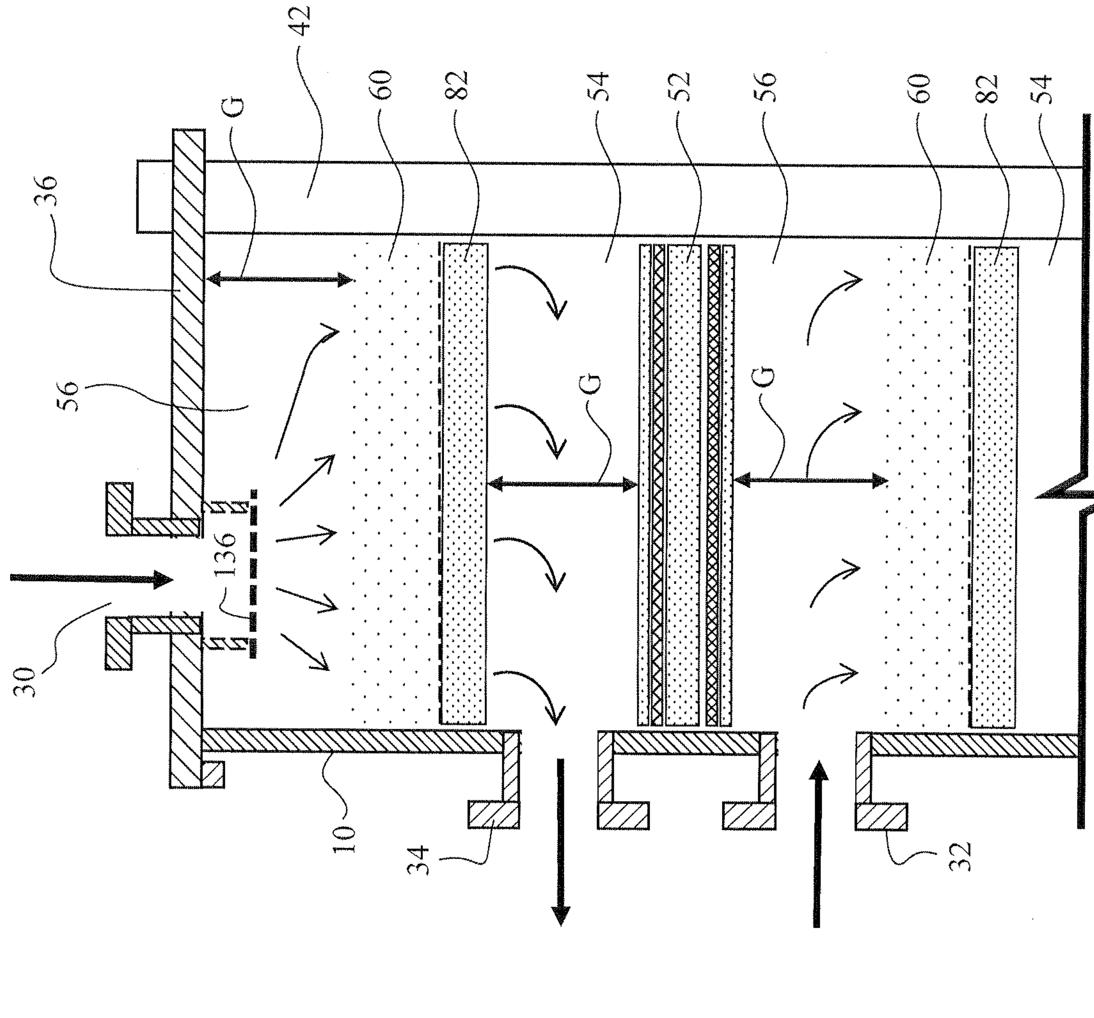

82
10
138
138
94
92

FIG. 19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56
G
42
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82
54
52
56
60
82
54
G
G
30
136
10
34
32

FIG. 18

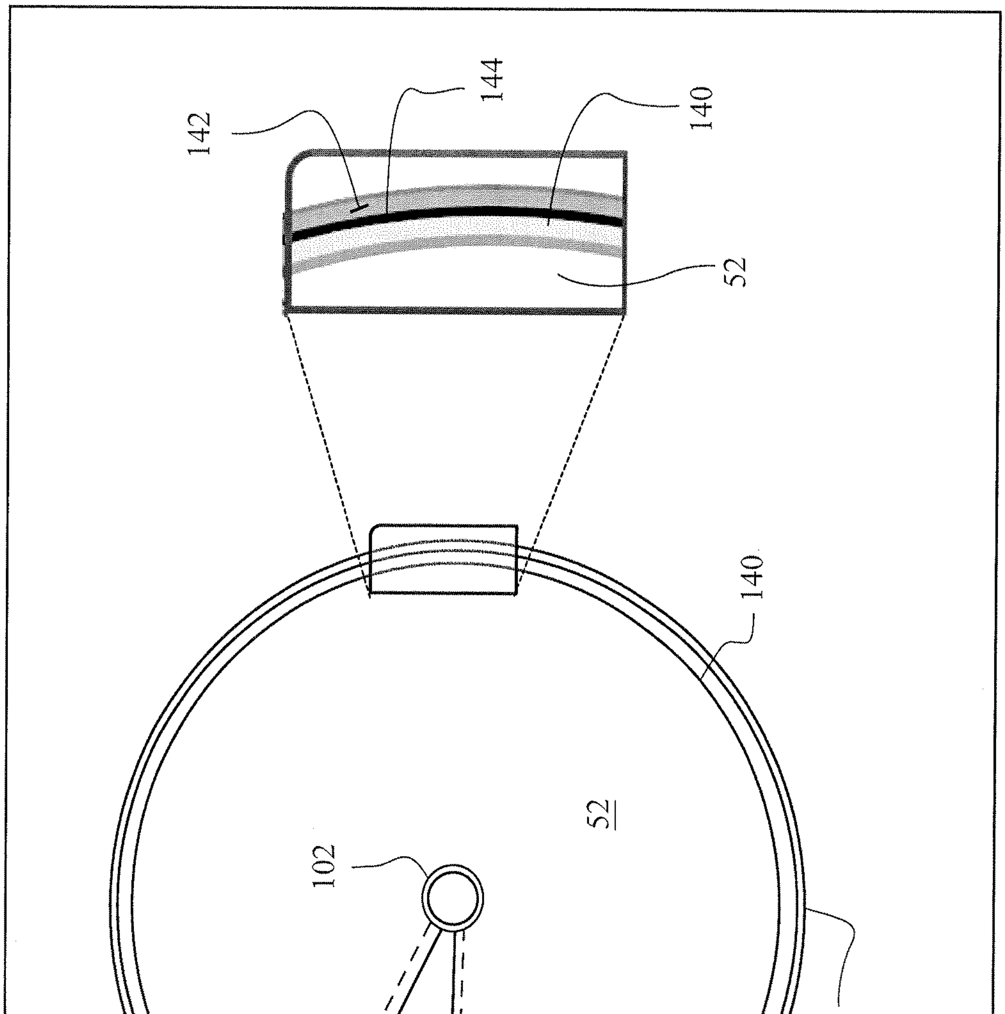

FIG. 20

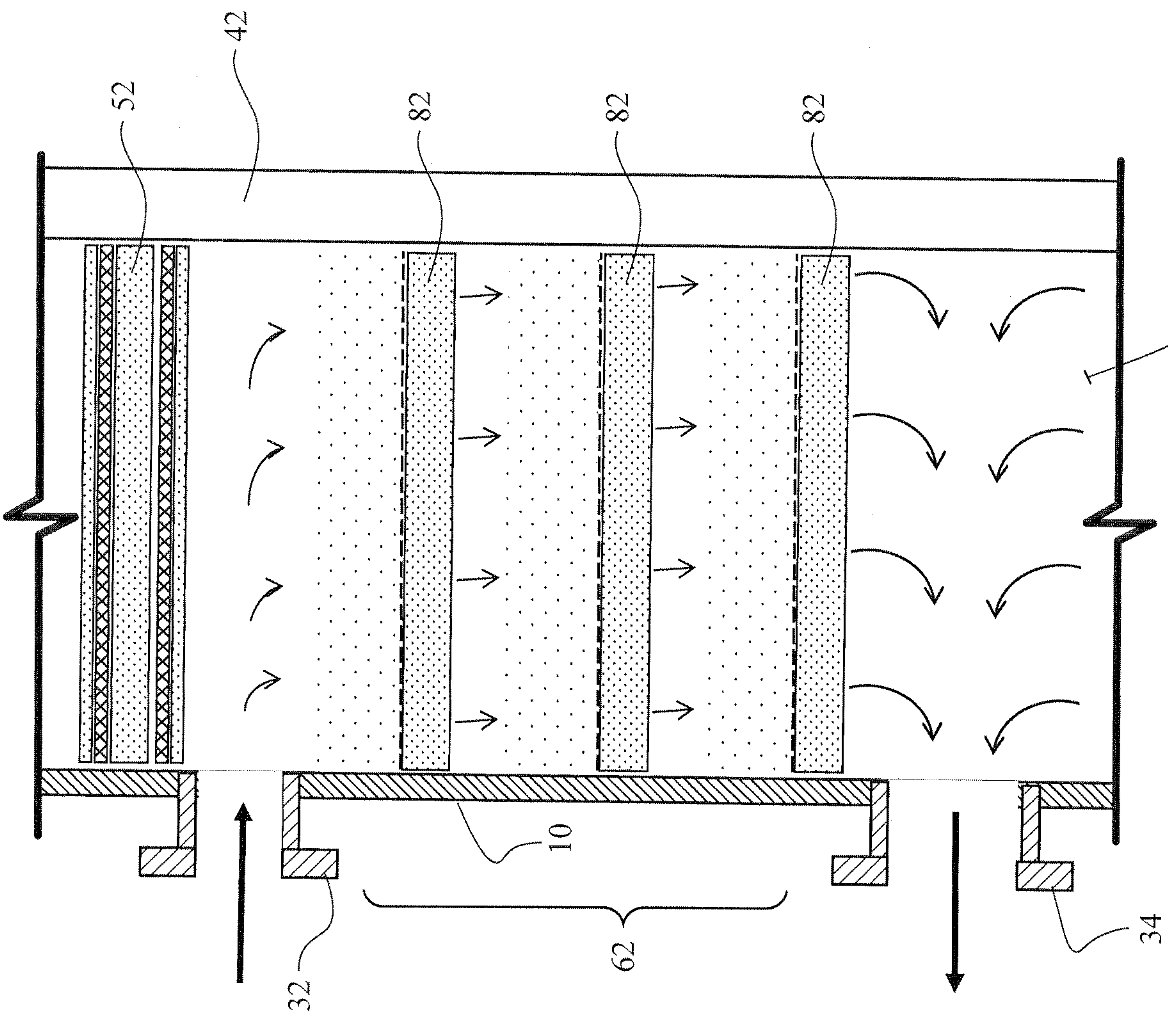

FIG. 21

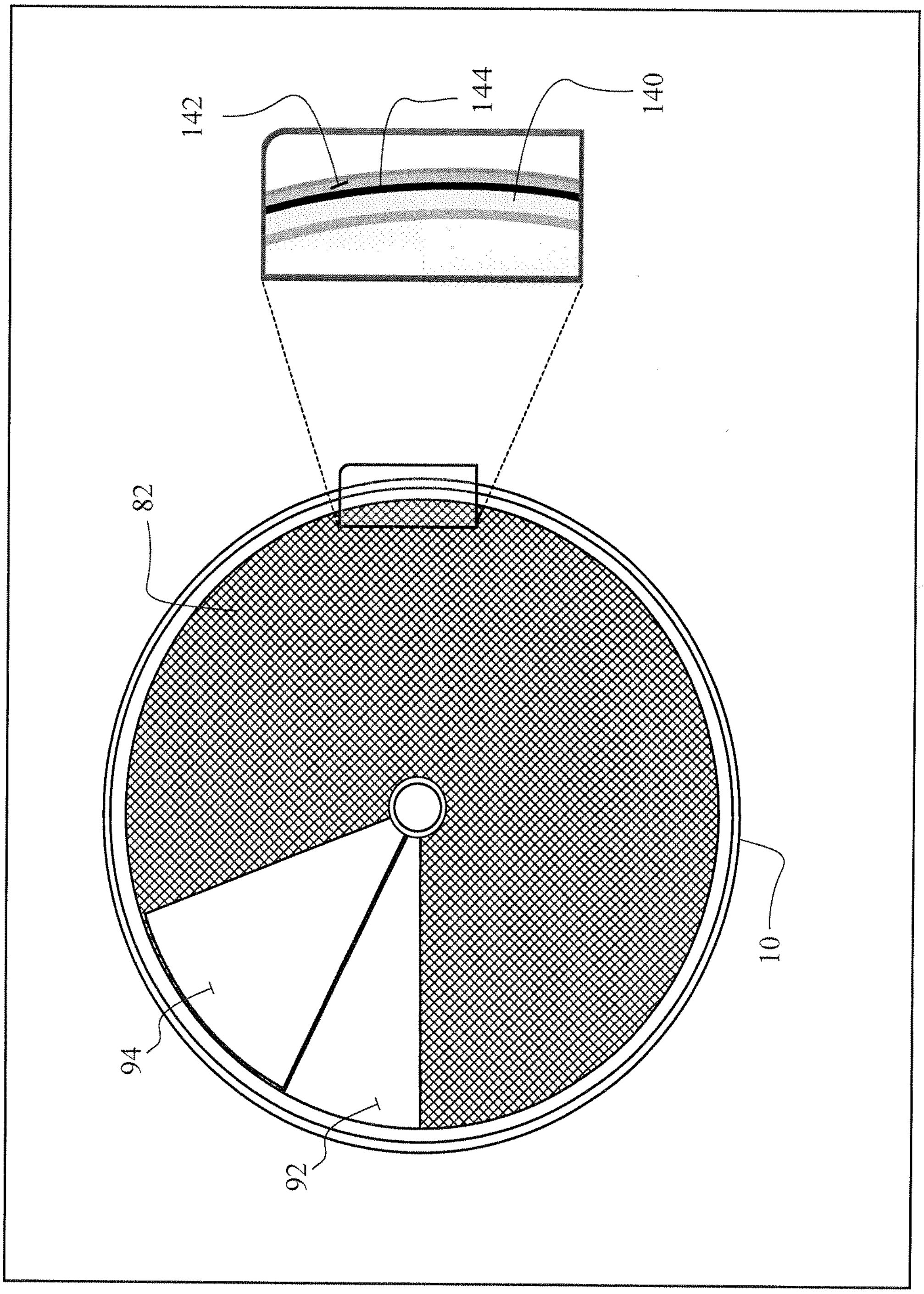

FIG. 22

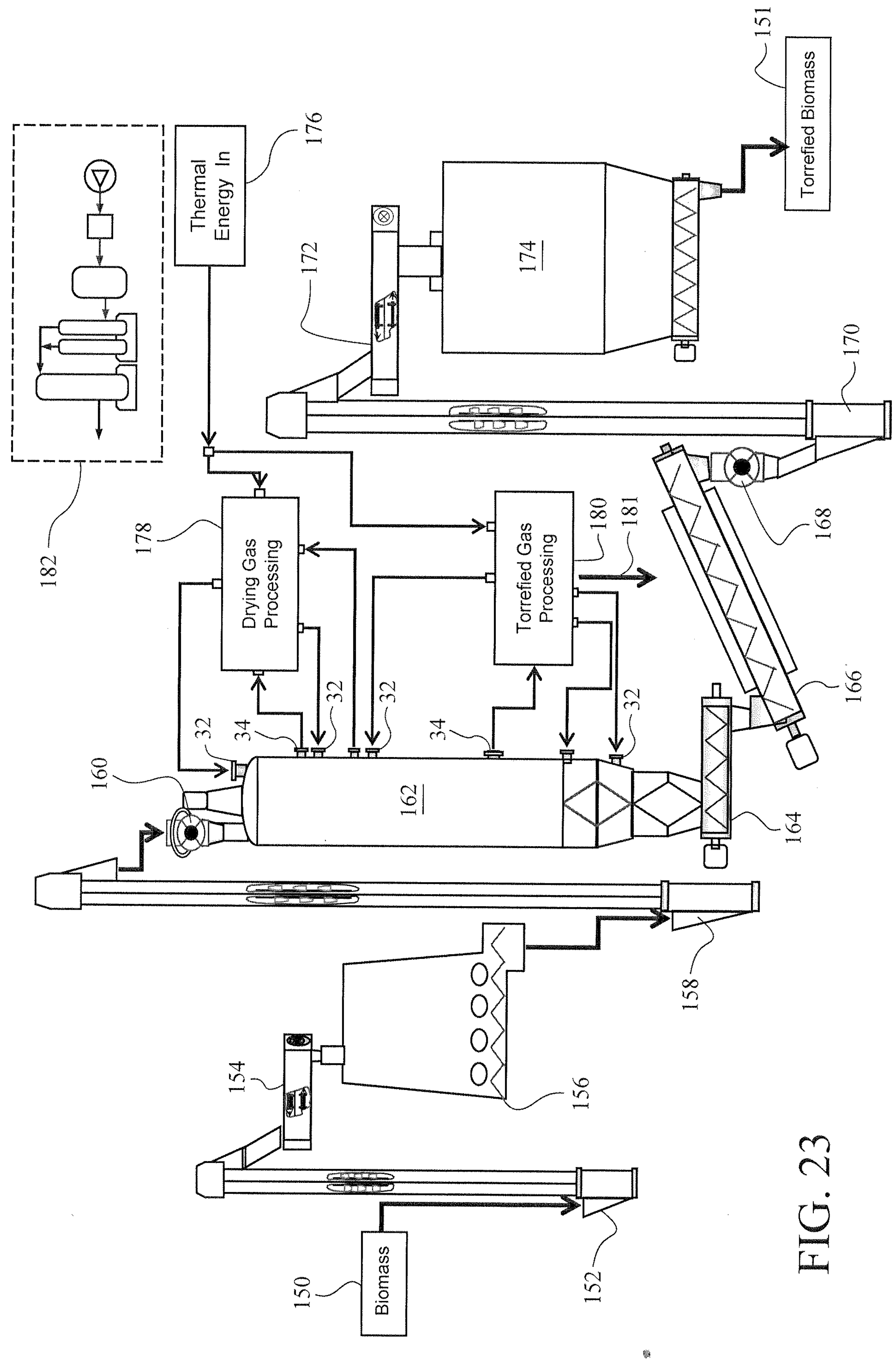
Torrefied Biomass
151
Thermal Energy In
176
174
172
170
168
166
182
178
Drying Gas Processing
180
181
Torrefied Gas Processing
32
34
160
162
164
158
154
156
Biomass
150
152

FIG. 23

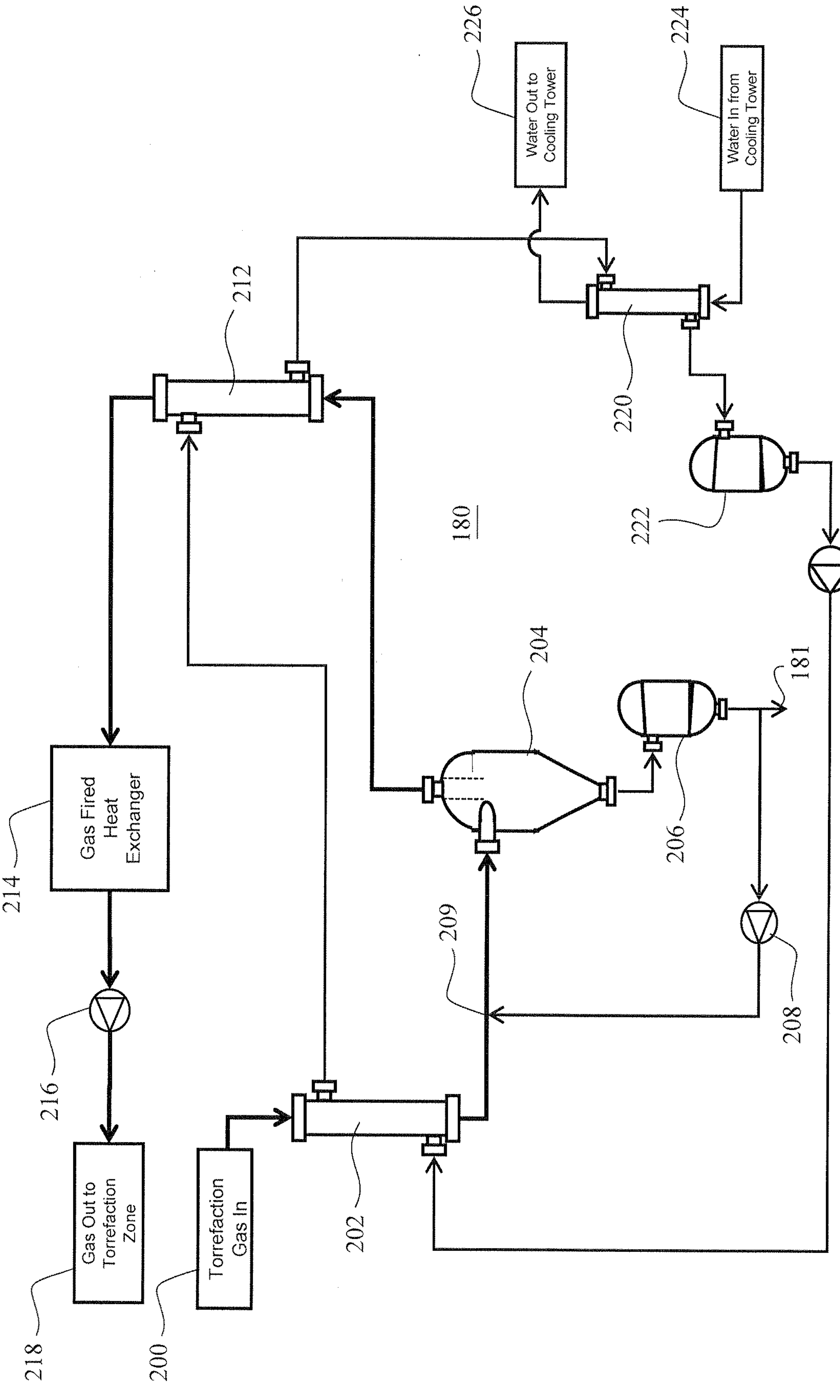
226
Water Out to Cooling Tower
224
Water In from Cooling Tower
212
220
180
222
204
181
210
206
Gas Fired Heat Exchanger
214
209
208
216
Gas Out to Torrefaction Zone
218
Torrefaction Gas In
200
202

FIG. 24