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(54) **VAPOR PHASE CATALYTIC REACTOR FOR UPGARDE OF FUELS PRODUCED BY FAST PYROLYSIS OF BIOMASS**

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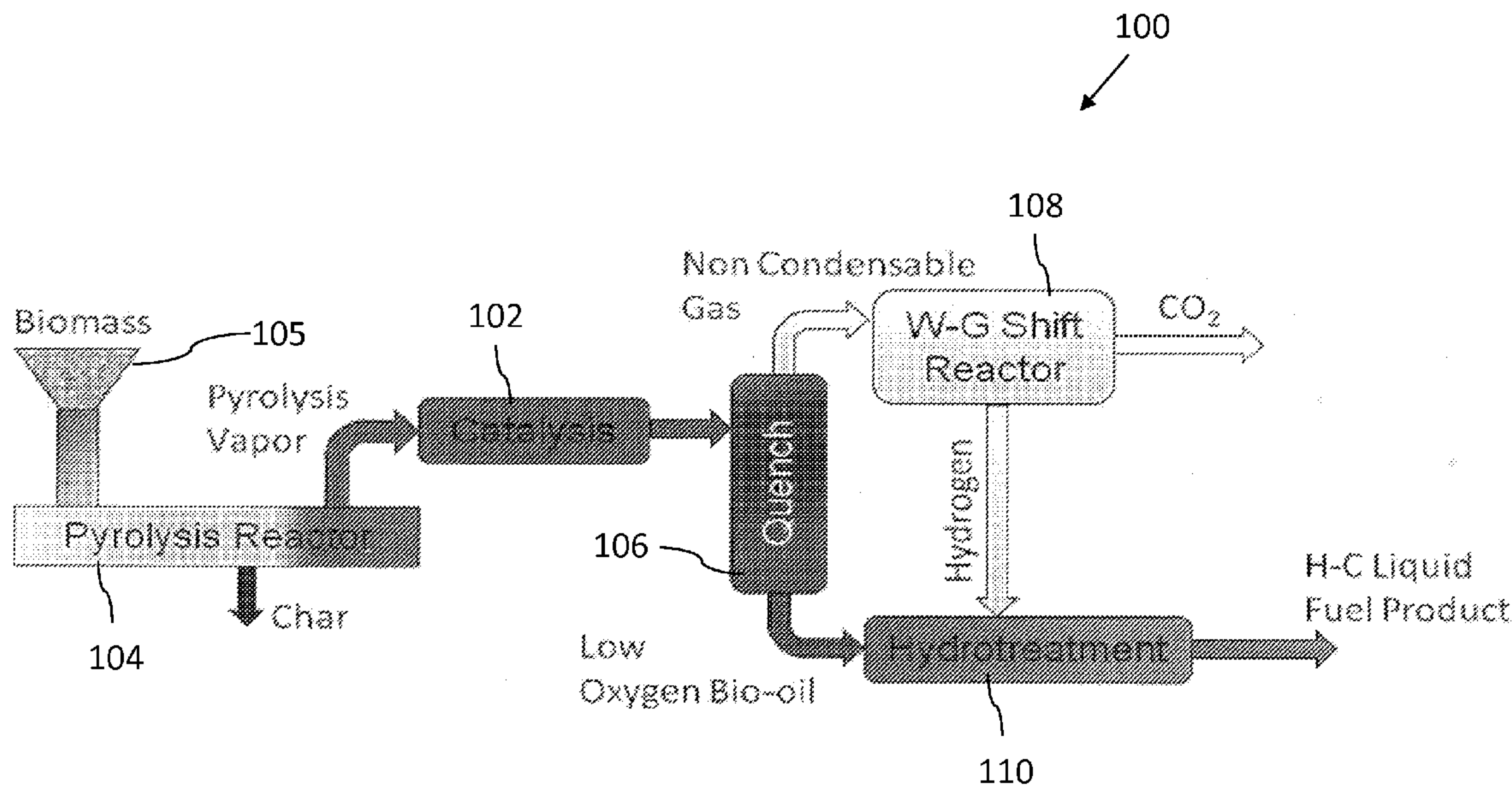
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(57) **ABSTRACT**

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Vapor phase catalytic reactors and methods for using the same for upgrade of fuels produced by fast pyrolysis of biomass are disclosed.



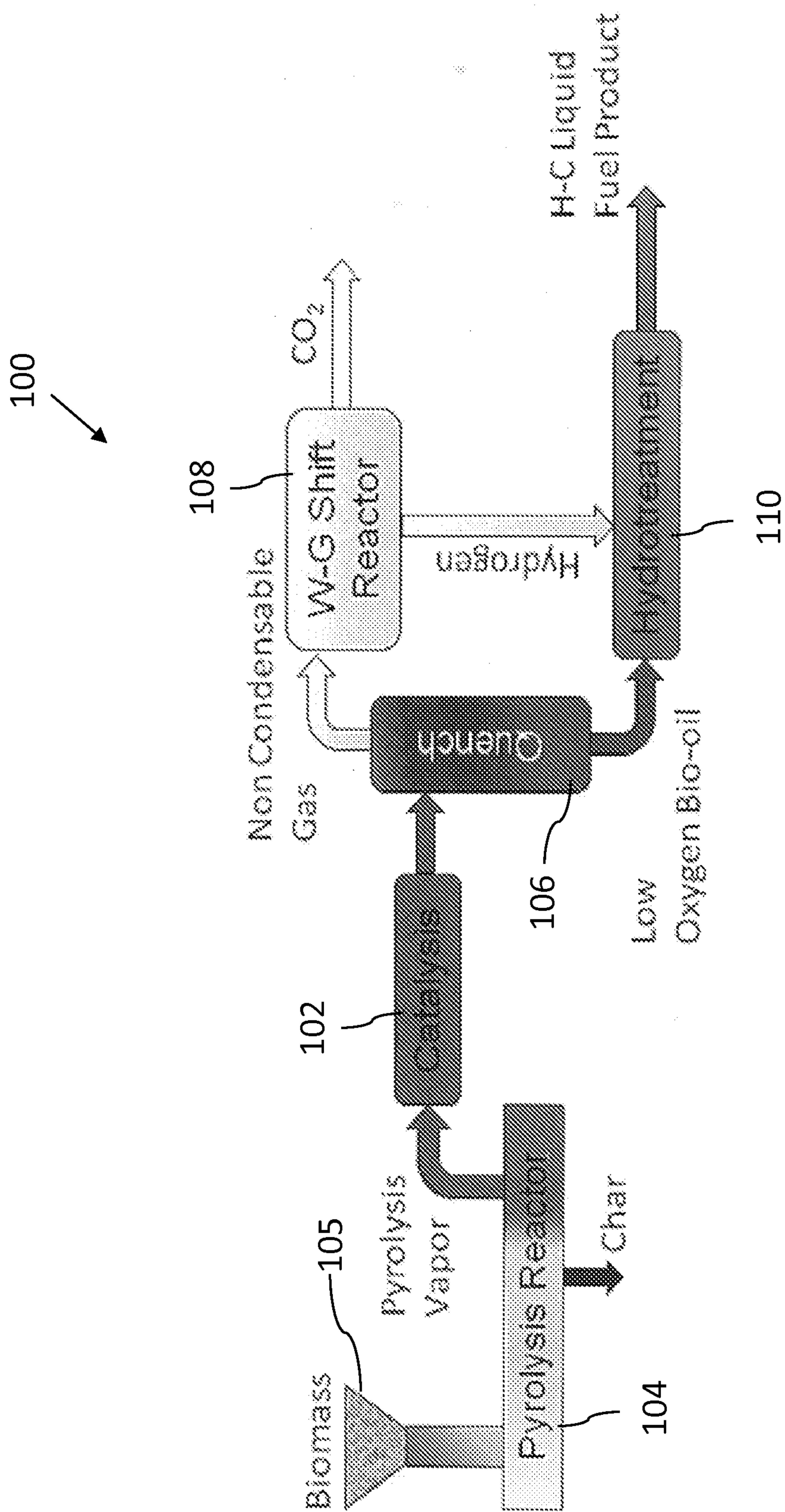
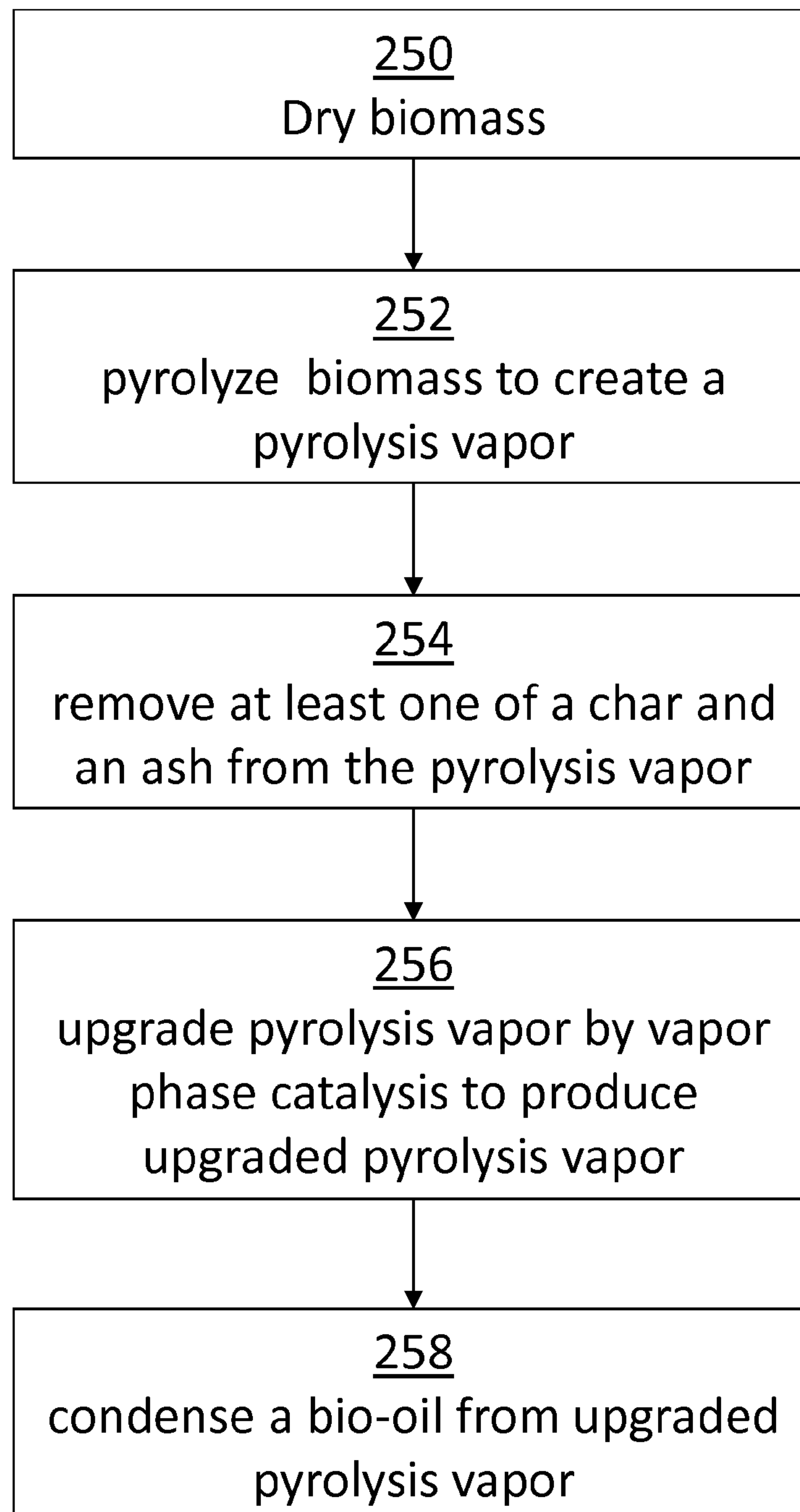


FIG. 1

201

**FIG. 2A**

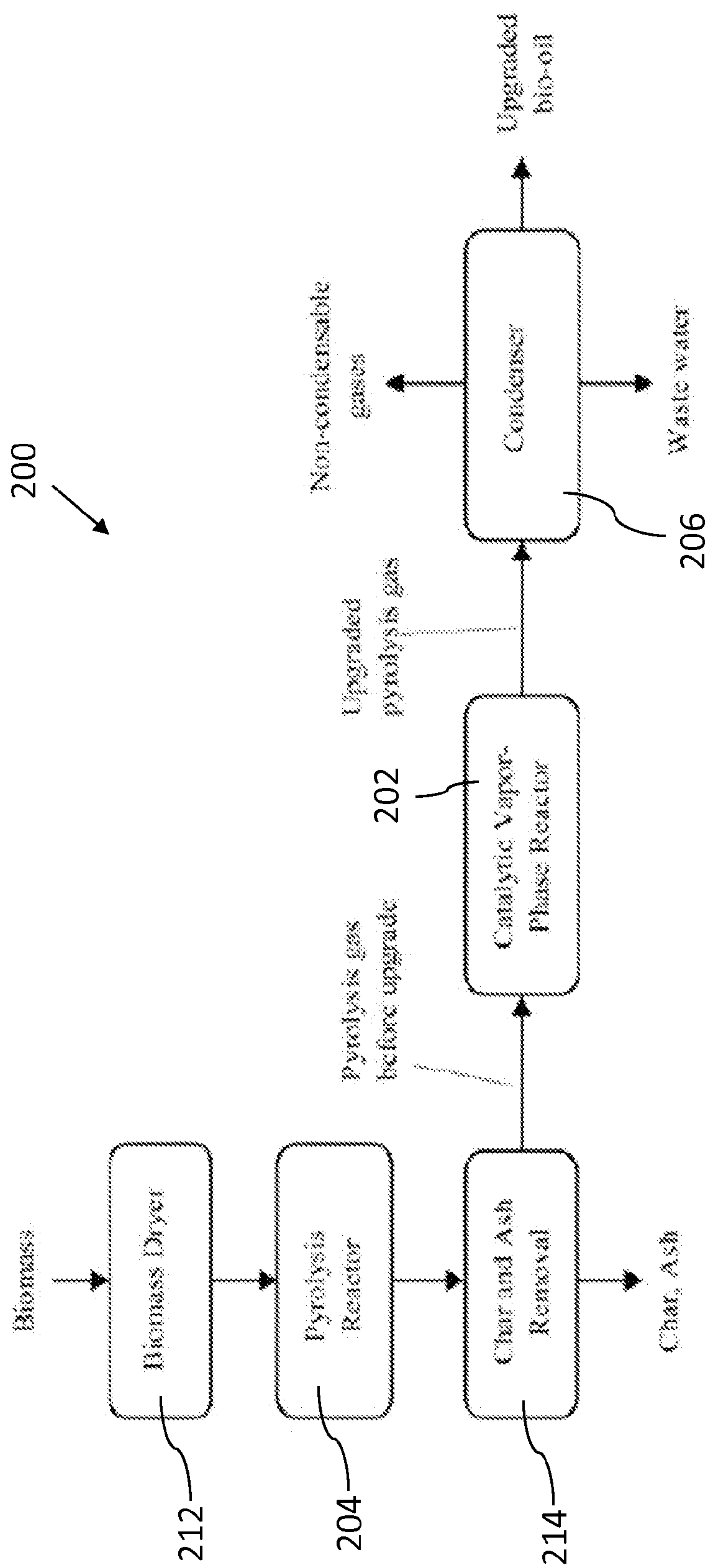


FIG. 2B



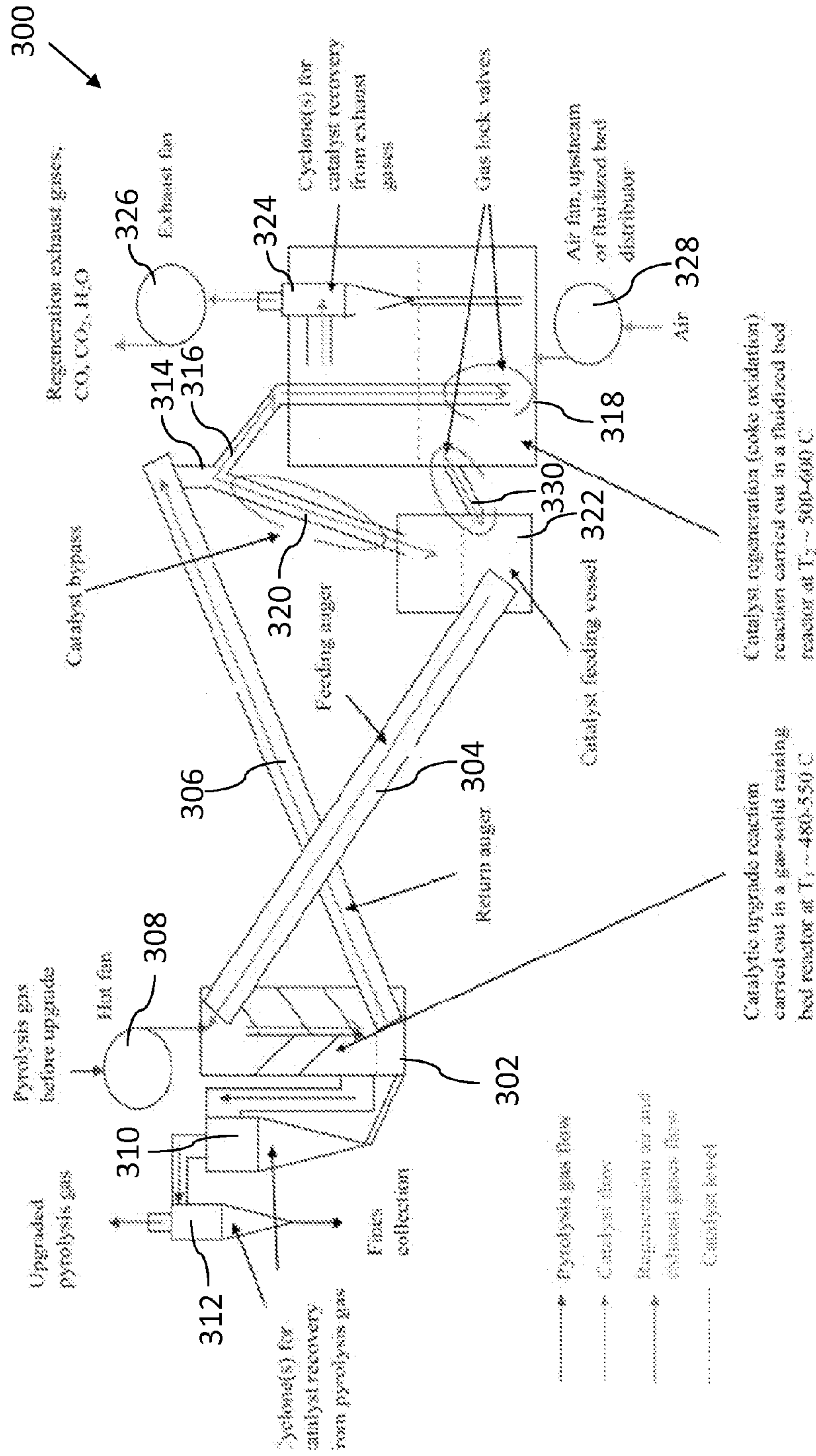


FIG. 3

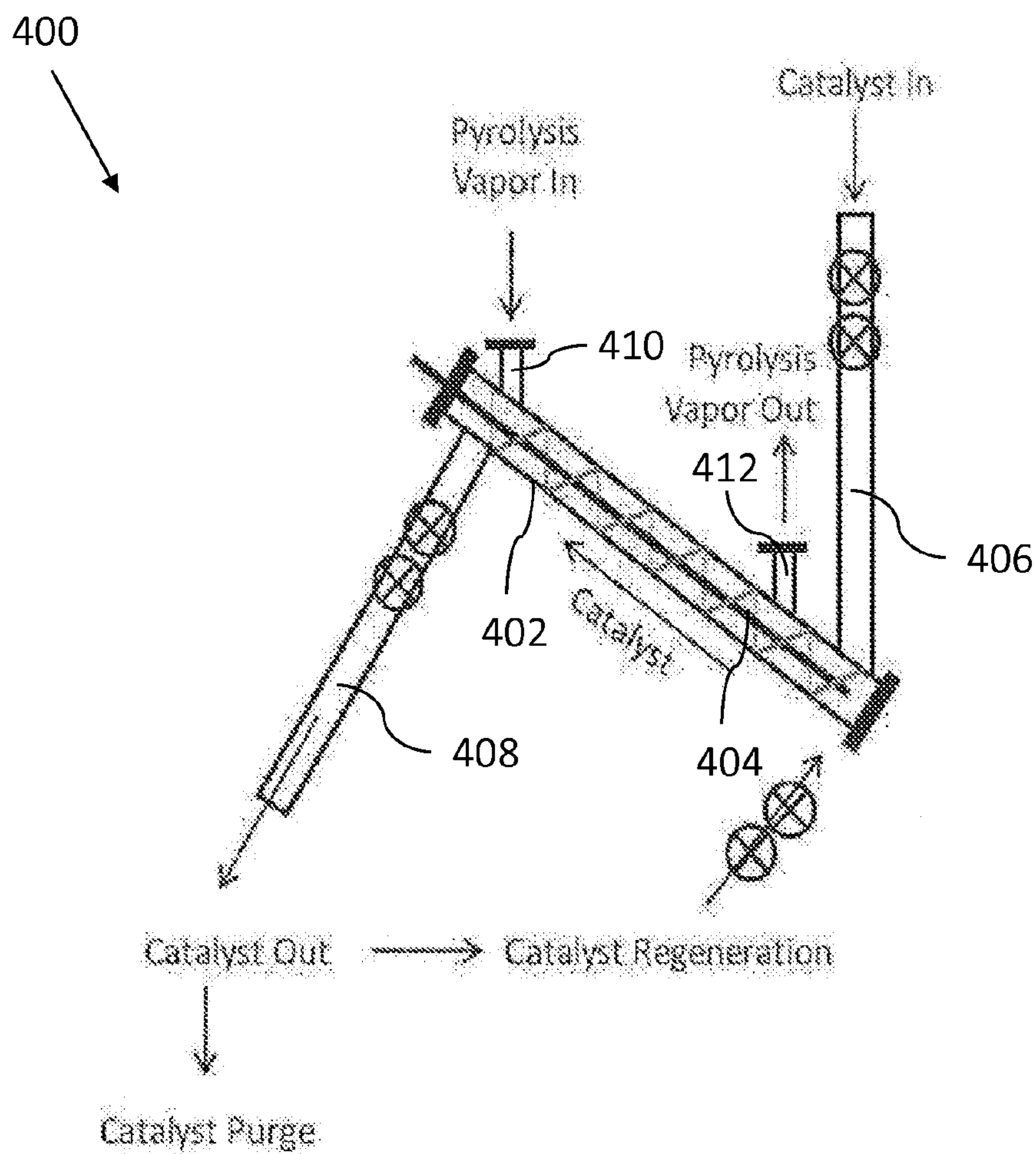


FIG. 4

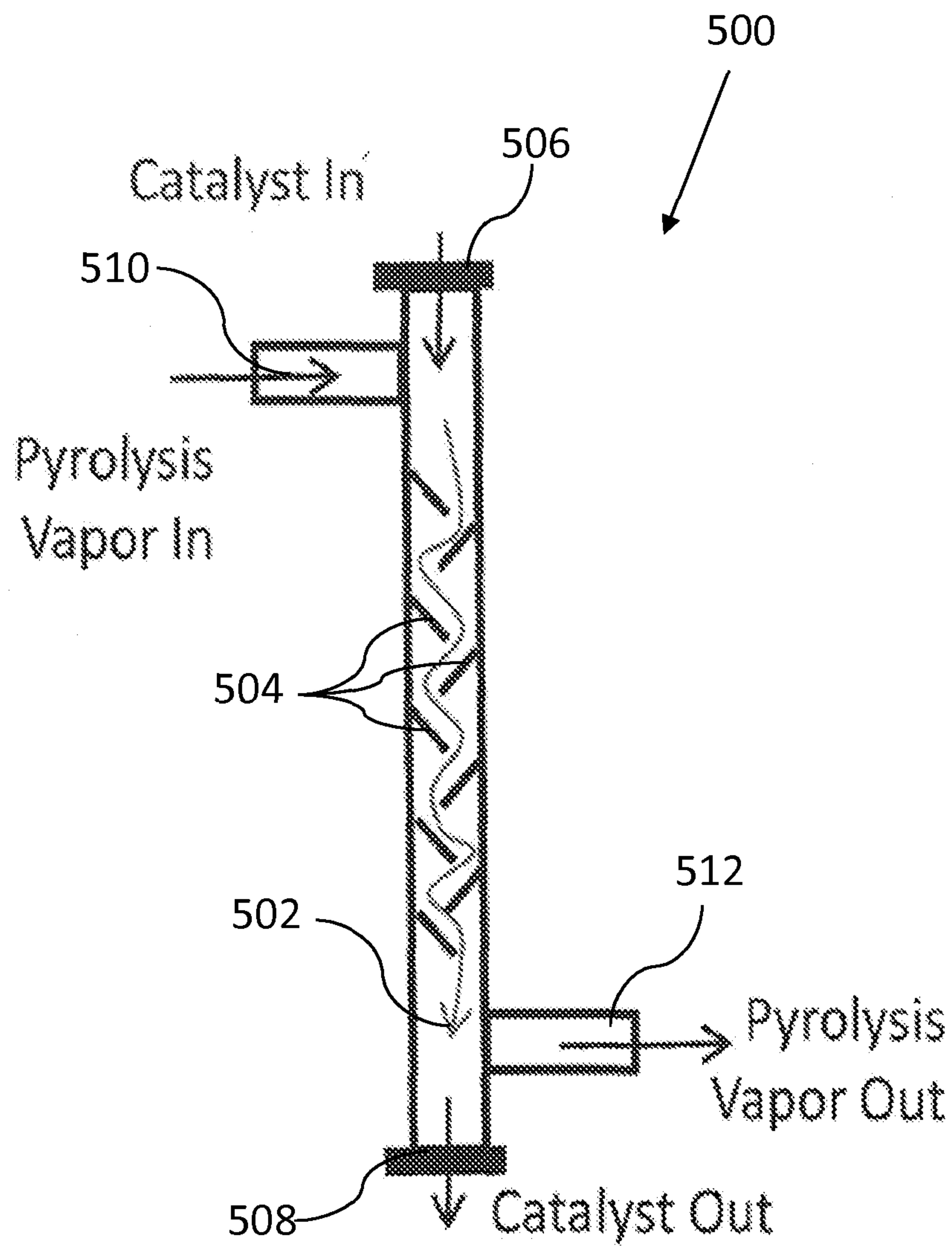


FIG. 5



**VAPOR PHASE CATALYTIC REACTOR FOR  
UPGRADE OF FUELS PRODUCED BY FAST  
PYROLYSIS OF BIOMASS**

CROSS-REFERENCE TO RELATED  
APPLICATIONS

[0001] This application claims priority from U.S. Provisional Patent Application No. 61/800,262, filed on Mar. 15, 2013, which is incorporated by reference herein in its entirety.

BACKGROUND

[0002] The extraction of bio-oil from biomass for use as a biofuel is an area of interest in the search for reliable alternative energy sources. Bio-oil produced by traditional fast pyrolysis processes is typically of relatively low quality due to the bio-oil's large degree of oxygenation, significant acidity, storage instability, tendency to polymerize, and the difficulty involved in separating the bio-oil from water and polar compounds. The low quality of the bio-oil limits its applicability in applications that require high quality fuels, such as transportation applications. Biofuels intended for these applications usually require additional processing.

[0003] Improved systems, methods, and apparatuses are needed for processing bio-oil and making biofuel.

SUMMARY

[0004] In one embodiment, a biofuel production system is provided, the system may include: a catalytic vapor phase reactor; a pyrolysis reactor operatively connected to the catalytic vapor phase reactor; a quench system operatively connected to the catalytic vapor phase reactor; a water gas shift reactor operatively connected to the quench system; and a hydrotreatment system operatively connected to the quench system.

[0005] In one embodiment, a method for catalytic pyrolysis of biomass is provided. The method may include drying a biomass. The method may include pyrolyzing the biomass to create a pyrolysis vapor. The method may include removing at least one of a char and an ash from the pyrolysis vapor. The method may include upgrading the pyrolysis vapor by vapor phase catalysis to produce an upgraded pyrolysis vapor. The method may include condensing a bio-oil from the upgraded pyrolysis vapor.

[0006] In one embodiment, a method for catalytic pyrolysis of biomass is provided, the method may include: drying a biomass in a biomass dryer; placing the biomass in a pyrolysis reactor and heating the biomass to about 500° C. to create a pyrolysis vapor; directing the pyrolysis vapor to a char and ash removal system and removing at least one of a char and an ash from the pyrolysis vapor; directing the pyrolysis vapor to a catalytic vapor phase reactor to upgrade the pyrolysis vapor; directing the pyrolysis vapor to a condenser; and extracting a bio-oil from the condenser.

[0007] In one embodiment, a catalytic vapor phase reactor apparatus is provided, the apparatus may include: a gas-solid catalytic reactor; a feeding auger; a return auger; a hot blower; a first blower; a second blower; a first cyclone; a second cyclone; a third cyclone; a split connection; a dip leg pipe; a fluidized bed reactor; a bypass connection; and a catalyst feeding vessel; wherein the feeding auger and the return auger are operatively connected to the gas-solid catalytic reactor and the fluidized bed reactor; wherein the first cyclone and the second cyclone are operatively connected to the gas-solid

catalytic reactor; and wherein the third cyclone is operatively connected to the fluidized bed reactor.

[0008] In another embodiment, a catalytic vapor phase reactor apparatus is provided, the apparatus may include: a housing may include an auger device, a catalyst inlet, a catalyst outlet, a pyrolysis vapor inlet, and a pyrolysis vapor outlet; wherein the auger device is configured to transport a solid catalyst through at least a portion of the housing; and wherein the housing is configured to permit a pyrolysis vapor to flow through at least a portion of the housing and come into contact with the solid catalyst.

[0009] In another embodiment, a catalytic vapor phase reactor apparatus is provided, the apparatus may include: a housing may include at least one baffle, a catalyst inlet, a catalyst outlet, a pyrolysis vapor inlet, and a pyrolysis vapor outlet; wherein the housing is at least one of substantially vertical and inclined; wherein the housing is configured to permit a solid catalyst to flow through at least a portion of the housing and over at least one baffle; and wherein the housing is configured to permit a pyrolysis vapor to flow through at least a portion of the housing and come into contact with the solid catalyst.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The accompanying figures, which are incorporated in and constitute a part of the specification, illustrate various example apparatuses, systems, and methods, and are used merely to illustrate various example embodiments.

[0011] FIG. 1 illustrates an example arrangement of a biofuels production system.

[0012] FIG. 2A illustrates an example arrangement of a process for catalytic fast pyrolysis of biomass.

[0013] FIG. 2B illustrates an example arrangement of a process for catalytic fast pyrolysis of biomass.

[0014] FIG. 3 illustrates an example arrangement of a catalytic vapor phase reactor for upgrading bio-oil vapors.

[0015] FIG. 4 illustrates an example arrangement of a catalytic vapor phase reactor.

[0016] FIG. 5 illustrates an example arrangement of a catalytic vapor phase reactor.

DETAILED DESCRIPTION

[0017] FIG. 1 illustrates an example arrangement of a biofuels production system 100. Biofuels production system 100 may include a catalytic vapor phase reactor ("VPR") 102 operatively connected to a pyrolysis reactor 104. Pyrolysis reactor 104 may be configured to receive a biomass 105. In one embodiment, biomass 105 may include a wood.

[0018] In one embodiment, biofuels production system 100 may include a conversion system to produce a hydrocarbon product from biomass 105. The production of the hydrocarbon fuel product may include upgrading a bio-oil product. In one embodiment, system 100 may be configured to produce at least one of a hydrocarbon fuel product, a gas, or a chemical, depending upon the catalyst type and reaction conditions.

[0019] In one embodiment, biomass 105 enters pyrolysis reactor 104 wherein biomass 105 may be pyrolyzed and converted to a pyrolysis vapor. In one embodiment, pyrolysis reactor 104 operates at an elevated temperature. In another embodiment, pyrolysis reactor 104 operates at a temperature between about 300° C. and about 600° C. In another embodiment, pyrolysis reactor 104 operates at a temperature between about 350° C. and about 550° C. In another embodiment,



pyrolysis reactor **104** operates at a temperature between about 400° C. and about 500° C. In another embodiment, pyrolysis reactor **104** operates at a temperature capable of converting biomass **105** to a vapor. In one embodiment, char produced in the pyrolysis of biomass **105** may be removed from pyrolysis reactor **104**. In one embodiment, pyrolysis reactor **104** may be internally heated. In another embodiment, pyrolysis reactor **104** may be externally heated. In another embodiment, pyrolysis reactor **104** may be heated via microwaves.

[0020] The pyrolysis vapor created in pyrolysis reactor **104** may be directed into VPR **102**. In one embodiment, VPR **102** may be configured to at least one of deoxygenate the pyrolysis vapor and break down higher molecular weight components of the pyrolysis vapor.

[0021] In one embodiment, VPR **102** may be an integral component of pyrolysis reactor **104**, and catalysis takes place in pyrolysis reactor **104**. In another embodiment, catalysis occurs in pyrolysis reactor **104** and VPR **102** may be eliminated.

[0022] The pyrolysis vapor may leave VPR **102** and enter a quench system **106**, which may be operatively connected to VPR **102**. Quench system **106** may quench the pyrolysis vapor, producing a bio-oil. In one embodiment, the bio-oil may be upgraded to produce a hydrocarbon fuel product. The quenching of the pyrolysis vapor in quench system **106** may produce at least one of a non-condensable gas and a low oxygen bio-oil.

[0023] In one embodiment, non-condensable gas may be directed from quench system **106** into a water gas shift reactor **108**, which may be operatively connected to quench system **106**. The non-condensable gas may be processed resulting in at least one of hydrogen and CO<sub>2</sub>. Hydrogen for the upgrading may be obtained via a water gas shift of the CO in the non-condensable gas exiting quench system **106**.

[0024] In one embodiment, low oxygen bio-oil may be directed from quench system **106** into a hydrotreatment system **110**, which may be operatively connected to quench system **106**. In one embodiment, hydrogen from water gas shift reactor **108** may be directed into hydrotreatment system **110**. In one embodiment, hydrogen may react with the low oxygen bio-oil to produce a hydrocarbon fuel product.

[0025] In one embodiment, biomass **105** may include a wood. Thus, in some embodiments, the bio-oil produced via pyrolysis may contain a mixture of water, organic acids, aldehydes, phenols, and sugar derivatives that require upgrading in order for the bio-oil to be more readily soluble and usable. In one embodiment, the upgrading may be achieved through reaction of the acids, phenols, and sugars with olefins to form esters and ethers. For example, in one embodiment, the bio-oil in the vapor phase may be passed through a catalyst bed after mixing with an injected amount of isoprene, isobutylene, or propylene. In one embodiment, the water may be converted to an alcohol form of the olefin. In one embodiment, the alcohols may be etherified. In one embodiment, the carboxylic acids may be esterified.

[0026] FIG. 2A illustrates an example arrangement of a process **201** configured, for example, for catalytic fast pyrolysis of biomass. Process **201** may generate high yields of condensable organics that may be used as liquid fuels. Process **201** may include **250** drying a biomass. Process **201** may include **252** pyrolyzing the biomass to create a pyrolysis vapor. Process **201** may include **254** removing at least one of a char and an ash from the pyrolysis vapor. Process **201** may include **256** upgrading the pyrolysis vapor by vapor phase

catalysis to produce an upgraded pyrolysis vapor. Process **201** may include **258** extracting a bio-oil from the upgraded pyrolysis vapor by condensation.

[0027] FIG. 2B illustrates an example arrangement of a process **200** configured, for example, for catalytic fast pyrolysis of biomass. Process **200** may be included within the scope of process **201**. Process **200** may generate high yields of condensable organics that may be used as liquid fuels. In one embodiment, process **200** may include heating of a biomass to about 500° C. for a short period of time, typically on the order of a second. Process **200** may include subsequent condensation of organic vapors into a bio-oil mixed with water. Process **200** may include the upgrading of bio-oil vapors in a VPR **202**.

[0028] Process **200** may include a system including VPR **202**, a pyrolysis reactor **204**, a condenser **206**, a biomass dryer **212**, and a char and ash removal system **214**. Thus, in one embodiment, process **200** may include: introducing a biomass into biomass dryer **212**; transferring dried biomass into pyrolysis reactor **204**; and directing pyrolysis vapor from pyrolysis reactor **204** into char and ash removal system **214**. Char and ash may be separated from the pyrolysis vapor in char and ash removal system **214**. Char and ash may be discarded from the system.

[0029] Pyrolysis vapor exiting char and ash removal system **214** may be directed into VPR **202**. In one embodiment, pyrolysis vapor may be upgraded in VPR **202**. In one embodiment, pyrolysis vapor may be contacted with a catalyst after pyrolysis and char/ash removal but before vapor condensing. Processing of the pyrolysis vapor between the char/ash removal but before vapor condensing may minimize contamination of the catalyst with ash and char generated during pyrolysis.

[0030] In one embodiment, temperatures in VPR **202** and pyrolysis reactor **204** may be substantially the same, or different. In another embodiment, residence time of reactants in VPR **202** and pyrolysis reactor **204** may be substantially the same. In another embodiment, residence time of reactants in VPR **202** and pyrolysis reactor **204** may be different.

[0031] In one embodiment, VPR **202** utilizes at least one of: a granulated catalyst, a powdered catalyst, and a catalyst mixture capable of bio-oil vapor or liquid/vapor upgrade. In another embodiment, VPR **202** utilizes a fluid catalytic cracking or a similar granulated catalyst. In one embodiment, the catalyst may be a granulated catalyst with a typical granule size between about 50 μm and about 100 μm. The catalyst may have very few granules smaller than about 20 μm. In one embodiment, the catalyst characteristics provide a desired combination of rapid external mass transfer in rapid gas-solid reactions combined with relatively easy gas-solid separation ability. In one embodiment, the catalyst may be a fluid catalytic cracking (“FCC”) catalyst. In one embodiment, the catalyst may be at least one of: fresh FCC, spent FCC, catalyst impregnated on top of fresh FCC, catalyst impregnated on top of spent FCC, and catalysts granulated by other means but with the same or similar particle size and flow characteristic as FCC. In another embodiment, the catalyst catalyzes at least one of the following reactions: deoxygenation, cracking, water-gas shift, and hydrocarbon formation.

[0032] Upgraded pyrolysis gas may be directed to condenser **206**, where the upgraded pyrolysis gas may be separated into at least one of: non-condensable gases, upgraded bio-oil, and waste water. Upgraded pyrolysis gas may be separated via condensation.



[0033] FIG. 3 illustrates an example arrangement of a VPR 300 for upgrading bio-oil vapors. VPR 300 may include a gas-solid catalytic reactor 302, a feeding auger 304, a return auger 306, a hot blower 308, a first cyclone 310, a second cyclone 312, and a split connection 314. Split connection 314 may be operatively connected to a dip leg pipe 316, a fluidized bed reactor 318, a bypass connection 320, and a catalyst feeding vessel 322. Fluidized bed reactor 318 may include a third cyclone 324 operatively connected to a first blower 326 and a second blower 328.

[0034] In one embodiment, VPR 300 may be configured for continuous mode operation. In another embodiment, VPR 300 may be configured for batch mode operation. In one embodiment, VPR 300 may be configured to operate utilizing air at atmospheric pressure for catalyst regeneration and does not require the use of gases with reduced oxygen content, including, for example, inert gases such as nitrogen, or another gas such as carbon dioxide.

[0035] In one embodiment, each of the components of VPR 300, with the exception of hot blower 308, first blower 326, and second blower 328, are configured to operate at relatively high temperatures. In one embodiment, the operation temperature may be between about 300° C. and about 700° C. In another embodiment, the operation temperature may be between about 350° C. and about 650° C. In another embodiment, the operation temperature may be between about 400° C. and about 600° C. In another embodiment, the operation temperature may be a temperature as high as may be required to drive a catalytic upgrade reaction and a catalyst regeneration (coke oxidation) reaction. In another embodiment, the operation temperature may be a temperature as high as may be required to avoid condensation of pyrolysis gases that can occur on surfaces of components, such as those below about 400° C. In one embodiment, operating temperature may be generated and/or maintained by placing VPR 300 in a hot box heated by at least one of a gas burner and an electric heater.

[0036] In one embodiment, a catalytic upgrade reaction takes place in gas-solid catalytic reactor 302. A catalyst (for example, a granulated catalyst) may be introduced at the top of gas-solid catalytic reactor 302. In one embodiment, pre-upgrade pyrolysis gas may be introduced at the top of gas-solid catalytic reactor 302. In another embodiment, pre-upgrade pyrolysis gas may be introduced at one or more of the top, bottom, or side of gas-solid catalytic reactor 302.

[0037] In one embodiment, pre-upgrade pyrolysis gas and a catalyst are allowed to rapidly mix within gas-solid catalytic reactor 302 to facilitate sufficient contact with the catalyst surface. Gas-solid catalytic reactor 302 may include a volume while the pre-upgrade pyrolysis gas may include a flow rate, which volume and flow rate may be adjusted relative to one another to optimize the contact time between pre-upgrade pyrolysis gas and a catalyst. In one embodiment, the pre-upgrade pyrolysis gas has a residence time within gas-solid catalytic reactor 302 of about 1 s. In one embodiment, mass transfer limitations and catalyst reactivity dictate preferable catalyst-to-pyrolysis gas ratios. In one embodiment, ratios may be about 1:1. In another embodiment, higher amounts of catalyst are required. In one embodiment, VPR 300 may be configured to modulate the catalyst-to-pyrolysis gas ratio over more than an order of magnitude.

[0038] Gas-solid catalytic reactor 302 may include a reaction temperature between about 350° C. and about 650° C. In another embodiment, gas-solid catalytic reactor 302 may include a reaction temperature between about 400° C. and

about 600° C. In another embodiment, gas-solid catalytic reactor 302 may include a reaction temperature between about 450° C. and about 550° C.

[0039] In one embodiment, gas-solid catalytic reactor 302 may include a raining bed reactor (“RBR”) having a series of angled baffles configured to facilitate contact between pre-upgrade pyrolysis gas and a catalyst. In another embodiment, gas-solid catalytic reactor 302 may include any of a variety of reactor designs, including those used in static mixers, empty reactor tubes, and other reactors with features to facilitate catalyst distribution.

[0040] Following contact with the catalyst in gas-solid catalytic reactor 302, upgraded pyrolysis gas exits gas-solid catalytic reactor 302 on at least one of: the bottom, the top, and the side of gas-solid catalytic reactor 302. Upgraded pyrolysis gas exiting gas-solid catalytic reactor 302 may include catalyst particles picked up in gas-solid catalytic reactor 302. Upgraded pyrolysis gas may be at least substantially separated from the catalyst particles.

[0041] In one embodiment, at least one of first cyclone 310 and second cyclone 312 are configured to receive upgraded pyrolysis gas. In another embodiment, first cyclone 310 and second cyclone 312 operate in series to receive upgraded pyrolysis gas. In another embodiment, additional cyclones may be used in the system. In another embodiment, at least one of first cyclone 310 and second cyclone 312 may be replaced with any of a variety of alternative solid-gas separation devices, such as baghouses.

[0042] In one embodiment, upgraded pyrolysis gas may be introduced into first cyclone 310. First cyclone 310 may process the upgraded pyrolysis gas to separate catalyst particles from the upgraded pyrolysis gas, which particles may be at least one of returned to gas-solid catalytic reactor 302 or removed from VPR 300. In one embodiment, upgraded pyrolysis gas may be directed from first cyclone 310 to second cyclone 312 where second cyclone 312 processes the upgraded pyrolysis gas to separate remaining catalyst particles from the upgraded pyrolysis gas, which particles may be at least one of returned to gas-solid catalytic reactor or removed from VPR 300. In one embodiment, catalyst particles separated in second cyclone 312 may be purged from VPR 300.

[0043] In one embodiment, at least one of first cyclone 310 and second cyclone 312 causes a pressure drop within VPR 300. Such pressure drop may be undesirable. In one embodiment, pressure within VPR 300 may be maintained using hot blower 308. Hot blower 308 may force gas into VPR 300 to cause a pressure increase that substantially balances the pressure drop experienced at first cyclone 310 and second cyclone 312.

[0044] The catalytic upgrade reaction may generate a considerable amount of coke. The coke may deposit on the catalyst, which may block the active sites and pores of the catalyst, thus rendering it less effective. As such, in one embodiment the coke should be removed from the catalyst. In one embodiment, the coke may be removed by continuous oxidation in air at a temperature between about 400° C. and about 700° C. In another embodiment, the coke may be removed by continuation oxidation in air at a temperature between about 450° C. and about 650° C. In another embodiment, the coke may be removed by continuous oxidation in air at a temperature between about 500° C. and about 600° C. In one embodiment, oxidation of the coke occurs inside fluidized bed reactor 318.



[0045] In one embodiment, fluidized bed reactor 318 may be operatively connected to at least one of a first blower 326 and a second blower 328. At least one of first blower 326 and second blower 328 causes an air flow within fluidized bed reactor 318. In another embodiment, at least one of first blower 326 and second blower 328 may be configured to direct air from fluidized bed reactor 318 into a distributor (not shown). Air flow and the volume of fluidized bed reactor 318 may be selected to optimize several design requirements, including at least one of: (1) air flow capable of generating appropriate fluidization conditions for the catalyst used, (2) air flow sufficient to deliver enough oxygen for coke oxidation, and (3) air flow, temperature, and fluidized bed reactor 318 volume must facilitate coke oxidation kinetics.

[0046] In one embodiment, the coke burning reaction may be highly exothermic and heat generated therein may be dissipated through any of various means, including heat transfer from fluidized bed reactor 318 to the gas atmosphere surrounding fluidized bed reactor 318. In another embodiment, heat dissipation may be enhanced by using room temperature air for fluidization. In another embodiment, heat dissipation may be enhanced by using another cooling medium directed into fluidized bed reactor 318.

[0047] Oxidation of coke may produce byproducts including carbon monoxide, carbon dioxide, and water. Significant quantities of carbon monoxide generated in oxidation of coke may be exhausted through at least one of third cyclone 324 and first blower 326.

[0048] Catalyst particles from fluidized bed reactor 318 may be entrained by the fluidizing air and/or exhaust gases. The catalyst particles may be removed from the fluidizing air to minimize catalyst losses. Third cyclone 324 may be used to process the fluidizing air to at least substantially separate catalyst from the fluidizing air, which catalyst may be at least one of returned to fluidized bed reactor 318 or discarded from VPR 300.

[0049] Third cyclone 324 may be contained within fluidized bed reactor 318. In one embodiment, additional cyclones may be utilized in series with third cyclone 324. In another embodiment, the additional cyclones and/or third cyclone 324 may be located inside or outside fluidized bed reactor 318 or a hot box surrounding VPR 300.

[0050] In one embodiment, at least one of first blower 326 and second blower 328 are needed to maintain a desired pressure balance between gas-solid catalytic reactor 302 and fluidized bed reactor 318. In another embodiment, at least one of first blower 326 and second blower 328 permit independent control of air flow in fluidized bed reactor 318 and internal pressure of fluidized bed reactor 318.

[0051] In one embodiment, feeding of the catalyst into gas-solid catalytic reactor 302 and fluidized bed reactor 318, and recirculation of catalyst between gas-solid catalytic reactor 302 and fluidized bed reactor 318 may be effected by feeding auger 304 and return auger 306. Feeding auger 304 and return auger 306 may be powered by at least one power source, for example an electric motor. The electric motor may be placed outside VPR 300 but coupled mechanically with feeding auger 304 and return auger 306. Feeding auger 304 and return auger 306 may include auger screws configured to rotate and advance catalyst material. Flow rate of the catalyst can be controlled by adjusting the rotation speed of feeding auger 304 and return auger 306. Such adjustment of the rotation speed of feeding auger 304 and return auger 306 may be utilized to adjust the catalyst to biomass ratio and effec-

tively control the catalytic reaction rate. Feeding auger 304 may direct catalyst from catalyst feeding vessel 322 to gas-solid catalytic reactor 302. Return auger 306 may direct catalyst from gas-solid catalytic reactor 302 to split connection 314.

[0052] Split connection 314 may be configured to preferably direct the catalyst to fluidized bed reactor 318 for regeneration. Split connection 314 may direct catalyst material to dip leg pipe 316 immersed into the catalyst contained in fluidized bed reactor 318. As a result of the hydrostatic balance of the catalyst within fluidized bed reactor 318, and the proper pressure balance between gas-solid catalytic reactor 302 and fluidized bed reactor 318, dip leg pipe 316 remains at least partially filled with catalyst. The partially filled state of dip leg pipe 316 acts as a gas lock to limit the amount of gas that can pass to and from fluidized bed reactor 318. This gas lock at least substantially separates the pyrolysis gas atmosphere existing inside gas-solid catalytic reactor 302, feeding auger 304, and return auger 306, from the oxygen-rich atmosphere inside fluidized bed reactor 318.

[0053] Bypass connection 320 allows catalyst to bypass fluidized bed reactor 318 in the event that catalyst may be not accepted into fluidized bed reactor 318 via dip leg pipe 316. In one embodiment, catalyst may be required to bypass fluidized bed reactor 318 due to insufficient fluidization inside fluidized bed reactor 318, or a loss of air flow into fluidized bed reactor 318. Bypass connection 318 may allow for uninterrupted catalytic upgrade reaction and will prevent return auger 306 from becoming backed up with catalyst.

[0054] Catalyst processed in fluidized bed reactor 318 may be transferred to catalyst feeding vessel 322 via a transfer connection 330. Upon reaching a sufficient level in fluidized bed reactor 318, catalyst may flow from fluidized bed reactor 318 to catalyst feeding vessel 322 via transfer connection 330. Similar to dip leg pipe 316, transfer connection 330 acts as a gas lock to limit the amount of gas that can pass to and from fluidized bed reactor 318.

[0055] Catalyst transferred through bypass connection 320 into catalyst feeding vessel 322 without passing through fluidized bed reactor 318 may be not processed to remove coke. However, a catalyst contaminated with coke may be utilized in gas-solid catalytic reactor 302 until it may be able to enter fluidized bed reactor 318 for processing.

[0056] FIG. 4 illustrates an example arrangement of a VPR 400. VPR 400 may include a housing 402 containing an auger device 404 configured to move a catalyst material and a biomass pyrolysis vapor in counter-current directions. VPR 400 may be configured to bring the pyrolysis vapor and the catalyst into close contact. Housing 402 and auger device 404 may include substantially circular cross-sections. In one embodiment, housing 402 may include an inner diameter that may be substantially the same as or slightly greater than the outside diameter of auger device 404.

[0057] In one embodiment, VPR 400 may be placed in a heated enclosure and coupled to a catalyst regeneration system, such as that illustrated in FIG. 3. VPR 400 may operate in a heated enclosure between about 300° C. and about 600° C. In another embodiment, VPR 400 operates in a heated enclosure between about 350° C. and about 550° C. In another embodiment, VPR 400 operates in a heated enclosure between about 400° C. and about 500° C. In another embodiment, VPR 400 operates at an elevated temperature configured to prevent condensation of the pyrolysis vapor.



[0058] In one embodiment, VPR 400 may include an inclined housing 402 and auger device 404. A catalyst may enter VPR 400 via a catalyst inlet 406. The catalyst may be transported through VPR 400 within housing 402 via rotation of an auger device 404. Catalyst may exit VPR 400 via a catalyst outlet 408.

[0059] In one embodiment, pyrolysis vapor enters VPR 400 at a pyrolysis vapor inlet 410. Pyrolysis vapor may move through housing 402 by virtue of a pressure differential, a blower, or a pump. Pyrolysis vapor may move through housing 402 in contact with the catalyst. In one embodiment, pyrolysis vapor moves spirally about auger device 404. In one embodiment, pyrolysis vapor exits VPR 400 via a pyrolysis vapor outlet 412. In one embodiment, pyrolysis vapor inlet 410 may be near the upper portion of housing 402 and pyrolysis vapor outlet 412 may be near the lower portion of housing 402. In another embodiment, pyrolysis vapor inlet 410 may be near the lower portion of housing 402 and pyrolysis vapor outlet 412 may be near the upper portion of housing 402. In one embodiment, pyrolysis vapor moves counter-current to the flow of the catalyst. In another embodiment, pyrolysis vapor moves concurrent to the flow of the catalyst.

[0060] In one embodiment, pyrolysis vapor flows downward within housing 402 in a spiral around auger device 404. Limited clearance between the outside diameter of auger device 404 and the inside diameter of housing 402 limits the bypass of gas around the catalyst, forcing pyrolysis vapor to contact the catalyst.

[0061] The catalyst may enter and exit VPR 400 through a double block valve system (such as that illustrated in FIG. 3) so as to substantially prevent pyrolysis vapor from exiting VPR 400 with the catalyst.

[0062] FIG. 5 illustrates an example arrangement of a VPR 500. VPR 500 may include a substantially vertical or inclined housing 502, within which at least one baffle 504 may be oriented. A catalyst may enter VPR 500 via a catalyst inlet 506 and may exit VPR 500 via a catalyst outlet 508. A pyrolysis vapor may enter VPR 500 via a pyrolysis vapor inlet 510 and may exit VPR 500 via a pyrolysis vapor outlet 512.

[0063] In one embodiment, at least one baffle 504 may be angled downward so as to cause a catalyst to pour off at least one baffle 504 with pyrolysis vapor moving through the stream of catalyst material. In another embodiment, VPR 500 may include a plurality of baffles 504 in alternating positions and heights within VPR 500, such that a catalyst pouring over baffles 504 forms successive curtains as it falls from a higher baffle 504 to a lower baffle 504. Pyrolysis vapor passes through the curtains of catalysts, and thus contacts the catalyst, as it travels through housing 502.

[0064] In one embodiment, pyrolysis vapor inlet 510 may be oriented near the top of VPR 500 and pyrolysis vapor outlet 512 may be oriented near the bottom of VPR 500. In this embodiment, pyrolysis vapor flows concurrently with the catalyst. In another embodiment, pyrolysis vapor inlet 510 may be oriented near the bottom of VPR 500 and pyrolysis vapor outlet 512 may be oriented near the top of VPR 500. In this embodiment, pyrolysis vapor flows counter-currently with the catalyst.

[0065] In one embodiment, VPR 500 may be placed in a heated enclosure and coupled to a catalyst regeneration system, such as that illustrated in FIG. 3. VPR 500 may operate in a heated enclosure between about 300° C. and about 600° C. In another embodiment, VPR 500 operates in a heated enclosure between about 350° C. and about 550° C. In

another embodiment, VPR 500 operates in a heated enclosure between about 400° C. and about 500° C. In another embodiment, VPR 500 operates at an elevated temperature configured to prevent condensation of the pyrolysis vapor.

[0066] The catalyst may enter and exit VPR 500 through a double block valve system (such as that illustrated in FIG. 3) so as to substantially prevent pyrolysis vapor from exiting VPR 500 with the catalyst.

[0067] In one embodiment, biomass may be directly added to the top of VPR 400 or VPR 500 to generate pyrolysis vapor while at the same time catalytically upgrading the pyrolysis vapor in a one-step process. In this embodiment, a pyrolysis reactor may not be necessary.

[0068] In various embodiments, a biofuel production system 100 is provided. The biofuel production system may include a catalytic vapor phase reactor (VPR) 102. The biofuel production system may include a pyrolysis reactor 104 operatively connected to the catalytic VPR 102. The biofuel production system may include a quench system 106 operatively connected to the catalytic VPR 102. The biofuel production system may include a water gas shift reactor 108 operatively connected to the quench system 106. The biofuel production system may include a hydrotreatment system 110 operatively connected to the quench system 106.

[0069] In some embodiments, the pyrolysis reactor 104 may be configured to receive a biomass 105. The pyrolysis reactor 104 may be configured to pyrolyze the biomass 105 to produce a pyrolysis vapor. The biomass 105 may include a wood.

[0070] The pyrolysis reactor 104 may be configured to operate at a temperature capable of converting at least a portion of biomass 105 to a pyrolysis vapor. The pyrolysis reactor may be configured to operate at a temperature in ° C. of about 250, 275, 300, 325, 350, 375, 400, 425, 450, 475, 500, 525, 550, 575, 600, 625, or 650, e.g., about 500° C., or between about any two of the preceding values, for example, between about 300° C. and about 600° C., between about 350° C. and about 550° C., between about 400° C. and about 500° C., and the like. For example, the pyrolysis reactor 104 may be configured to operate at a temperature between about 300° C. and about 600° C.

[0071] In several embodiments, the pyrolysis reactor 104 may be configured to pyrolyze a biomass 105 to produce a pyrolysis vapor and char. The system 100 further may include a char removal system (not shown) configured to remove the char from the pyrolysis reactor 104. The pyrolysis reactor 104 may be configured to pyrolyze a biomass 105 to produce a pyrolysis vapor. The pyrolysis vapor may include one or more of: water, an organic acid, an aldehyde, a phenol, and a sugar; or one or more derivatives thereof. A heater (not shown) may be operatively coupled to the pyrolysis reactor 104. The heater may be configured to at least one of internally and externally heat pyrolysis reactor 104. The heater may include one or more of a resistive heating element, a combustor, a heat exchanger, or a microwave generator.

[0072] In various embodiments, the catalytic VPR 102 may be configured to receive a pyrolysis vapor. The catalytic VPR 102 may be configured to modify the pyrolysis vapor to produce a modified pyrolysis vapor. The catalytic VPR 102 may be configured to produce a modified pyrolysis vapor by deoxygenating a pyrolysis vapor produced by pyrolyzing a biomass. The catalytic VPR 102 may be configured to produce a modified pyrolysis vapor by cracking or breaking down one or more higher molecular weight components of a



pyrolysis vapor produced by pyrolyzing a biomass. The catalytic VPR **102** may include a catalyst may include one or more of: a granulated catalyst, a powdered catalyst, and a fluid catalytic cracking catalyst (FCC). The catalyst may include one or more of: fresh FCC, spent FCC, catalyst impregnated on top of the fresh FCC, or catalyst impregnated on top of the spent FCC. The catalytic VPR **102** may include the granulated catalyst. The granulated catalyst may be characterized by particle size and flow characteristics substantially similar to the FCC. The catalytic VPR **102** may include a granulated catalyst characterized by a granule size between about 50  $\mu\text{m}$  and about 100  $\mu\text{m}$ . The granulated catalyst may be characterized by a size distribution of granules. A substantial fraction of the size distribution may be greater than about 20  $\mu\text{m}$ . The catalytic VPR **102** may include a catalyst configured to catalyze at least one of: deoxygenation, cracking, water-gas shift, and hydrocarbon formation.

[**0073**] In some embodiments, the pyrolysis reactor **104** and the catalytic VPR **102** may be configured together as a single unit. The quench system **106** may be configured to quench a pyrolysis vapor to form a liquid bio-oil. The quench system **106** may be configured to quench a modified pyrolysis vapor to form a modified bio-oil. The bio-oil may be a low oxygen bio-oil. The quench system **106** may be configured to direct a non-condensable gas into the water gas shift reactor **108**. The water gas shift reactor **108** may be configured to process a non-condensable gas including CO to form at least one of hydrogen and CO<sub>2</sub>. The hydrotreatment system **110** may be configured to accept hydrogen from the water gas shift reactor **108**. The hydrotreatment system **110** may be configured to hydrotreat a bio-oil, e.g., a low oxygen bio-oil, with hydrogen to produce a hydrocarbon fuel product.

[**0074**] The biofuel production system **100** may include a conversion system (not shown). The conversion system may be operatively coupled to the catalytic vapor phase reactor **102**. The conversion system may be operatively coupled to pyrolysis reactor **104**. The conversion system may be operatively coupled to the hydrotreatment system **110**. The conversion system may be configured to produce a hydrocarbon product from biomass **105** by upgrading a bio-oil. The bio-oil may be produced by one or more of: the catalytic vapor phase reactor **102**, the pyrolysis reactor **104**, or the hydrotreatment system **110**. The bio-oil may be a liquid or vapor bio-oil. The bio-oil may be modified or upgraded, e.g., by hydrotreating. The conversion system may be configured to produce at least one of: a hydrocarbon fuel product, a gas, or a chemical.

[**0075**] In various embodiments, a method **201** for catalytic pyrolysis of biomass is provided. The method may include **250** drying a biomass. The method may include **252** pyrolyzing the biomass to create a pyrolysis vapor. The method may include **254** removing at least one of a char and an ash from the pyrolysis vapor. The method may include **256** upgrading the pyrolysis vapor by vapor phase catalysis to produce an upgraded pyrolysis vapor. The method may include **258** condensing a bio-oil from the upgraded pyrolysis vapor.

[**0076**] In various embodiments, pyrolyzing the biomass may be conducted at a temperature in ° C. of about 250, 275, 300, 325, 350, 375, 400, 425, 450, 475, 500, 525, 550, 575, 600, 625, 650, 675, or 700, for example, about 500° C., or between about any two of the preceding values, for example, between about 300° C. and about 700° C., between about 300° C. and about 600° C., between about 350° C. and about 550° C., between about 400° C. and about 500° C., and the like. Upgrading the pyrolysis vapor may be conducted at any

of the temperatures or temperature ranges described herein for pyrolyzing the biomass. Pyrolyzing the biomass and upgrading the pyrolysis vapor may be conducted at about the same temperature, for example, at about substantially the same temperature. Pyrolyzing the biomass and upgrading the pyrolysis vapor may be conducted at different temperatures, for example, at substantially different temperatures.

[**0077**] In some embodiments, pyrolyzing the biomass may be conducted at a biomass residence time of about 2 seconds or less. Pyrolyzing the biomass may be conducted at a biomass residence time of less than about 1 second, for example, about 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, or 0.1 seconds, or less. Pyrolyzing the biomass and upgrading the pyrolysis vapor may be characterized by about the same residence time, for example, about substantially the same residence time. Pyrolyzing the biomass and upgrading the pyrolysis vapor may be characterized by different residence times, for example, substantially different residence times.

[**0078**] In various embodiments, upgrading the pyrolysis vapor by vapor phase catalysis to produce the upgraded pyrolysis vapor may be conducted after pyrolyzing the biomass to create the pyrolysis vapor and removing at least one of the char and the ash from the pyrolysis vapor, and before condensing the bio-oil from the upgraded pyrolysis vapor. The pyrolysis vapor may include one or more of: water, an organic acid, an aldehyde, a phenol, and a sugar; or one or more derivatives thereof.

[**0079**] In some embodiments, pyrolyzing the biomass to create the pyrolysis vapor may include at least one of internally or externally heating a pyrolysis reactor. Pyrolyzing the biomass to create the pyrolysis vapor may include heating by resistive heating, combustion heating, heat exchanging, or microwave irradiation. Upgrading the pyrolysis vapor by vapor phase catalysis may include deoxygenating the pyrolysis vapor to produce the upgraded pyrolysis vapor. Upgrading the pyrolysis vapor by vapor phase catalysis may include cracking one or more higher molecular weight components of the pyrolysis vapor to produce the upgraded pyrolysis vapor. Upgrading the pyrolysis vapor by vapor phase catalysis may include contacting the pyrolysis vapor to one or more of: a granulated catalyst, a powdered catalyst, and a fluid catalytic cracking catalyst (FCC). Upgrading the pyrolysis vapor by vapor phase catalysis may include contacting the pyrolysis vapor to one or more of: fresh FCC, spent FCC, catalyst impregnated on top of the fresh FCC, or catalyst impregnated on top of the spent FCC. Upgrading the pyrolysis vapor by vapor phase catalysis may include contacting the pyrolysis vapor to the granulated catalyst, the granulated catalyst characterized by particle size and flow characteristics substantially similar to the FCC. Upgrading the pyrolysis vapor by vapor phase catalysis may include contacting the pyrolysis vapor to a granulated catalyst characterized by a granule size between about 50  $\mu\text{m}$  and about 100  $\mu\text{m}$ . Upgrading the pyrolysis vapor by vapor phase catalysis may include contacting the pyrolysis vapor to a granulated catalyst characterized by a size distribution of granules. A substantial fraction of the size distribution may be greater than about 20  $\mu\text{m}$ .

[**0080**] In several embodiments, pyrolyzing the biomass and upgrading the pyrolysis vapor may be conducted in a single pyrolysis-catalytic vapor phase reactor unit. The bio-oil may be a low oxygen bio-oil. Pyrolyzing the biomass may include producing a non-condensable including CO. The method may include reacting a non-condensable including CO in a water gas shift reaction to form at least one of



hydrogen and CO<sub>2</sub>. The method may include hydrotreating the bio oil with hydrogen from the water gas shift reaction to produce a hydrocarbon fuel product. The method may include hydrotreating the bio oil with hydrogen to produce a hydrocarbon fuel product.

[0081] In some embodiments, the method may include drying the biomass in a biomass dryer **212**. The method may include placing the biomass in a pyrolysis reactor **204** and pyrolyzing the biomass at about 500° C. to create a pyrolysis vapor. The method may include directing the pyrolysis vapor to a char and ash removal system **214** and removing at least one of a char and an ash from the pyrolysis vapor. The method may include directing the pyrolysis vapor to a catalytic vapor phase reactor **202** and upgrading the pyrolysis vapor to form an upgraded pyrolysis vapor. The method may include directing the upgraded pyrolysis vapor to a condenser **206**. The method may include extracting a bio-oil from the condenser **206**.

[0082] In various embodiments, a catalytic vapor phase reactor apparatus **300** is provided. The apparatus may include: a gas-solid catalytic reactor **302**; a feeding auger **304**; a return auger **306**; a hot blower **308**; a first blower **326**; a second blower **328**; a first cyclone **310**; a second cyclone **312**; a third cyclone **324**; a split connection **314**; a dip leg pipe **316** operatively coupled to the split connection; a fluidized bed reactor **318**; a bypass connection **320**; and a catalyst feeding vessel **322**. The feeding auger **304** and the return auger **306** may be operatively connected to the gas-solid catalytic reactor **302** and the fluidized bed reactor **318**. The first cyclone **310** and the second cyclone **312** may be operatively connected to the gas-solid catalytic reactor **302**. The third cyclone **324** may be operatively connected to the fluidized bed reactor **318**, the first blower **326**, and the second blower **328**.

[0083] In some embodiments, the catalytic vapor phase reactor apparatus may be configured for continuous mode operation. The apparatus may be configured for batch mode operation. The apparatus may be configured to operate using air at atmospheric pressure for catalyst regeneration. The apparatus may be configured for catalyst regeneration without using gases with reduced oxygen content compared to air.

[0084] In various embodiments, catalytic vapor phase reactor apparatus **300** may be configured to operate, at least in part, at a temperature in ° C. of about 250, 275, 300, 325, 350, 375, 400, 425, 450, 475, 500, 525, 550, 575, 600, 625, 650, 675, or 700, for example, about 500° C., or between about any two of the preceding values, for example, between about 300° C. and about 700° C., between about 300° C. and about 600° C., between about 350° C. and about 550° C., between about 400° C. and about 500° C., and the like. In some embodiments, the components of catalytic vapor phase reactor apparatus **300** may be configured to operate at any of the preceding temperatures or temperature ranges, with the exception of hot blower **308**, first blower **326**, and second blower **328**. The catalytic vapor phase reactor apparatus may be configured at least in part to operate at a temperature effective to drive one or more of: a catalytic upgrade reaction, a catalyst regeneration reaction, or a coke oxidation reaction. The catalytic vapor phase reactor apparatus may be configured at least in part to operate at a temperature effective to mitigate condensation of condensable pyrolysis gases.

[0085] In some embodiments, the catalytic vapor phase reactor apparatus may include a heater operatively coupled to gas-solid catalytic reactor **302**. The heater may include one or

more of a resistive heating element, a combustor, a heat exchanger, or a microwave generator.

[0086] In several embodiments, the gas-solid catalytic reactor **302** may be configured to conduct a catalytic upgrade reaction. The gas-solid catalytic reactor **302** may be configured to accept introduction of a granulated catalyst. The gas-solid catalytic reactor **302** may be configured to accept introduction of a pre-upgrade pyrolysis gas. The gas-solid catalytic reactor **302** may be configured to mix the pre-upgrade pyrolysis gas and a catalyst effective to contact the catalyst surface with the pre-upgrade pyrolysis gas. The gas-solid catalytic reactor **302** may be configured to conduct the pre-upgrade pyrolysis gas with a residence time of about 1 second. The gas-solid catalytic reactor **302** may include a raining bed reactor configured to contact the pre-upgrade pyrolysis gas and the catalyst. The gas-solid catalytic reactor **302** may be configured to remove coke from the catalyst by continuous oxidation in air.

[0087] In various embodiments, at least one of the first cyclone **310** and the second cyclone **312** may be configured to receive upgraded pyrolysis gas. The first cyclone **310** and the second cyclone **312** may be configured to operate in series to receive upgraded pyrolysis gas. The first cyclone **310** may be configured to separate an upgraded pyrolysis gas from at least a first portion of a plurality of catalyst particles. The first cyclone **310** may be configured to direct the first portion of the plurality of catalyst particles separated from the upgraded pyrolysis gas to one of: the gas-solid catalytic reactor **302**; or an exit of the catalytic vapor phase reactor apparatus. The first cyclone **310** may be configured to direct upgraded pyrolysis gas to the second cyclone **312**. The second cyclone **312** may be configured to separate the upgraded pyrolysis gas from at least a second portion of the plurality of catalyst particles. The second cyclone **312** may be configured to direct the second portion of the plurality of catalyst particles separated from the upgraded pyrolysis gas to one of: the gas-solid catalytic reactor **302**; or an exit of the catalytic vapor phase reactor apparatus.

[0088] In some embodiments, bed reactor **318** may be operatively connected to at least one of the first blower **326** and the second blower **328**. Feeding auger **304** and return auger **306** may be operatively connected for feeding of a catalyst into the gas-solid catalytic reactor **302** and the fluidized bed reactor **318**. Feeding auger **304** and return auger **306** may be operatively connected for recirculation of catalyst between gas-solid catalytic reactor **302** and fluidized bed reactor **318**.

[0089] In several embodiments, split connection **314** may be configured to direct a catalyst to the fluidized bed reactor **318** for regeneration. Bypass connection **320** may be configured to cause catalyst to bypass fluidized bed reactor **318**. Transfer connection **330** may be configured to direct a catalyst processed in fluidized bed reactor **318** to catalyst feeding vessel **322**.

[0090] In various embodiments, a catalytic vapor phase reactor apparatus **400** is provided. The apparatus may include a housing **402**. The housing **402** may include an auger device **404**, a catalyst inlet **406**, a catalyst outlet **408**, a pyrolysis vapor inlet **410**, and a pyrolysis vapor outlet **412**. The auger device **404** may be configured to transport a solid catalyst through at least a portion of the housing **402**. The housing **402** may be configured to permit a pyrolysis vapor to flow through at least a portion of the housing **402** and come into contact with the solid catalyst.



[0091] In some embodiments, the auger device **404** may be configured to direct the catalyst material and the biomass pyrolysis vapor in counter-current directions. The auger device **404** may be configured to direct the catalyst material and the biomass pyrolysis vapor in concurrent directions. The apparatus may be configured to bring the pyrolysis vapor and the catalyst into contact. The apparatus may be configured within a heated enclosure. The heated enclosure configured to heat to a temperature between about 300° C. and about 700° C., for example, about any temperature or temperature range described herein. The apparatus may be operatively coupled to a catalyst regeneration system, for example as depicted in FIG. 3 in apparatus **300**.

[0092] In various embodiments, a catalytic vapor phase reactor apparatus **500** is provided. The apparatus may include a housing **502**. The housing **502** may include at least one baffle **504**, a catalyst inlet **506**, a catalyst outlet **508**, a pyrolysis vapor inlet **510**, and a pyrolysis vapor outlet **512**. The housing **502** may be at least one of substantially vertical and inclined, for example, with reference to a local direction of gravity. The housing **502** may be configured to permit a solid catalyst to flow through at least a portion of the housing **502** and over at least one baffle **504**. The housing **502** may be configured to permit a pyrolysis vapor to flow through at least a portion of the housing **502** and come into contact with the solid catalyst. The at least one baffle **504** may be angled effective to cause a catalyst to pour off the at least one baffle **504** with the pyrolysis vapor moving through the stream of the solid catalyst. The apparatus further may include a plurality of baffles **504** configured effective to cause a catalyst pouring over the plurality of baffles **504** to form successive curtains of the catalyst while falling between each of the plurality of baffles **504**. The pyrolysis vapor inlet **510** and the pyrolysis vapor outlet **512** may be configured to direct a pyrolysis vapor to flow concurrently with the solid catalyst. The pyrolysis vapor inlet **510** and the pyrolysis vapor outlet **512** may be configured to direct a pyrolysis vapor to flow counter-currently with the solid catalyst. The apparatus may be configured within a heated enclosure. The heated enclosure may be configured to heat to a temperature between about 300° C. and about 700° C., for example, about any temperature or temperature range described herein. The apparatus may be operatively coupled to a catalyst regeneration system, e.g., as described in FIG. 3 and apparatus **300**.

[0093] To the extent that the term “includes” or “including” is used in the specification or the claims, it is intended to be inclusive in a manner similar to the term “comprising” as that term is interpreted when employed as a transitional word in a claim. Furthermore, to the extent that the term “or” is employed (e.g., A or B) it is intended to mean “A or B or both.” When the applicants intend to indicate “only A or B but not both” then the term “only A or B but not both” will be employed. Thus, use of the term “or” herein is the inclusive, and not the exclusive use. See Bryan A. Garner, *A Dictionary of Modern Legal Usage* 624 (2d. Ed. 1995). Also, to the extent that the terms “in” or “into” are used in the specification or the claims, it is intended to additionally mean “on” or “onto.” To the extent that the term “selectively” is used in the specification or the claims, it is intended to refer to a condition of a component wherein a user of the apparatus may activate or deactivate the feature or function of the component as is necessary or desired in use of the apparatus. To the extent that the term “operatively connected” is used in the specification or the claims, it is intended to mean that the identified com-

ponents are connected in a way to perform a designated function. To the extent that the term “substantially” is used in the specification or the claims, it is intended to mean that the identified components have the relation or qualities indicated with degree of error as would be acceptable in the subject industry. As used in the specification and the claims, the singular forms “a,” “an,” and “the” include the plural. Finally, where the term “about” is used in conjunction with a number, it is intended to include  $\pm 10\%$  of the number. In other words, “about 10” may mean from 9 to 11.

[0094] As stated above, while the present application has been illustrated by the description of embodiments thereof, and while the embodiments have been described in considerable detail, it is not the intention of the applicants to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will readily appear to those skilled in the art, having the benefit of the present application. Therefore, the application, in its broader aspects, is not limited to the specific details, illustrative examples shown, or any apparatus referred to. Departures may be made from such details, examples, and apparatuses without departing from the spirit or scope of the general inventive concept.

**1-103.** (canceled)

**104.** A biofuel production system, comprising:

- a catalytic vapor phase reactor (VPR);
- a pyrolysis reactor operatively connected to the catalytic VPR;
- a quench system operatively connected to the catalytic VPR;
- a water gas shift reactor operatively connected to the quench system; and
- a hydrotreatment system operatively connected to the quench system.

**105.** The biofuel production system of claim **1**, the pyrolysis reactor being configured to pyrolyze a biomass to produce a pyrolysis vapor and char, the system further comprising a char removal system configured to remove the char from the pyrolysis reactor.

**106.** The biofuel production system of claim **1**, further comprising a heater operatively coupled to the pyrolysis reactor, the heater being configured to at least one of internally and externally heat pyrolysis reactor to a temperature between about 300° C. and about 600° C.

**107.** The biofuel production system of claim **106**, the heater comprising one or more of a resistive heating element, a combustor, a heat exchanger, or a microwave generator.

**108.** The biofuel production system of claim **1**, the catalytic VPR comprising a catalyst comprising one or more of: a granulated catalyst; a powdered catalyst; a fluid catalytic cracking catalyst (FCC); fresh FCC; spent FCC; catalyst impregnated on top of the fresh FCC; catalyst impregnated on top of the spent FCC;

the granulated catalyst characterized by a granule size between about 50  $\mu\text{m}$  and about 100  $\mu\text{m}$ ;

the granulated catalyst characterized by a size distribution of granules, a substantial fraction of the size distribution being greater than about 20  $\mu\text{m}$ ; and

a catalyst selected to catalyze at least one of: deoxygenation, cracking, water-gas shift, and hydrocarbon formation.

**109.** The biofuel production system of claim **1**, the pyrolysis reactor and the catalytic VPR being configured together as a single unit.



**110.** The biofuel production system of claim 1, further comprising a conversion system operatively coupled to one or more of: the catalytic vapor phase reactor, the pyrolysis reactor, and the hydrotreatment system; the conversion system being configured to produce a hydrocarbon product from biomass by upgrading a bio-oil produced by one or more of: the catalytic vapor phase reactor, the pyrolysis reactor, and the hydrotreatment system.

**111.** A method for catalytic pyrolysis of biomass, the method comprising:

- drying a biomass;
- pyrolyzing the biomass to create a pyrolysis vapor;
- removing at least one of a char and an ash from the pyrolysis vapor;
- upgrading the pyrolysis vapor by vapor phase catalysis to produce an upgraded pyrolysis vapor; and
- condensing a bio-oil from the upgraded pyrolysis vapor.

**112.** The method of claim 111, pyrolyzing the biomass being conducted at one or more of:

- a temperature between about 300° C. and about 600° C.; and
- at a biomass residence time of about 2 seconds or less.

**113.** The method of claim 111, upgrading the pyrolysis vapor by vapor phase catalysis to produce the upgraded pyrolysis vapor being conducted after pyrolyzing the biomass to create the pyrolysis vapor and removing at least one of the char and the ash from the pyrolysis vapor, and before condensing the bio-oil from the upgraded pyrolysis vapor.

**114.** The method of claim 111, the pyrolysis vapor comprising one or more of: water, an organic acid, an aldehyde, a phenol, and a sugar; or one or more derivatives thereof.

**115.** The method of claim 111, upgrading the pyrolysis vapor by vapor phase catalysis comprising one or more of:

- deoxygenating the pyrolysis vapor to produce the upgraded pyrolysis vapor;
- cracking one or more higher molecular weight components of the pyrolysis vapor to produce the upgraded pyrolysis vapor;
- contacting the pyrolysis vapor to one or more of: a granulated catalyst, a powdered catalyst, and a fluid catalytic cracking catalyst (FCC);
- contacting the pyrolysis vapor to one or more of: fresh FCC, spent FCC, catalyst impregnated on top of the fresh FCC, and catalyst impregnated on top of the spent FCC;
- contacting the pyrolysis vapor to the granulated catalyst, the granulated catalyst characterized by particle size and flow characteristics substantially similar to the FCC;
- contacting the pyrolysis vapor to a granulated catalyst characterized by a granule size between about 50 μm and about 100 μm; and
- contacting the pyrolysis vapor to a granulated catalyst characterized by a size distribution of granules, a substantial fraction of the size distribution being greater than about 20 μm.

**116.** The method of claim 111, further comprising one or more of:

- producing a non-condensable gas comprising CO during the pyrolyzing the biomass;
- reacting the non-condensable gas comprising CO in a water gas shift reaction to form at least one of hydrogen and CO<sub>2</sub>; and
- hydrotreating the bio oil with hydrogen from the water gas shift reaction to produce a hydrocarbon fuel product.

**117.** The method of claim 111, comprising:

- drying the biomass in a biomass dryer;
- placing the biomass in a pyrolysis reactor and pyrolyzing the biomass at about 500° C. to create a pyrolysis vapor;
- directing the pyrolysis vapor to a char and ash removal system and removing at least one of a char and an ash from the pyrolysis vapor;
- directing the pyrolysis vapor to a catalytic vapor phase reactor and upgrading the pyrolysis vapor to form an upgraded pyrolysis vapor;
- directing the upgraded pyrolysis vapor to a condenser; and
- extracting a bio-oil from the condenser.

**118.** A catalytic vapor phase reactor apparatus, the apparatus comprising:

- a gas-solid catalytic reactor;
  - a feeding auger;
  - a return auger;
  - a hot blower;
  - a first blower;
  - a second blower;
  - a first cyclone;
  - a second cyclone;
  - a third cyclone;
  - a split connection;
  - a dip leg pipe operatively coupled to the split connection;
  - a fluidized bed reactor;
  - a bypass connection; and
  - a catalyst feeding vessel;
- the feeding auger and the return auger being operatively connected to the gas-solid catalytic reactor and the fluidized bed reactor;
- the first cyclone and the second cyclone being operatively connected to the gas-solid catalytic reactor; and
- the third cyclone being operatively connected to the fluidized bed reactor, the first blower, and the second blower.

**119.** The catalytic vapor phase reactor apparatus of claim 118, further comprising a heater operatively coupled to the gas-solid catalytic reactor, the heater comprising one or more of: a resistive heating element, a combustor, a heat exchanger, and a microwave generator.

**120.** The catalytic vapor phase reactor apparatus of claim 118, the gas-solid catalytic reactor comprising a raining bed reactor configured to contact the pre-upgrade pyrolysis gas and the catalyst.

**121.** The catalytic vapor phase reactor apparatus of claim 118, the fluidized bed reactor being operatively connected to at least one of the first blower and the second blower.

**122.** The catalytic vapor phase reactor apparatus of claim 118, feeding auger and return auger being operatively connected for feeding of a catalyst into the gas-solid catalytic reactor and the fluidized bed reactor, and recirculation of catalyst between gas-solid catalytic reactor and fluidized bed reactor.

**123.** The catalytic vapor phase reactor apparatus of claim 118, comprising a catalyst comprising one or more of: a granulated catalyst; a powdered catalyst; a fluid catalytic cracking catalyst (FCC); fresh FCC; spent FCC; catalyst impregnated on top of the fresh FCC; catalyst impregnated on top of the spent FCC; the granulated catalyst, characterized by a granule size between about 50 μm and about 100 μm; the granulated catalyst, characterized by a size distribution of granules, a substantial fraction of the size distribution being

greater than about 20  $\mu\text{m}$ ; and a catalyst configured to catalyze at least one of: deoxygenation, cracking, water-gas shift, and hydrocarbon formation.

\* \* \* \* \*