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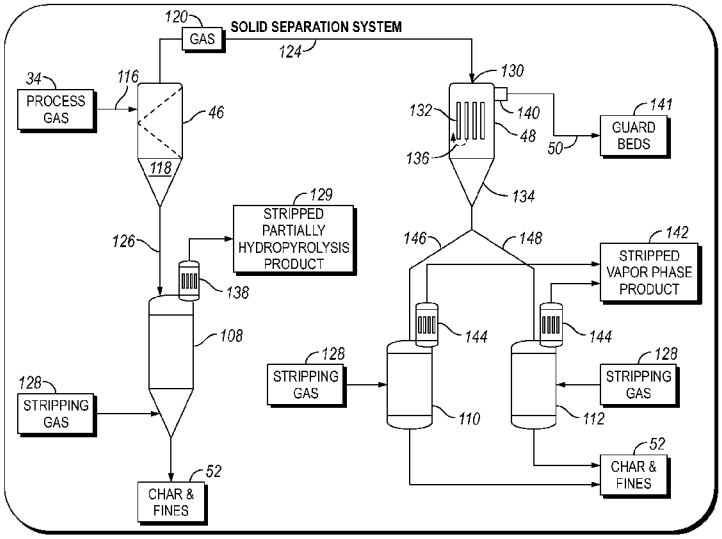


FIG. 2

(57) Abstract: A system for producing liquid hydrocarbon products from a solid feedstock includes a hydropyrolysis reactor that may generate a process gas stream including partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, C_1 - C_3 gases, and solids including char and catalyst fines. The solid feedstock includes biomass, waste plastic, or both. The systems also includes a solid separation system disposed downstream from and fluidly coupled to the hydropyrolysis reactor. The solid separation system may receive the process gas stream and separate the solids from the process gas to generate a vapor phase product and includes a swirl tube separator. The vapor phase product includes the partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, and C_1 -C_3 gases. The system further includes a hydroconversion reactor disposed downstream from and fluidly coupled to the

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solid separation system. The hydroconversion reactor may receive the vapour phase product from the solid separation system and generate a hydrocarbon product from the vapour phase product, the hydrocarbon product includes substantially fully deoxygenated hydrocarbon product, H_2O, CO, CO_2, and C_1 - C_3 gases.

PARTICULATE REMOVAL SYSTEM FOR USE IN HYDROPROCESSING

[0001] The present disclosure generally relates to systems and methods for removal of particulates. More specifically, the present disclosure relates to a solid removal system integrated into a hydroprocessing system, the solid removal system having a swirl tube separator.

BACKGROUND OF THE DISCLOSURE

[0002] The demand for energy is increasing as a result of worldwide economic growth and development. This increase in the demand for energy has contributed to an increase in the amount of greenhouse gases and the overall carbon footprint. In addition, with increasing demand for liquid transportation fuels, decreasing reserves of crude petroleum oil that may be accessed and recovered easily and increasing constraints on carbon footprints of such fuels, it may be desirable to develop routes to produce liquid transportation fuels from renewable resources in an efficient manner. Such liquid transportation fuels produced from biomass are sometimes also referred to as biofuels. Biomass offers a source of renewable carbon. Examples of suitable biomass include vegetable oils, oils obtained from algae and animal fats, deconstruction materials such as pyrolyzed recyclable materials and wood, straws, forestry residues, among others. Therefore, when using fuels derived from renewable resources, it may be possible to achieve more sustainable CO_2 emissions over petroleum-derived fuels. For biofuels to replace all or at least a portion of the carbon-based fossil fuels, the biofuels should meet the required performance and emission specifications of the carbon-based fossil fuels.

[0003] Currently, systems used for removing particulates (e.g., biochar, ash, catalyst fines) from a product gas stream generated in a hydroprocessing reactor include conventional tangential cyclones. For example, existing systems may include one or multiple consecutive conventional tangential cyclones that receive the product gas stream and remove the particulates entrained in the product gas stream. However, the efficiency of these cyclones to remove the entrained particulates from the product gas stream is approximately 99.9%, which is undesirable. Therefore, hydroprocessing systems that use conventional tangential cyclones alone to remove the entrained particulates also include guard beds downstream of the solid removal system to capture and remove the particulates that were not removed by the cyclones. These guard beds are generally large, which increase the complexity of the hydroprocessing system and the overall cost.

Accordingly, it would be advantageous to provide a solid removal system having an improved particulate removal efficiency that may be integrated into hydroprocessing systems without the use of a guard bed or other solid removal systems.

SUMMARY

[0004] In an embodiment, a system for producing liquid hydrocarbon products from a solid feedstock includes a hydropyrolysis reactor that may generate a process gas stream including partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, C_1 - C_3 gases, and solids including char and catalyst fines. The solid feedstock includes biomass, waste plastic, or both. The systems also includes a solid separation system disposed downstream from and fluidly coupled to the hydropyrolysis reactor. The solid separation system may receive the process gas stream and separate the solids from the process gas to generate a vapor phase product and includes a swirl tube separator. The vapor phase product includes the partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, and C_1 -C_3 gases. The system further includes a hydroconversion reactor disposed downstream from and fluidly coupled to the solid separation system. The hydroconversion reactor may receive the vapour phase product from the solid separation system and generate a hydrocarbon product from the vapour phase product, the hydrocarbon product includes substantially fully deoxygenated hydrocarbon product, H_2O, CO, CO_2, and $C_1 - C_3$ gases.

[0005] In another embodiment, a process for producing liquid hydrocarbon products from a solid feedstock including hydropyrolysing the solid feedstock in a first stage hydropyrolysis reactor to generate a process gas stream having partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, C_1 - C_3 gases, and char and catalyst fines. The solid feedstock includes biomass, waste plastic, or a combination thereof. The process also includes feeding the process gas stream to a solid separation system having a swirl tube separator that may separate the char and catalyst fines from the process gas to generate a vapour phase product. The vapour phase product includes the partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, and C_1 -C_3 gases.

[0006] In a further embodiment, a system for producing liquid hydrocarbon products from a solid feedstock including a hydropyrolysis reactor that may generate a process gas stream having partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, C_1 - C_3 gases, and solids having char and catalyst fines, wherein the solid feedstock comprises biomass, waste plastic, or

both; and a solid separation system disposed downstream from and fluidly coupled to the hydropyrolysis reactor. The solid separation system may receive the process gas stream and separate the solids from the process gas to generate a vapor phase product and includes a cyclone and a swirl tube separator, and the vapor phase product includes the partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, and C_1 -C_3 gases.

[0007] Additional features and advantages of exemplary implementations of the disclosure will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by the practice of such exemplary implementations. The features and advantages of such implementations may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features will become more fully apparent from the following description and appended claims, or may be learned by the practice of such exemplary implementations as set forth hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Advantages of the disclosure may become apparent upon reading the following detailed description and upon reference to the drawings in which:

[0009] FIG. 1 is a block diagram of a hydroprocessing system having a first stage and a second stage used to produce hydrocarbons from biomass, whereby the system includes a solid separation system having a cyclone separator and a swirl tube separator, in accordance with an embodiment of the present disclosure; and

[0010] FIG. 2 is a diagram of the solid separation system of FIG. 1, whereby the cyclone separator and the swirl tube separator are arranged in series, in accordance with an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0011] One or more specific embodiments of the present disclosure will be described below. These described embodiments are examples of the presently disclosed techniques. Additionally, in an effort to provide a concise description of these embodiments, not all features of an actual implementation may be described in the specification. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous

implementation-specific decisions will be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one implementation to another. Moreover, it should be appreciated that such a development effort might be complex and time consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

[0012] When introducing elements of various embodiments of the present disclosure, the articles "a," "an," and "the" are intended to mean that there are one or more of the elements. The terms "comprising," "including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements. Additionally, it should be understood that references to "one embodiment" or "an embodiment" of the present disclosure are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features.

[0013] The terms "approximately," "about," and "substantially" as used herein represent an amount close to the stated amount that still performs a desired function or achieves a desired result. For example, the terms "approximately," "about," and "substantially" may refer to an amount that is within less than 10% of, within less than 5% of, within less than 1% of, within less than 0.1% of, and within less than 0.01% of a stated amount.

[0014] The disclosed embodiments include a solid separation system that uses a combination of a cyclone separator (e.g., a conventional tangential cyclone separator) and a swirl tube separator to remove entrained solids/particulates (e.g., biochar) from a process gas generated in a hydroprocessing reactor (e.g., a hydropyrolysis reactor). Hydroprocessing is a catalytic process that includes hydropyrolysis, hydroconversion, and/or hydrotreating of certain carbon-containing materials to generate hydrocarbon fuels. During hydropyrolysis, the carbon-containing materials (e.g., biomass, waste plastic, and other solid feedstock from renewable resources) undergoes partial deoxygenation in the presence of hydrogen under hydropyrolysis conditions. The hydropyrolysis of the solid feedstock generates a process gas having partially deoxygenated hydrocarbons and solids such as char and fines (e.g., ash, catalyst fines, etc.). The solids may be entrained in the process gas when it exists the hydropyrolysis reactor. Therefore, to avoid plugging of flow lines, fouling of downstream equipment, and other undesirable effects, the entrained solids are removed in a solid separation system downstream of the hydropyrolysis reactor. Existing solid

separation systems used in hydroprocessing systems include multiple cyclones (e.g., conventional tangential cyclone separators) that separate the entrained solids from the process gas. However, the separation efficiency of these cyclones is undesirable as a portion of the entrained solids remain in the process gas after passing through the cyclones.

[0015] For example, hydroprocessing systems having cyclones generally remove approximately 99.9% or less of the entrained solids in the process gas exiting the hydropyrolysis reactor. Even when multi-stage cyclone systems are used (e.g., in series), the separation efficiency is not improved beyond 99.9% and an undesirable amount of solids remain entrained in the process gas downstream of the solid separation systems. The entrained solids remaining in the process gas may lead to plugging and/or fouling of downstream equipment and impacts the overall efficiency of hydroprocessing. To mitigate plugging and/or fouling of downstream equipment, one or more guard beds are positioned downstream of the solid separation system to remove entrained solids remaining in the process gas. However, due to the undesirable solid separation efficiency of the cyclones, the downstream guard beds may be large such that they have the capacity to trap the solids remaining in the process gas. This increases the overall cost and complexity of the hydroprocessing system. Accordingly, it is desirable to develop a solid separation system having an improved separation efficiency and decreased overall operational cost compared to existing systems that use cyclones for solid separation. Moreover, by improving the separation efficiency of the solid separation system, a size of the guard beds positioned downstream of the system may be greater than 2 times less than guard beds used in existing systems, and their lifespan may be prolonged compared to existing hydroprocessing systems. For example, guard beds used with the system disclosed herein are such that operational and capital expenses are at least 3 to 5 times lower than in existing systems, the lifespan of the guard beds is at least doubled, and process safety risk is reduced due, in part, to the system having less equipment (e.g., the number of guard beds may be reduced).

[0016] In addition to the large guard beds, separation systems having multiple cyclones have an undesirable solids flux. For example, in multi-stage cyclone separation system a minimum solids flow rate is needed to ensure that the solids move through the system and not plug flow lines. However, second stage cyclones generally have a low solids flux. That is, there are not sufficient solids in the second stage cyclone to maintain the solids in motion. As such, flows lines may

become blocked by the solids. To mitigate the undesirable solids flux in the second stage cyclone, a loop-seal arrangement is provided. The loop-seal arrangement allows for the transfer of separated solids from a first stage cyclone to the second stage cyclone. This transfer of separated solids increases the solids flux in the second stage separator. However, loop-seal arrangements are not robust and may be inefficient and introduce additional complexity to the system. It has been found that by replacing the second stage cyclone with a swirl tube separator (also known as a third stage separator (TSS)), the loop seal is not required to maintain solids in motion. In addition, the separation efficiency of solid separation systems that use a combination of a cyclone in the first stage and a swirl tube separator in the second stage is improved, thereby reducing the size of downstream guard beds, decreasing the overall operational costs, and simplifying system design compared to separation systems having multi-stage cyclones.

[0017] As discussed in further detail below, a separation system having both a cyclone and a swirl tube separator arranged in series is used to removed entrained solids from process gas generated in a hydropyrolysis reactor with improved separation efficiency compared to existing systems. For example, by using a swirl tube separator in the second stage downstream of the cyclone (e.g., first stage separator) the separation efficiency of the solid separation system disclosed herein is improved from 99.9% to greater than 99.99% compared to separation systems having multi-stage cyclones (e.g., first and second stage cyclones). An improvement in the separation efficiency of greater than approximately 0.05% or more results in a desirable decrease in the overall cost of operating the hydroprocessing system compared to systems that use multi-stage cyclones for separating entrained solids. In addition, by using the swirl tube separator in the second stage of the solid separation system disclosed herein, guard beds generally used in existing systems downstream of the solid separation system may be reduced in size or, in some instances, omitted, thereby reducing the complexity of the hydroprocessing systems.

[0018] With the foregoing in mind, **FIG. 1** is a block diagram of an embodiment of a system **10** that includes a swirl tube separator in a solid separation system for providing a process gas that is essentially free of entrained solids. As used herein, the phrase "essentially free of entrained solids" is defined as the presence of less than or equal to 0.01% (or less than 1 milligram (mg)/normal cubic meters (Nm^3)) entrained solids. As should be appreciated, the process gas and other hydroprocessing products disclosed herein may be generated by any suitable hydroprocessing

technique such as those disclosed in U.S. Patent No. 9,447,328, which is hereby incorporated by reference in its entirety. In the illustrated embodiment, the system **10** includes a solid feedstock feeding system **12**, a hydropyrolysis reactor **14** positioned downstream from and fluidly coupled to the solid feedstock feeding system **12**, and a hydroconversion reactor **16** positioned downstream from and fluidly coupled to the hydropyrolysis reactor **14**. As discussed in further detail below, the reactors **14**, **16** are used to convert a solid feedstock **18** into an intermediate hydrocarbon fuel fraction (e.g., a GO/diesel fraction) that may be used to generate a commercially viable biodiesel. As illustrated, the reactors **14**, **16** are disposed within one of two stages. For example, the system **10** includes a first stage **20** and a second stage **24**. The first stage **20** includes the hydropyrolysis reactor **14**, and the second stage **24** includes the hydroconversion reactor **16**.

[0019] The reaction pressure in the first stage **20** and the second stage **24** may be varied to tailor the boiling point distribution and composition of the resultant hydrocarbon product(s) generated by the second stage **24**. The ability to tailor the boiling point distribution and/or composition of the resultant hydrocarbon product by varying the reaction pressure may provide an efficient process for generating commercially viable hydrocarbon biofuels that meet the different requirements set forth by the location and/or market in which the hydrocarbon biofuel will be used. For example, when the reaction pressure is less than approximately 0.6 megapascals (MPa) the occurrence of undesirable olefin and/or aromatic saturation reactions may be decreased and cetane numbers for biodiesel and/or gasoline fractions may be increased compared to reaction pressures above 2.0 MPa. However, the cetane numbers may still not be at a desired level to meet specifications set forth for commercial biodiesel fuels. Therefore, the biodiesel fraction may need to undergo additional processing (e.g., hydropolishing) to upgrade the biodiesel and increase the cetane number above approximately 50. Therefore, in certain embodiments, the hydroprocessing system may include a third stage downstream of the second stage **24** where one or more the biodiesel fraction(s) undergo additional processing.

First Stage

[0020] In the illustrated embodiment, the solid feedstock **18** having biomass (e.g., lignocellulose) and/or waste plastics and molecular hydrogen (H_2) **28** are introduced into the hydropyrolysis reactor **14**. For example, the solid feedstock **18** is fed to the solid feedstock feeding system **12**. The solid feedstock feeding system **12** includes a feeder suitable for feeding solids such as a screw

conveyor, piston feeder, or the like. The solid feedstock feeding system **12** may also include metering or dosing systems downstream from and fluidly coupled to the feeder and the hydropyrolysis reactor **14**. While in the illustrated embodiment, the system **10** has a single hydropyrolysis reactor **14**, it should be appreciated that the system **10** may have multiple hydropyrolysis reactors **14**. In embodiments, in which the system **10** includes multiple hydropyrolysis reactors **14**, the solid feedstock feeding system **12** is fluidly coupled to and provides the solid feedstock **18** to each of the reactors **14**.

[0021] The hydropyrolysis reactor **14** contains a deoxygenation catalyst that facilitates partial deoxygenation of the solid feedstock **18.** For example, in the hydropyrolysis reactor **14**, the solid feedstock **18** undergoes hydropyrolysis, producing a process gas **34** having char, partially deoxygenated products of hydropyrolysis, light gases (C_1 - C_3 gases, carbon monoxide (CO), carbon dioxide (CO_2), and H_2), water (H_2O) vapor and catalyst fines. As discussed above, the partially deoxygenated products of hydropyrolysis are not fully converted and may continue to react with other components in the process gas **34** to form condensates and tars, which may accumulate on surface of equipment downstream of the hydropyrolysis reactor **14**. As discussed in further detail below, controlling the temperature of the process gas **34** such that it is above a condensation temperature mitigates formation of the condensates and tars which facilitates separation of entrained solids (e.g., catalyst fines, char, ash) in the process gas **34**.

[0022] The hydropyrolysis reactor **14** may be a fluidized bed reactor (e.g., a fluidized bubbling bed reactor), fixed-bed reactor, or any other suitable reactor. In embodiments in which the hydropyrolysis reactor **14** is a fluidized bed reactor, the fluidization velocity, catalyst particle size and bulk density, and solid feedstock particle size and bulk density are selected such that the deoxygenation catalyst remains in the bubbling fluidized bed, while the char produced is entrained with the partially deoxygenated products (e.g., the process gas **34**) exiting the hydropyrolysis reactor **14**. As should be appreciated, while the majority of the deoxygenation catalyst remains in the bubbling fluidized bed, attrition of the catalyst particles may occur over time and generate catalyst fines. The catalyst fines may become entrained in the process gas **34** along with the char and other fine solids (e.g., ash).

[0023] The solid feedstock **18** used in the disclosed process may include a residual waste feedstock and/or a biomass feedstock containing lignin, lignocellulosic, cellulosic, hemicellulosic material, or any combination thereof. Lignocellulosic material may include a mixture of lignin, cellulose and hemicelluloses in any proportion and also contains ash and moisture. Suitable lignocellulose-containing biomass includes woody biomass and agricultural and forestry products and residues (whole harvest energy crops, round wood, forest slash, bamboo, sawdust, bagasse, sugarcane tops and trash, cotton stalks, corn stover, corn cobs, castor stalks, Jatropha whole harvest, Jatropha trimmings, de-oiled cakes of palm, castor and Jatropha, coconut shells, residues derived from edible nut, rice husk, rice straw production and mixtures thereof), animal waste and municipal solid wastes containing lignocellulosic material. The municipal solid waste (MSW) may include any combination of lignocellulosic material (yard trimmings, pressure-treated wood such as fence posts, plywood), discarded paper and cardboard and waste plastics, along with refractories such as glass, metal. Prior to use in the process disclosed herein, municipal solid waste may be optionally converted into pellet or briquette form. The pellets or briquettes are commonly referred to as Refuse Derived Fuel in the industry. Certain feedstocks (such as algae and lemna) may also contain protein and lipids in addition to lignocellulose. Residual waste feedstocks are those having mainly waste plastics. In certain embodiments, the solid feedstock **18** may be different ranks of coal, peat or any other suitable solid feedstock that may be fed to a pressurized reactor.

[0024] Suitable means for introducing the solid feedstock **18** into the hydropyrolysis reactor **14** include, but are not limited to, an auger, fast-moving (greater than about 5 minutes (m)/second (sec)) stream of carrier gas (such as inert gases and H_2), and constant-displacement pumps, impellers, turbine pumps, piston feeder, or the like. In an embodiment of the present disclosure, the solid feedstock feeding system **12** includes a double-screw system having a slow screw for metering the solid feedstock **18** followed by a fast screw to push the solid feedstock **18** into the reactor without causing torrefaction in the screw housing used for dosing. An inert gas or hydrogen flow is maintained over the fast screw to further reduce the residence time of the solid feedstock **18** in the fast screw housing.

[0025] The hydropyrolysis step is carried out in the hydropyrolysis reactor **14** at a temperature in the range of from approximately 300 Celsius (°C) and 650 °C, preferably in the range of from

approximately 330 °C to approximately 500 °C, more preferably in the range of from approximately 350 °C to approximately 480 °C, and a pressure in the range of from approximately 0.50 megapascal (MPa) to approximately 7.5 MPa (approximately 5-75 bar). The heating rate of the solid feedstock **18** is preferably greater than about 100 watts/meter^2 (W/m^2). The weight hourly space velocity (WHSV) in grams (g) biomass/g catalyst/hour (h) for the hydropyrolysis step is in the range of from approximately 0.2 h^{-1} to approximately 10 h^{-1}, preferably in the range of from approximately 0.3 h^{-1} to 3 h^{-1}.

[0026] The temperatures used in hydropyrolysis rapidly devolatilize the solid feedstock **18**. Thus, in a preferred embodiment, the hydropyrolysis step includes the use of an active catalyst (e.g., a deoxygenation catalyst) to stabilize the hydropyrolysis vapors. The activity of the catalyst used herein remains high and stable over a long period of time such that it does not rapidly coke. Any deoxygenation catalyst suitable for use in the temperature range of the hydropyrolysis process may be used. Preferably, the deoxygenation catalyst is selected from sulfided catalysts having one or more metals from the group consisting of nickel (Ni), cobalt (Co), molybdenum (Mo) or tungsten (W) supported on a metal oxide. Suitable metal combinations include sulfided NiMo, sulfided CoMo, sulfided NiW, sulfided CoW and sulfided ternary metal systems having any 3 metals from the family consisting of Ni, Co, Mo and W. Monometallic catalysts such as sulfided Mo, sulfided Ni and sulfided W are also suitable for use. Metal combinations for the deoxygenation catalyst used in accordance with certain embodiments of the present disclosure include sulfided NiMo and sulfided CoMo. Supports for the sulfided metal catalysts include metal oxides such as, but not limited to, alumina, silica, titania, ceria and zirconia. Binary oxides such as silica-alumina, silica-titania and ceria-zirconia may also be used. Preferably, the supports include alumina, silica and titania. In certain embodiments, the support contains recycled, regenerated and revitalized fines of spent hydrotreating catalysts (e.g., fines of CoMo on oxidic supports, NiMo on oxidic supports and fines of hydrocracking catalysts containing NiW on a mixture of oxidic carriers and zeolites). Total metal loadings on the deoxygenation catalyst are preferably in the range of from approximately 1.5 weight percent (wt%) to approximately 50 wt% expressed as a weight percentage of calcined deoxygenation catalyst in oxidic form (e.g., weight percentage of Ni (as NiO) and Mo (as MoO_3) on calcined oxidized NiMo on alumina support). Additional elements such as phosphorous (P) may be incorporated into the deoxygenation catalyst to improve the dispersion of the metal.

[0027] The first stage **20** of the process disclosed herein produces the process gas **34** having a partially deoxygenated hydropyrolysis product and entrained solids (e.g., char, ash, catalyst fines). The term "partially deoxygenated" as used herein denotes a material in which at least 30 weight % (wt%), preferably at least 50 wt%, more preferably at least 70 wt% of the oxygen present in the original solid feedstock **18** has been removed. The extent of oxygen removal refers to the percentage of the oxygen in the solid feedstock **18** (e.g., biomass), excluding that contained as free moisture in the solid feedstock **18**. This oxygen is removed in the form of water (H_2O), carbon monoxide (CO) and carbon dioxide (CO_2) in the hydropyrolysis step. Although it is possible that nearly 100 wt% of the oxygen present in the solid feedstock **18** is removed, generally at most 99 wt%, suitably at most 95 wt% will be removed in the hydropyrolysis step.

Solids Removal

[0028] As discussed above, the process gas **34** produced from the hydropyrolysis step in the hydropyrolysis reactor **14** is a mixed solid and vapor product that includes biochar, ash, catalyst fines, partially deoxygenated hydropyrolysis product, light gases (C_1 - C_3 gases, CO, CO_2, hydrogen sulfide (H_2S), ammonia (NH_3) and H_2), H_2O vapor, vapors of C_{4+} hydrocarbons and oxygenated hydrocarbons. Biochar, ash, and catalyst fines are entrained with the vapor phase product. Therefore, between the hydropyrolysis and hydroconversion steps, the first stage **20** and the second stage **24**, respectively, biochar and catalyst fines are removed from the vapor phase product (e.g., the partially deoxygenated hydropyrolysis product) in the solid separation system **42**. Any ash present may also be removed at this stage.

[0029] In existing systems, the biochar, ash, and catalyst fines entrained in the process gas **34** are removed via multi-stage cyclones (e.g., first and second stage cyclones). However, as discussed above cyclone separation alone does not provide the desired separation efficiency. For example, the separation efficiency of a separation system having multi-stage cyclones is such that greater than approximately 0.05% solids remain entrained in the resultant vapor phase product after having passed through the cyclone(s). This amount of entrained solids may have an undesirable impact on the overall efficiency of the hydroprocessing process. For example, the remaining entrained solids may plug and/or foul downstream equipment. As such, hydroprocessing systems that utilize first and second stage cyclones to remove entrained solids also include one or more guard beds downstream of the cyclones to capture and remove the remaining solids from the process gas **34**.

The guard beds, however, are large due to the amount of solids remaining in the resultant vapor phase product. The inefficient separation of solids from the process gas **34** when using first and second stage cyclones, and the addition of large guard bed designs, increase the overall cost and complexity of hydroprocessing systems. However, by replacing the second stage cyclone with a swirl tube separator, the separation efficiency of the solid separation system **42** is improved from approximately 99.9% to greater than approximately 99.99% compared to solid separation systems having first and second stage cyclones. Due to the improved separation efficiency of the disclosed solid separation system **42**, a size of the guard bed are more than 2 times less than guard beds used in existing systems. The improved separation efficiency of the solid separation system **42** also increases the cycle length of the overall system **10** before shutdown may be required for maintenance compared to existing systems. For example, without the solid separation system **42** disclosed herein, downstream guard beds may need to be replaced or cleaned due to the amount of solid carryover in the gas exiting the separation systems. Therefore, because the downstream guard beds are saturated with solids removed from the process gas, the amount of time the system may be operated before having to shutdown for maintenance/cleanup of the guard beds is shorter compared to systems having the disclosed separation system **42**. Accordingly, the improved separation efficiency of the separation system **42** results in reduced operational and capital costs for hydroprocessing systems.

[0030] Accordingly, the disclosed solid separation system **42** includes a cyclone **46** in a first stage and a swirl tube separator **48** in a second stage downstream from the first stage that remove the biochar and other solids in the process gas **34** to generate a vapor phase product **50**. The vapor phase product **50** is essentially free (e.g., less than approximately 0.01%) of entrained solids. For example, as illustrated in **FIG. 1**, the process gas **34** is fed to the solid separation system **42** in which the cyclone **46** separates/removes a portion of the entrained solids (e.g., biochar, ash, and catalyst fines **52**) from the process gas **34** and the swirl tube separator **48** removes the remaining portion of the entrained solids resulting in the vapor phase product **50**. The first portion of the entrained solids may have a particle size greater than approximately 30 microns (μm). However, because biochar is soft, it may attrit into particles having a particle size less than 30 μm. For example, the remaining entrained solids in the process gas **34** that has passed through the cyclone **46** may have particles having a particle size of between approximately 1 μm and 29 μm.

[0031] As discussed in further detail below, by incorporating the swirl tube separator **48** in the second stage downstream of the first stage cyclone **46**, the solid separation system **42** of the present disclosure removes greater than approximately 99.99% of the entrained solids from the process gas **34**. In certain embodiments, the vapor phase product **50** may pass through a guard bed disposed downstream of the solid separation system **42** to remove residual solids (e.g., solids having a particle size of less than approximately 5 μm) remaining in the vapor phase product **50**. However, unlike existing systems, guard beds used in conjunction with the separation system **42** disclosed herein have a smaller design compared to guard beds used in hydroprocessing systems that do not use a swirl tube separator to remove biochar. The smaller guard bed design is due to the higher amount of entrained solids being removed from the process gas **34** in the separation system **42** compared to systems whose separation system does not include the swirl tube separator **48**. As such, a capacity of the downstream guard beds may be reduced as the amount of solids in the vapor phase product **50** is less than an amount of solids in a vapor phase product generated in a separation system that does not include the swirl tube separator **48**.

Second Stage

[0032] Following removal of the biochar and catalyst fines **52**, the vapor phase product **50** (e.g., the partially deoxygenated hydropyrolysis product) together with the H_2, CO, CO_2, H_2O, and C_1 - C_3 gases from the hydropyrolysis step (e.g., the first stage **20**) are fed into the hydroconversion reactor **16** in the second stage **24** and subjected to a hydroconversion step. The hydroconversion step is carried out at a temperature in the range of from approximately 300 °C to approximately 600 °C and a pressure in the range of from approximately 0.1 MPa to approximately 5 MPa. As should be noted, pressures higher than 0.6 MPa may be used to tailor the boiling point distribution and composition of the resultant hydrocarbon product based on the desired specifications of the hydrocarbon fuel produced by the hydroprocessing. The weight hourly space velocity (WHSV) for this step is in the range of approximately 0.1 h^{-1} to approximately 2 h^{-1}. The hydroconversion reactor **16** is a fixed bed reactor. However, in certain embodiments, the hydroconversion reactor **16** may be a fluidized bed reactor. The vapor phase product **50** undergoes hydroconversion in the presence of a hydroconversion catalyst to generate a fully deoxygenated hydrocarbon product **58**. The term "fully deoxygenated" as used herein denotes a material in which at least 98 wt%, preferably at least 99 wt%, more preferably at least 99.9 wt% of the oxygen present in the original

solid feedstock **18** (e.g., lignocelluloses-containing biomass) has been removed. The hydrocarbon product **58** contains light gaseous hydrocarbons, such as methane, ethane, ethylene, propane and propylene, naphtha range hydrocarbons, middle-distillate range hydrocarbons, hydrocarbons boiling above 370 °C (based on ASTM D86), hydrogen and by-products of the hydroconversion reactions such as H_2O, H_2S, NH_3, CO and CO_2.

[0033] The solid feedstock **18** used in the disclosed processes may contain metals such as, but not limited to, sodium (Na), potassium (K), calcium (Ca) and phosphorus (P). These metals may poison the hydroconversion catalyst used in the second stage **24**. However, these metals may be removed with the char and ash products (e.g., the char and catalyst fines **52**) in the first stage **20**. Accordingly, the hydroconversion catalyst used in the hydroconversion step is protected from Na, K, Ca, P, and other metals present in the solid feedstock **18** which may otherwise poison the hydroconversion catalyst. Moreover, by hydropyrolysis of the solid feedstock **18** in the first stage **20**, the hydroconversion catalyst is advantageously protected from olefins and free radicals. The conditions under which hydropyrolysis occurs in the first stage **20** stabilize free radicals generated during high temperature devolatilization of the solid feedstock **18** (e.g., biomass) by the presence of hydrogen and catalyst, thereby generating stable hydrocarbon molecules that are less prone to, for example, coke formation reactions which may deactivate the hydroconversion catalyst.

[0034] The hydroconversion catalyst used in the hydroconversion step includes any suitable hydroconversion catalyst having a desired activity in the temperature range of the disclosed hydroconversion process. For example, the hydroconversion catalyst is selected from sulfided catalysts having one or more metals from the group consisting of Ni, Co, Mo or W supported on a metal oxide. Suitable metal combinations include sulfided NiMo, sulfided CoMo, sulfided NiW, sulfided CoW and sulfided ternary metal systems having any three metals from the family consisting of Ni, Co, Mo and W. Catalysts such as sulfided Mo, sulfided Ni and sulfided W are also suitable for use. The metal oxide supports for the sulfided metal catalysts include, but are not limited to, alumina, silica, titania, ceria, zirconia, as well as binary oxides such as silica-alumina, silica-titania and ceria-zirconia. Preferred supports include alumina, silica and titania. The support may optionally contain regenerated and revitalized fines of spent hydrotreating catalysts (e.g., fines of CoMo on oxidic supports, NiMo on oxidic supports and fines of hydrocracking catalysts containing NiW on a mixture of oxidic carriers and zeolites). Total metal loadings on the catalyst

are in the range of from approximately 5 wt% to approximately 35 wt% (expressed as a weight percentage of calcined catalyst in oxidic form, e.g., weight percentage of nickel (as NiO) and molybdenum (as MoO_3) on calcined oxidized NiMo on alumina catalyst). Additional elements such as phosphorous (P) may be incorporated into the catalyst to improve the dispersion of the metal. Metals can be introduced on the support by impregnation or co-mulling or a combination of both techniques. The hydroconversion catalyst used in the hydroconversion step may be, in composition, the same as or different to the deoxygenation catalyst used in the hydropyrolysis step (e.g., first stage **20**). In one embodiment of the present disclosure, the hydropyrolysis catalyst includes sulfided CoMo on alumina support and the hydroconversion catalyst includes sulfided NiMo on alumina support.

[0035] Following the hydroconversion step, the fully deoxygenated hydrocarbon product **58** is fed to one or more condensers that condenses the hydrocarbon product **58**. The condensed hydrocarbon product **58** is fed to a gas-liquid separator **60** to provide a liquid phase product **64** having substantially fully deoxygenated C_{4+} hydrocarbon liquid and aqueous material. The term "substantially fully deoxygenated" is used herein to denote a material in which at least 90 wt% to 99 wt% of the oxygen present in the original lignocellulose containing biomass (e.g., the solid feedstock **18**) has been removed. Accordingly, the resulting liquid phase product **64** (e.g., the substantially fully deoxygenated hydrocarbon C_{4+} liquid) contains less than 2 wt%, preferably less than 1 wt%, and most preferably less than 0.1 wt% oxygen. The substantially fully deoxygenated C4+ hydrocarbon liquid is compositionally different from bio-oil that is generated using other low pressure hydroprocesses. For example, the oxygen content of bio-oil is greater (e.g., between approximately 5 wt% to 15 wt%) compared to the liquid phase product **64** (e.g., less than 2 wt%). Therefore, due, in part, to the lower oxygen content of the liquid phase product **64**, an amount of acid components (as measured by total acid number) and polar compounds is decreased compared to the bio-oil. By way of non-limiting example, the acid components include carboxylic acids, phenols and mixtures thereof.

[0036] The hydrocarbon product **58** undergoes a separation process in the gas-liquid separator **60** that separates and removes the aqueous material from the substantially fully deoxygenated C_{4+} hydrocarbon liquid. Any suitable phase separation technique may be used to separate and remove the aqueous material from the substantially fully deoxygenated C_{4+} hydrocarbon liquid, thereby

generating the liquid phase product **64** having the substantially fully deoxygenated C_{4+} hydrocarbon and non-condensable gases **68**. The non-condensable gases **68** include mainly H_2, CO, CO_2 and light hydrocarbon gases (typically C_1 to C_3 and may also contain some C_{4+} hydrocarbons).

[0037] In certain embodiments, the non-condensable gases **68** are fed to a gas clean-up system **70**. The gas clean-up system **70** removes H_2S **74**, NH_3 **76** and trace amounts of organic sulfur-containing compounds, if present, as by-products of the process, thereby generating a hydrocarbon stream **80** having CO, CO_2, H_2 and the light hydrocarbon gases. The gas clean-up system **70** includes one or more process units that remove the H_2S **74** and the NH_3 **76** from the non-condensable gases **68** as by-products of the process. The hydrocarbon stream **80** may be sent to a separation, reforming and water-gas shift section **82** where the hydrogen **28** is produced from the light hydrocarbon gases in the hydrocarbon stream **80** and renewable CO_2 **84** is discharged as a by-product of the process. A fuel gas stream may be recovered as a by-product of this process. The produced hydrogen **28** may be re-used in the process. For example, the hydrogen **28** may be recycled to the hydropyrolysis reactor **14** in the first stage **20**. Sufficient hydrogen is produced for use in the entire process disclosed herein. That is, the quantity of the hydrogen **28** produced by the separation, reforming and water-gas shift section **82** is equal to or greater than the hydrogen required to maintain fluidization and sustain chemical consumption of hydrogen in the process.

[0038] The liquid phase product **64** recovered from the gas-liquid separator **60** is fed to a product recovery section **86**. In the product recovery section **86**, aqueous product **90** is removed from the liquid phase product **64** to generate an intermediate liquid phase product **92**. The intermediate liquid phase product **92** may undergo distillation to separate the substantially fully deoxygenated C_{4+} hydrocarbon liquid into fractions according to ranges of the boiling points of the liquid products contained in the intermediate liquid phase product **92**. For example, the substantially fully deoxygenated C_{4+} hydrocarbon liquid in the intermediate liquid phase product **92** includes naphtha range hydrocarbons, middle distillate range hydrocarbons (e.g., gas oil, diesel) and vacuum gasoil (VGO) range hydrocarbons. Accordingly, in the illustrated embodiment, the intermediate liquid product **92** is fed to a distillation unit **94** to recover gasoline product **96** and a distillate product **98** (e.g., a middle distillate). In certain embodiments, kerosene/jet fuel **100** are recovered as separate streams from the distillation unit **94**. The distillate product **98** (e.g., the

middle distillate) contains gas oil (GO), for example biodiesel, and is substantially fully free from oxygen, sulfur and nitrogen.

Solid Separation System

[0039] As discussed above, the solid separation system **42** uses the cyclone **46** in the first separation stage and the swirl tube separator **48** in the second separation stage to remove greater than 99.99% of the entrained solids from the process gas **34**. **FIG. 2** is a schematic of the solid separation system **42** of the present disclosure. As shown in the illustrated embodiment, in addition to the cyclone **46** and the swirl tube separator **48**, the solid separation system **42** includes a first vessel **108**, a second vessel **110**, and a third vessel **112**. The first vessel **108** is downstream of and fluidly coupled to the cyclone **46**, and the vessels **110**, **112** are downstream of and fluidly coupled to the swirl tube separator **48**. Additional vessels **108**, **110**, **112** may be used without departing from the scope of the present disclosure. The vessels **108**, **110**, **112** receive solids (e.g., the biochar and fines **52**) removed from the process gas **34**. For example, in operation, the process gas **34** exiting the hydropyrolysis reactor (e.g., the hydropyrolysis reactor **14**) flows into the cyclone **46** (e.g., a tangential cyclone separator) through conduit **116**. The process gas **34** flows within the cyclone **46** in a manner that causes the entrained solids to separate from the process gas **34** and fall into a bottom section **118** of the cyclone **46**. A gas **120** containing the vapor product (e.g., partially deoxygenated hydropyrolysis product, light gases (C_1 - C_3 gases, CO, CO_2, hydrogen sulfide (H_2S), ammonia (NH_3) and H_2), H_2O vapor, vapors of C_{4+} hydrocarbons and oxygenated hydrocarbons) having a reduced amount (e.g., 0.1 wt.%) of entrained solids exits the cyclone **46** and flows into the swirl tube separator **48** via conduit **124**.

[0040] The solids separated from the process gas **34** exit the cyclone **46** through conduit **126** and flow into the first vessel **108**. Once an amount of solids in the first vessel **108** reaches a desired level, the solids are removed from the first vessel **108**. The solids (e.g., biochar) may contain residual partially deoxygenated hydropyrolysis product that is trapped between interstitial spaces of the solids. A stripping gas **128** is injected into the first vessel **108** to recover the partially deoxygenated hydropyrolysis product. For example, the stripping gas **128** strips off the partially deoxygenated hydropyrolysis product from the solids, thereby generating a stripped partially deoxygenated hydropyrolysis product **129**. The stripped partially deoxygenated hydropyrolysis product **129** may be reintroduced to the cyclone **46** by injecting into the conduit **116** and mixing

with the process gas **34**. In other embodiment, the stripped partially deoxygenated hydropyrolysis product **129** may be directed to the swirl tube separator **48** by, for example, injecting into the conduit **124** and mixing with the gas **120**. As should be noted, the stripped partially deoxygenated hydropyrolysis product **129** may be fed to the cyclone **46**, the swirl tube separator **48**, or both through a dedicated line. That is, the stripped partially deoxygenated hydropyrolysis product **129** may be directly fed into the cyclone **46**, the swirl tube separator **48**, or both without mixing with the process gas **34** or the gas **120**, respectively. In one embodiment, the stripped partially deoxygenated hydropyrolysis product **129** may be fed to a hydropyrolysis reactor (e.g., the hydropyrolysis reactor **14**). In another embodiment, the stripped deoxygenated hydropyrolysis product **129** may be fed to a hydroconversion reactor (e.g., the hydroconversion reactor **16**). By recovering and feeding the stripped partially deoxygenated hydropyrolysis product **129** back to the hydropyrolysis reactor or hydroconversion reactor, hydrocarbon loss may be reduced. The stripped partially deoxygenated hydropyrolysis product **129** may flow through a filter **138** to remove any residual entrained solids before feeding to the cyclone **46**, the swirl tube separator **48**, the hydropyrolysis reactor, or a combination thereof. By way of non-limiting example, the stripping gas **128** may be carbon dioxide, nitrogen, hydrogen, or any other suitable gas and combinations thereof. The cyclone **46** may be fluidly coupled to multiple vessels **108**. For example, the cyclone **46** may be fluidly coupled to 1, 2, 3, 4, 5, 6, or more vessels **108** operating in series to allow for continuous operation of the hydroprocessing system. In embodiments in which multiple vessels **108** are used to collect the separated solids from the cyclone **46**, the vessels may be arranged in series, parallel, or both (e.g., a portion may be arranged in series and another portion arranged in parallel).

[0041] While the cyclone **46** removes approximately 99.9% of the entrained solids from the process gas **34**, an undesirable amount of solids still remain entrained in the separated gas (e.g., the gas **120**). However, by providing the gas **120** to the swirl tube separator **48**, the remaining solids are removed such that the vapor phase product **50** exiting the solids separation system **42** is essentially free of solids (e.g., contains less than approximately 0.01% solids). In the illustrated embodiment, the gas **120** is provided to the swirl tube separator **48** through an axial inlet **130**. The swirl tube separator **48** includes features that cause the gas **120** to swirl in a downward direction (e.g., a direction away from the inlet **130**). For example, the swirl tube separator **48** includes a plurality of swirl vanes **132** that impart centrifugal forces to the entrained solids in the gas **120**,

which causes them to move toward and impinge on walls of the swirl tube separator **48**. Impingement of the solids on the walls of the swirl tube separator **48** decreases their velocity causing them to fall toward a swirl tube bottom section **134** and separate from the gas **120**. As the gas **120** reaches the exit of the swirl vanes **132**, the lighter components in the gas **120** change flow directions (e.g., make a U-turn), as shown by arrow **136**, and flow in an upward direction (e.g., a direction toward the inlet **130**). Entrained solids that remain in the gas **120** are unable to make the directional change due to their weight and gravitational forces. As such, the entrained solids fall into the swirl tube bottom section **134**, thereby generating the vapor phase product **50**. The vapor phase product **50** that is essentially free of solids exits the swirl tube separator **48** at an outlet **140** located at a top of the swirl tube separator **48** (e.g., near the inlet **130**). After exiting the swirl tube separator **48**, the vapor phase product **50** may flow through a guard bed **141** to remove any residual solids.

[0042] The separated solids collected in the swirl tube bottom section **134** are transferred to one or both of the vessels **110**, **112** via conduits **146**, **148**, respectively. While in the illustrated embodiment, the vessels **110**, **112** are arranged in a parallel configuration, in certain embodiments the vessels **110**, **112** may be arranged in series. Any number of vessels **110**, **112** may be used without departing from the scope of the present disclosure. For example, the solid separation system may have 1, 2, 3, 4, or more vessels **110, 112**. Similar to the solids in the first vessel **108**, the solids contained in the vessels **110**, **112** may have trapped vapor phase product **50**. Accordingly, the stripping gas **128** is injected into the respective vessel **110**, **112** to strip and recover the vapor phase product **50** from the solids, thereby generating a stripped vapor phase product **142**. The stripped vapor phase product **142** may be fed to the swirl tube separator **48** via the conduit **124** or through a dedicated line. In certain embodiment, the stripped vapor phase product **142** may be fed to the hydropyrolysis reactor (e.g., the hydropyrolysis reactor **14**), a hydroconversion reactor (e.g., the hydroconversion reactor **16**), or both. The stripped vapor phase product **142** may contain residual entrained solids. Therefore, prior to feeding the stripped vapor phase product **142** to the respective system component (e.g., the swirl tube separator **48**, the hydroconversion reactor **16**, or other component), the stripped vapor phase product **142** may flow through a filter **144** to remove the residual entrained solids.

[0043] To provide efficient separation of the entrained solids remaining in the gas **120**, a velocity of the gas **120** as it exits the swirl vanes **132** should be higher than the inlet velocity (e.g., the velocity at the inlet **130**) of the gas **120** as it enters the swirl tube separator **48**. Existing systems (e.g., catalytic crackers) that use swirl tube separators to remove solids require inlet velocities above 45 meters/second (m/s) (0.72 actual cubic meter per second (ACMS)). However, as discussed above, biochar is soft and may easily attrite into smaller particles during separation. At inlet velocities above approximately 45 m/s (0.72 ACMS), the particle size of the solids may be reduced from greater than approximately 30 microns (μm) down to less than approximately 26 μm due to attrition caused by the solids impinging the walls of the swirl tube separator **48**. The smaller biochar particles may be difficult to remove and the removal efficiency of the solid separation **42** may be undesirable. Therefore, the velocity of the gas **120** should be such that the separation efficiency of the swirl tube separator **48** is maintained and attrition of the solids is mitigated. By way of non-limiting example, the inlet velocity of the gas **120** at the inlet **130** is between approximately 0.40 and 1.0 actual cubic meters/second (ACMS). For example, the inlet velocity of the gas **120** may be between approximately 0.45 and 0.75 ACMS, approximately 0.50 and 0.65 ACMS, or 0.55 and 0.60.

[0044] In addition to having an optimized velocity that mitigates attrition of the solids, the solids should be kept in motion to facilitate separation and avoid undesirable accumulation in components of the swirl tube separator **48**. An underflow gas is also provided to the swirl tube separator **48** to move the solids from the swirl tube separator bottom section **134** through the outlet **140** and into the vessel **110**, **112**. In accordance with an embodiment of the present disclosure, approximately 0.40% to approximately 4.0% of an underflow gas is provided to the swirl tube separator **48**. For example, the underflow gas may be between 0.45% to 3.5%, 0.50% to 3.0%, 0.60% to 2.0%, or 0.80 to 1.0%. As should be noted, the amount of underflow gas and the inlet gas velocities used to maintain the remaining entrained solids in motion and for their removal, respectively, when using the swirl tube separator **48** are lower than those used in other systems (e.g., catalytic crackers) that utilize swirl tube separators. Surprisingly, at the lower amount of underflow gas and inlet gas velocities used in the second separation stage, the separation efficiency of the swirl tube separator was maintained at desirable levels. The separation efficiency of the swirl tube separator **48** at an inlet gas velocity between 0.40 and 1.0 ACMS and an amount of underflow gas between 0.40% and 4.0% is between approximately 95% and 98%.

[0045] As discussed above, the process gas **34** includes partially deoxygenated hydropyrolysis product and catalyst fines. The partially deoxygenated hydropyrolysis product may continue to react while in the solid separation system **42** which may lead to coking and formation of tars and condensates. The tars and condensates may collect on and plug conduits (e.g., the conduit **124**), inlets (e.g., the inlets **126**), and outlets. As such, a temperature of the process gas **34** and gas **120** is maintained above their respective condensation temperatures to avoid coking and formation of condensates and tars. In addition, in certain embodiments, the temperature of the gas **34**, **120** is maintained above a desublimation temperature of the salts (e.g., ammonia chloride (NH_4Cl) present to mitigate degradation of the solid separation system **42** and other system components that may decrease their overall performance. For example, if the temperature of the gas **34**, **120** is below the desublimation temperature, corrosive salts may sublime and collect on portions of the cyclone **46** and/or swirl tube separator **48**, thereby fouling their respective surfaces, blocking flow of the gas **120**, and decreasing the overall performance of the solid separation system **42**.

[0046] To test the separation efficiency of the swirl tube separator (e.g., the swirl tube separator **48**), a gas stream containing between 0 and 1200 milligrams/cubic meter (mg/m^3) biochar was feed into a swirl tube separator test unit having a filter that collects the biochar separated from the gas stream. The flow conditions were allowed to stabilized before measuring a pressure drop across various locations of the test unit. The gas stream was feed into the test unit for a predetermined period of time after which the flow of the gas stream was stopped. Air was feed into the test unit for 10 minutes to ensure fines that may have adhered to walls of the test unit are transported to the filters. The filters are removed, dried for 4 hours at 51 °C, and weighed to determine the amount of biochar collected on the filters. The separation efficiency was determined as follows – (mass of biochar in gas stream – mass of biochar collected on filter)/mass of biochar in gas stream. As shown in Table 1, the separation efficiency of the swirl tube separator test unit at various gas inlet velocities and amounts of overflow gas is greater than 96%.

Table 1. Separation Efficiency of Second Stage Swirl Tube Separator

RUN NO.	FEED GAS FLOW RATE (ACMS)	FEED SOLIDS LOADING (mg/m^3)	UNDERFLOW GAS FLOW FRACTION OF FEED	TSS EFFICIENCY (%)
1	0.64	1172	3%	96.76%
2	0.71	847	3%	96.99%
3	0.42	904	3%	97.11%
4	0.42	951	0.50%	96.53%
5	0.5	921	0.50%	95.86%
6	0.42	847	0.00%	96.14%
7	0.42	335	0.50%	97.15%
8	0.42	914	0.50%	96.72%

[0047] As discussed above, the solid separation system disclosed herein includes a cyclone in a first stage in combination with a swirl tube separator in a second stage to remove entrained solids/particulates from a process gas generated in a hydropyrolysis processes in an efficient manner without the use of additional cyclones (e.g., second and third stage cyclones) and large guard bed designs compared to existing hydroprocessing systems. The disclosed system also removes the requirement of a loop seal to mitigate low solid flux when using second or multi-stage cyclones. Moreover, gas inlet velocities and underflow gas generally used in swirl tube separators was reduced without impacting separation efficiency. By replacing second stage cyclones used in existing hydroprocessing systems with a swirl tube separator, the removal efficiency of solids of the solid separation system may be improved, smaller guard bed designs may be used, and the overall cost of the hydroprocessing system and process may decreased compared to existing hydroprocessing systems that use cyclones.

[0048] The present disclosure may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the disclosure is, therefore, indicated by the appended claims rather than by the foregoing description. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.

CLAIMS

We claim:

1. A system for producing liquid hydrocarbon products from a solid feedstock comprising:

a hydropyrolysis reactor configured to generate a process gas stream comprising partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, C_1 - C_3 gases, and solids comprising char and catalyst fines, wherein the solid feedstock comprises biomass, waste plastic, or both;

a solid separation system disposed downstream from and fluidly coupled to the hydropyrolysis reactor, wherein the solid separation system is configured to receive the process gas stream and to separate the solids from the process gas to generate a vapor phase product and comprises a swirl tube separator, and wherein the vapor phase product comprises the partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, and C_1 -C_3 gases; and

a hydroconversion reactor disposed downstream from and fluidly coupled to the solid separation system, wherein the hydroconversion reactor is configured to receive the vapour phase product from the solid separation system and to generate a hydrocarbon product from the vapour phase product, wherein the hydrocarbon product comprises substantially fully deoxygenated hydrocarbon product, H_2O, CO, CO_2, and C_1 – C_3 gases.

2. The system of claim 1, wherein the solid separation system comprises a cyclone disposed upstream from and fluidly coupled to the swirl tube separator, and wherein the cyclone is configured to remove a first portion of the solids from the process gas and the swirl tube separator is configured to remove a second portion of the solids from the process gas to generate the vapor phase product.

3. The system of claim 2, comprising a first vessel disposed downstream from and fluidly coupled to the cyclone and configured to receive the first portion of the solids separated from the process gas.

4. The system of claim 3, comprising a second vessel and a third vessel disposed downstream

from and fluidly coupled to the swirl tube separator, wherein the second vessel and the third vessel are configured to receive the second portion of the solids separated from the process gas.

5. The system of claim 2, comprising one or more guard beds disposed between the solid separation system and the hydroconversion reactor.

6. The system of claim 1, wherein the vapor phase product has less than 0.01 wt.% solids.

7. A process for producing liquid hydrocarbon products from a solid feedstock comprising:

hydropyrolysing the solid feedstock in a first stage hydropyrolysis reactor to generate a process gas stream comprising partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, C_1 - C_3 gases, and char and catalyst fines, wherein the solid feedstock comprises biomass, waste plastic, or a combination thereof; and

feeding the process gas stream to a solid separation system comprising a swirl tube separator configured to separate the char and catalyst fines from the process gas to generate a vapour phase product, wherein the vapour phase product comprises the partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, and C_1 -C_3 gases.

8. The process of claim 7, comprising feeding the process gas to a cyclone disposed within the solid separation system, wherein the cyclone is upstream from and fluidly coupled to the swirl tube separator.

9. The process of claim 8, wherein the cyclone is configured to remove a first portion of the char and catalyst fines from the process gas.

10. The process of claim 9, wherein the swirl tube separator is configured to remove a second portion of the char and catalyst fines from the process gas to generate the vapor phase product.

11. The process of claim 7, wherein the vapor phase product has a solids content of less than approximately 0.01 wt.%.

12. A system for producing liquid hydrocarbon products from a solid feedstock comprising:

a hydropyrolysis reactor configured to generate a process gas stream comprising partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, C_1 - C_3 gases, and solids comprising char and catalyst fines, wherein the solid feedstock comprises biomass, waste plastic, or both; and

a solid separation system disposed downstream from and fluidly coupled to the hydropyrolysis reactor, wherein the solid separation system is configured to receive the process gas stream and to separate the solids from the process gas to generate a vapor phase product and comprises a cyclone and a swirl tube separator, and wherein the vapor phase product comprises the partially deoxygenated hydropyrolysis product, H_2O, H_2, CO_2, CO, and C_1 -C_3 gases.

13. The system of claim 12, wherein the cyclone is disposed upstream from and fluidly coupled to the swirl tube separator, and wherein the cyclone is configured to remove a first portion of the solids from the process gas and the swirl tube separator is configured to remove a second portion of the solids from the process gas to generate the vapor phase product.

14. The system of claim 12, comprising a hydroconversion reactor disposed downstream from and fluidly coupled to the solid separation system, wherein the hydroconversion reactor is configured to receive the vapour phase product from the solid separation system and to generate a hydrocarbon product from the vapour phase product, wherein the hydrocarbon product comprises substantially fully deoxygenated hydrocarbon product, H_2O, CO, CO_2, and C_1 – C_3 gases.

15. The system of claim 12, wherein the vapor phase product has less than 0.01 wt.% solids.

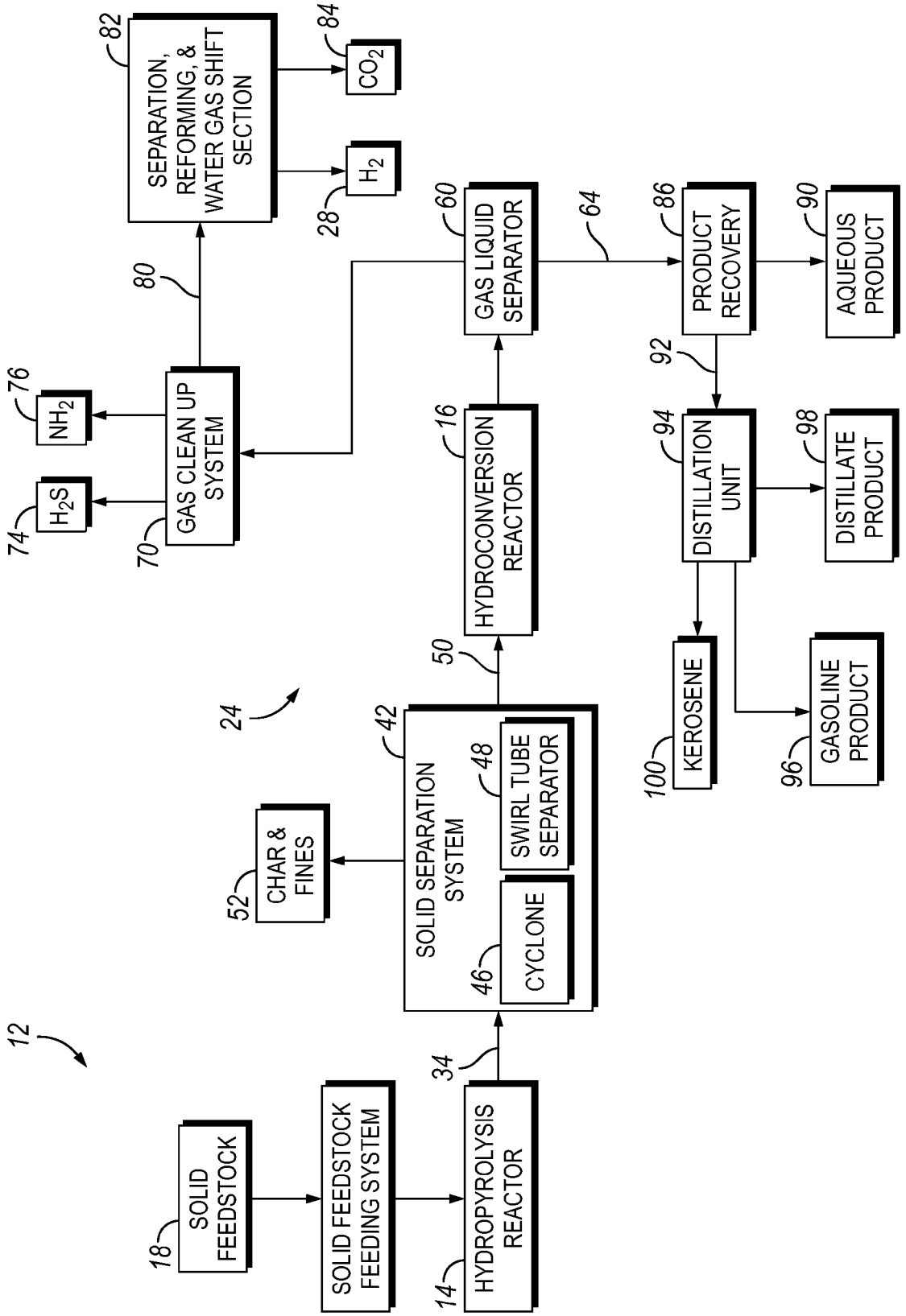

12
18
SOLID FEEDSTOCK
SOLID FEEDSTOCK FEEDING SYSTEM
14
HYDROPYROLYSIS REACTOR
34
24
42
SOLID SEPARATION SYSTEM
48
SWIRL TUBE SEPARATOR
46
CYCLONE
52
CHAR & FINES
50
16
HYDROCONVERSION REACTOR
60
GAS LIQUID SEPARATOR
64
86
PRODUCT RECOVERY
90
AQUEOUS PRODUCT
92
94
DISTILLATION UNIT
98
DISTILLATE PRODUCT
100
KEROSENE
96
GASOLINE PRODUCT
80
82
SEPARATION, REFORMING, & WATER GAS SHIFT SECTION
84
CO_2
28
H_2
70
GAS CLEAN UP SYSTEM
74
H_2S
76
NH_2

FIG. 1

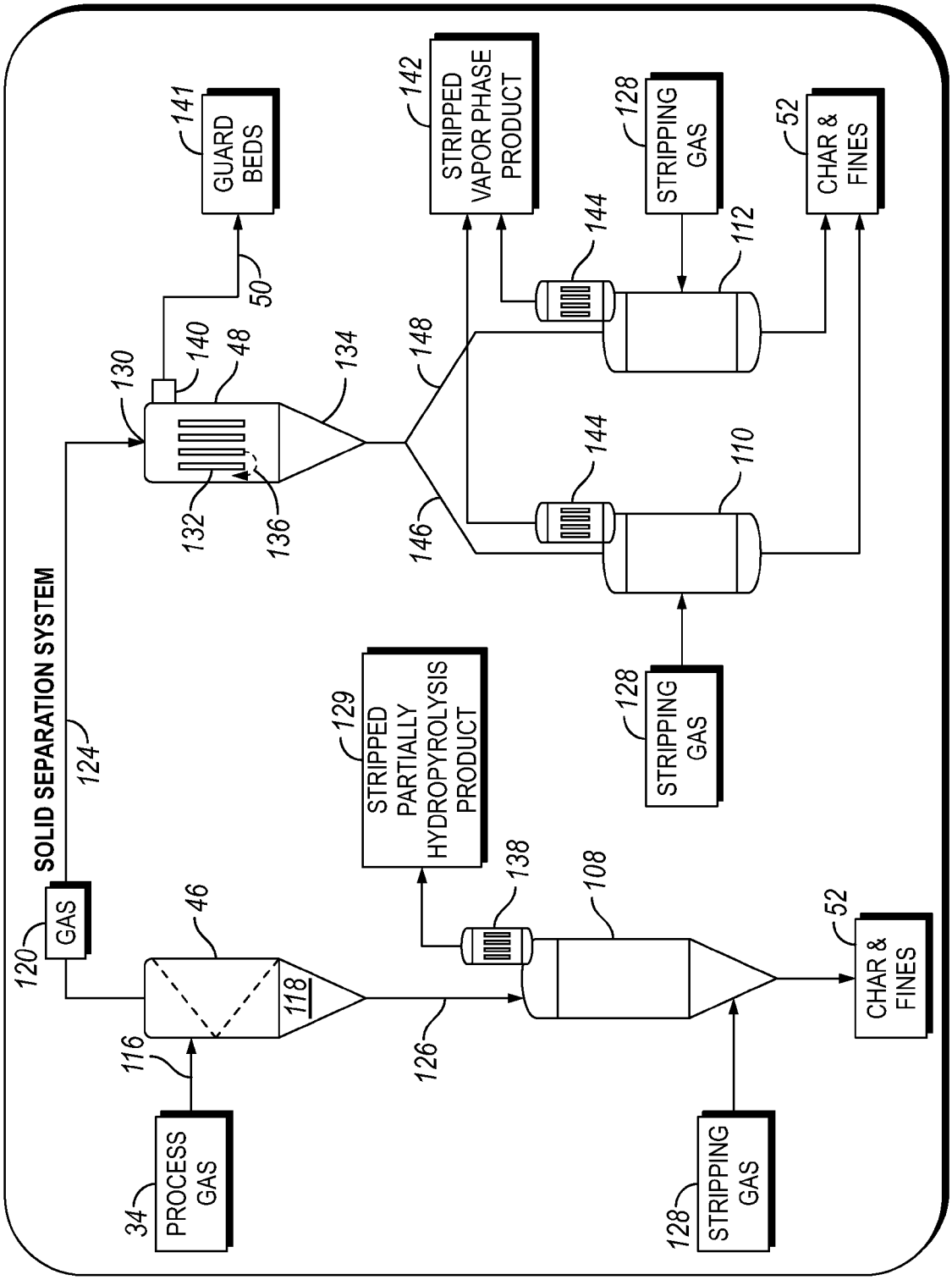

SOLID SEPARATION SYSTEM
GAS
120
124
PROCESS GAS
34
116
46
118
126
STRIPPED PARTIALLY HYDROPYROLYSIS PRODUCT
129
138
108
STRIPPING GAS
128
CHAR & FINES
52
STRIPPING GAS
128
110
144
112
144
STRIPPED VAPOR PHASE PRODUCT
142
CHAR & FINES
52
GUARD BEDS
141
50
130
140
48
134
148
132
136
146

FIG. 2

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/056969

A. CLASSIFICATION OF SUBJECT MATTER
INV. C10G1/06 C10G1/10 C10G3/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C10G B01J B04C C10K

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
21 February 2025	05/03/2025

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Baumlin, Sébastien

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/056969

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