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**SYSTEM FOR HYDROPROCESSING A SOLID FEEDSTOCK WITH PISTON
FEEDSTOCK FEEDER SYSTEM HAVING
A T-SHAPE ANNULAR PISTON SEALING RING**

[0001] The present disclosure generally relates to systems and methods for hydroprocessing of renewable feedstocks. More specifically, the present disclosure relates to a solid feedstock feeder system integrated into a hydroprocessing system.

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, among others. Therefore, when using fuels derived from renewable resources, it may be possible to achieve more sustainable CO₂ 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, solid feedstock (e.g., solid biomass) is feed into a hydroprocessing reactor by pressurizing a volume of the solid feedstock in, for example, a lock hopper system. While this approach is suitable for introducing the solid feedstock into the reactor, it requires a large vessel and consumes an undesirable amount of pressurized gas. In addition, existing lock hopper systems have a complex design. For example, the lock hopper system includes an atmospheric vessel, a sluice vessel, and a pressurized vessel along with several sets of valves. Moreover, because lock hopper systems pressurize the volume of the solid feedstock, a source of pressurized gas is required. It would be advantageous to use a solid feedstock feeding system that

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does not require the use of large amounts of pressurized gas and has a simpler design compared to existing lock hopper systems.

SUMMARY

[0004] In an embodiment, a system for hydroprocessing of a solid feedstock includes a hydropyrolysis reactor having one or more inlets that may receive the solid feedstock and to generate a product stream having partially deoxygenated hydropyrolysis product, H₂O, H₂, CO₂, CO, C₁-C₃ gases, char, and fines. The hydropyrolysis reactor includes one or more deoxygenation catalysts. The system also includes a solid feedstock feeding system disposed upstream from and fluidly coupled to the hydropyrolysis reactor. The solid feedstock feeding system includes a piston feeder having an inlet, an outlet, at least one piston disposed between the inlet and the outlet, the at least one piston includes a chamber and a barrel disposed in and that may translocate within the chamber, the barrel includes a terminal end having a seal, and the seal includes an annular ring having a first wall and a second wall, the second wall is orthogonal to and extends from the first wall such that a first portion of the first wall protrudes away from the second wall in a first direction and a second portion of the first wall protrudes away from the second wall in a second direction that is substantially opposite from the first direction.

[0005] In another embodiment, a system for hydroprocessing of a solid feedstock includes a hydropyrolysis reactor having one or more inlets that may receive the solid feedstock and that may generate a product stream having partially deoxygenated hydropyrolysis product, H₂O, H₂, CO₂, CO, C₁-C₃ gases, char, and fines. The system also includes a hydroconversion reactor disposed downstream from and fluidly coupled to the hydropyrolysis reactor. The hydroconversion reactor may receive the product stream, the partially deoxygenated hydropyrolysis product in the product stream undergoes hydroconversion in the hydroconversion reactor to generate a vapour phase product having substantially fully deoxygenated hydrocarbon product, H₂O, CO, CO₂, and C₁ – C₃ gases. The system also includes a solid feedstock feeding system disposed upstream from and fluidly coupled to the hydropyrolysis reactor. The solid feedstock feeding system includes a piston feeder having an inlet, an outlet, at least one piston disposed between the inlet and the outlet, the at least one piston has a barrel disposed in and that

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may translocate within a chamber and having a seal on a terminal end, the seal has an annular ring having a T-shaped cross-sectional geometry.

[0006] 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

[0007] Advantages of the disclosure may become apparent upon reading the following detailed description and upon reference to the drawings in which:

[0008] 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 feedstock feeding system having a piston feeder and a dosing tank, in accordance with an embodiment of the present disclosure;

[0009] FIG. 2 is a diagram of the solid feedstock feeding system of FIG. 1, whereby the piston feeder includes various pistons, in accordance with an embodiment of the present disclosure;

[0010] FIG. 3 is a diagram of a piston feeder that may be used in the solid feedstock feeding system of FIG. 2, whereby the piston feeder includes a piston in a slanted configuration, in accordance with an embodiment of the present disclosure;

[0011] FIG. 4 is a perspective view of the components that make up a terminal end of a piston associated with the piston feeder of FIGS. 2 and 3, in accordance with an embodiment of the present disclosure;

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[0012] FIG. 5 is a perspective view of the components of the terminal end of a piston associated with the piston feeder of FIGS. 2 and 3, in accordance with an embodiment of the present disclosure;

[0013] FIG. 6 is a perspective view of a terminal end of a piston associated with the piston feeder of FIGS. 2 and 3, in accordance with an embodiment of the present disclosure;

[0014] FIG. 7 is a cross-sectional view of the terminal end of the piston in FIG. 6 along line 7-7, in accordance with an embodiment of the present disclosure;

[0015] FIG. 8 is an exploded cross-sectional view of a portion of the terminal end of the piston in FIG. 7, in accordance with an embodiment of the present disclosure;

[0016] FIG. 9 is a cross-sectional view of the terminal end of a piston within a chamber of the piston feeder of FIGS. 2 and 3, in accordance with an embodiment of the present disclosure;

[0017] FIG. 10 is a cross-sectional view of the terminal end of the piston within a chamber of the piston feeder of FIGS. 2 and 3, whereby the terminal end includes a spring, in accordance with an embodiment of the present disclosure;

[0018] FIG. 11 is a cross-sectional view of the terminal end of the piston within a chamber of the piston feeder of FIGS. 2 and 3, whereby the terminal end includes a pressure assisted seat, in accordance with an embodiment of the present disclosure;

[0019] FIG. 12 is a cross-sectional view of the dosing tank of the solid feedstock feeding system of FIG. 2, whereby the dosing tank includes agitators and solid transport devices to move the solid feedstock, in accordance with an embodiment of the present disclosure;

[0020] FIG. 13 is flow diagram of a method for using the piston feeder of FIGS. 2 and 3 to provide a solid feedstock to the dosing tank, in accordance with an embodiment of the present disclosure;

[0021] FIG. 14 is a cross-sectional view of the piston feeder of FIG. 2, whereby a first chamber and a second chamber are in fluid communication and isolated from an outlet of the piston feeder, in accordance with an embodiment of the present disclosure;

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[0022] FIG. 15 is a cross-section view of the piston feeder of FIG. 2, whereby the solid feedstock has been fed to the second chamber and the outlet is isolated from the second chamber, in accordance with an embodiment of the present disclosure;

[0023] FIG. 16 is a cross-sectional view of the piston feeder of FIG. 2, whereby the second chamber having the solid feedstock is isolated from a first chamber and the outlet, in accordance with an embodiment of the present disclosure;

[0024] FIG. 17 is a cross-sectional view of the piston feeder of FIG. 2, whereby the second chamber having the solid feedstock is in fluid communication with the outlet and isolated from the first chamber, in accordance with an embodiment of the present disclosure; and

[0025] FIG. 18 is a cross-sectional view of the piston feeder of FIG. 2, whereby a feed chamber is aligned with an inlet, and the second chamber and the outlet are isolated from the first chamber and the feed chamber, in accordance with an embodiment of the present disclosure; and

[0026] FIG. 19 is plot of the number of cycles as a function of leak flow for the piston feeder, in accordance with an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0027] 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.

[0028] 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

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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.

[0029] 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.

[0030] As discussed in further detail below, the disclosed embodiments include a piston feeder system that may be used to provide solid feedstock (e.g., biomass) to 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. Carbon-containing materials that may be used to generate hydrocarbon fuels via hydroprocessing include solid feedstocks from renewable resources such as, for example, biomass and waste plastics, among others. Certain existing hydroprocessing systems use a lock hopper to provide solid feedstock (e.g., biomass) to a hydropyrolysis reactor. Lock hoppers generally require the use of multiple vessels for storing, transferring, and discharging/blowing the solid feedstock into the hydropyrolysis reactor. One problem with existing lock hoppers is that, when the solid biomass falls into each vessel, the solid biomass is compacted. For example, certain lock hopper configurations have a storage tank that supplies the solid feedstock to a transfer vessel that is pressurized after having received the solid feedstock from the storage tank. As the solid feedstock falls from the storage tank into the transfer vessel, the solid feedstock gets compacted. Compacting of the solid feedstock in the transfer vessel results in lumps or clusters of solid feedstock, which impact the operation of the hydropyrolysis reactor and the efficiency of the hydroprocessing process. For example, a lump or cluster of solid feedstock has substantially less surface area than the total surface area of the solid feedstock parts forming the lump or cluster; which may hinder the process efficiency. In addition, feedstock lumps

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or clusters will make the feeding operation unreliable due to bridging and blocking of the feed flow path by the lumps or clusters. Operation of the hydrolysis reactor is impacted as a result of the unstable and unreliable feeding as well as forming of solid tar lumps within the adjacent feeding system to the hydrolysis reactor (e.g., when using solid biomass to generate biofuels). Therefore, it is desirable to develop a solid feedstock feeding system that may provide industrial-scale volumes of solid feedstock to a hydrolysis reactor in a manner that does result in compaction of the feedstock,

[0031] Moreover, the lock hopper feeding systems used in industrial-scale applications are based on batch-wise transportation of volumes of solid feedstock through the lock hopper vessels to the reactors, thereby the vessels used in the lock hopper feeding systems are generally large (e.g., typically holding volumes in the order of 50 – 80 cubic meters (m^3)). As such, the amount of pressurized gas (e.g., approximately 5000 kilogram/hour (kg/hr)) used to transfer the required volume of the solid feedstock into the reactor may be undesirable. For example, the amount of pressurized gas required may impact the efficiency of the process due, in part, to the amount of energy used to pressurize the gas. Accordingly, it would be advantageous to develop a solid feedstock feeding system that does not require or uses a small amount of pressurized gas, and has a smaller/compact configuration that mitigates compaction of the solid feedstock compared to existing lock hopper feeding systems. It has been recognized that a piston feeder may be used to feed solid feedstock into a hydrolysis reactor at an industrial scale while mitigating the undesirable compacting, vessel size, and pressurized gas quantity associated with lock hopper feeding systems.

[0032] Piston feeders generally use o-rings to seal and maintain pressure within its chambers (i.e. cylinders). However, over time, forces exerted on the o-rings from the reciprocating motion of the piston may result in creep and eventually damage to the o-ring such that the seal and the desired pressure within a respective chamber of the piston feeder is not maintained. Therefore, it may be advantageous to provide a piston feeder and seal that mitigate the problems associated with existing feedstock feeding systems. Disclosed herein is a piston feeder system having an improved seal for delivering a solid feedstock to hydrolysis reactor in a manner that maintains

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a desired pressure in respective chambers and does not rely on pressurized gas nor results in compaction of the solid feedstock.

[0033] With the foregoing in mind, **FIG. 1** is a block diagram of an embodiment of a system **10** that may include the disclosed piston feeder for providing a solid feedstock (e.g., biomass and/or waste plastics/oils) to a reactor (e.g., a hydrolysis reactor) used in a hydroprocessing process that generates a biofuel. As should be appreciated, solid feedstock-derived hydrocarbon 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 hydrolysis 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 hydrolysis 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 hydrolysis reactor **14**, and the second stage **24** includes the hydroconversion reactor **16**. The reaction pressure in the first stage **20** and the second stage **22** 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

[0034] In the illustrated embodiment, the solid feedstock **18** having biomass (e.g., lignocellulose) and/or waste plastics and molecular hydrogen (H₂) **28** are introduced into the hydrolysis reactor **14**. For example, the solid feedstock **18** is fed to a piston feeder **30** of the solid feedstock feeding system **12**. As described in further detail below, the piston feeder **30** does not require the use of a pressurized gas and various vessels as in existing lock hopper feeding systems. Moreover, the piston feeder **30** has vessels (e.g., chambers or cylinders) for receiving and transferring the solid feedstock **18** that are between approximately 35% and 75% smaller than the vessels used in existing lock hopper feeding systems. The solid feedstock feeding system **12** also includes a dosing tank **32** downstream from and fluidly coupled to the piston feeder **30** and the hydrolysis reactor **14**. The configuration of the piston feeder **30** and the dosing tank **32** mitigate compacting of the solid feedstock **18** in the solid feedstock feeding system **12**. While in the illustrated embodiment, the system **10** has a single hydrolysis reactor **14**, it should be appreciated that the system **10** may have multiple hydrolysis reactors **14**. In embodiments, in which the system **10** includes multiple hydrolysis reactors **14**, the dosing tank **32** is fluidly coupled to and provides the solid feedstock **18** to each of the reactors **14**.

[0035] The hydrolysis reactor **14** contains a deoxygenation catalyst that facilitates partial deoxygenation of the solid feedstock **18**. For example, in the hydrolysis reactor **14**, the solid feedstock **18** undergoes hydrolysis, producing an output **34** having char, partially deoxygenated products of hydrolysis, light gases (C₁ - C₃ gases, carbon monoxide (CO), carbon dioxide (CO₂), and H₂), water (H₂O) vapor and catalyst fines. The hydrolysis 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 hydrolysis 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 output **30**) exiting the hydrolysis reactor **14**. The hydrolysis step in the first stage **20**

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employs a rapid heat up of the solid feedstock **18** such that a residence time of the pyrolysis vapors in the hydropyrolysis reactor **14** is preferably less than approximately 1 minute, more preferably less than approximately 30 seconds and most preferably less than approximately 10 seconds.

[0036] 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. Such material is more difficult to convert into fungible liquid hydrocarbon products than cellulosic and hemicellulosic material. It is an advantage of the present process that it can be used for lignocellulose-containing biomass. 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.

[0037] The solid feedstock **18** may be provided to the hydropyrolysis reactor **14** in the form of loose biomass particles having a majority of particles preferably less than about 3.5 millimeters (mm) in size or in the form of a biomass/liquid slurry. However, as appreciated by those skilled in the art, the solid feedstock **18** may be pre-treated or otherwise processed in a manner such that larger particle sizes may be accommodated. Suitable means for introducing the

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solid feedstock **18** into the hydrolysis 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 H₂), and constant-displacement pumps, impellers, turbine pumps or the like. In an embodiment of the present disclosure, 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 is 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.

[0038] The hydrolysis step is carried out in the hydrolysis reactor **14** at a temperature in the range of from approximately 300 Celsius (°C) to approximately 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/meter² (W/m²). The weight hourly space velocity (WHSV) in grams (g) biomass/g catalyst/hour (h) for the hydrolysis 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.

[0039] The temperatures used in hydrolysis rapidly devolatilize the solid feedstock **18**. Thus, in a preferred embodiment, the hydrolysis step includes the use of an active catalyst (e.g., a deoxygenation catalyst) to stabilize the hydrolysis 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. Catalyst particle sizes, for use in the hydrolysis reactor **14**, are preferably in the range of from approximately 0.3 millimeter (mm) to approximately 4.0 mm, more preferably in the range of from approximately 0.6 mm to approximately 3.0 mm, and most preferably in the range of from approximately 1 mm to approximately 2.4 mm.

[0040] Any deoxygenation catalyst suitable for use in the temperature range of the hydrolysis 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

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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 MoO₃) 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.

[0041] The first stage **20** of the process disclosed herein produces the output **30** having a partially deoxygenated hydropyrolysis product. 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** (e.g., lignocelluloses-containing biomass) 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 in the free moisture in the solid feedstock **18**. This oxygen is removed in the form of water (H₂O), carbon monoxide (CO) and carbon dioxide (CO₂) 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.

Char Removal

[0042] As discussed above, the output **30** produced from the hydropyrolysis step in the hydropyrolysis reactor **14** includes a mixed solid and vapor product that includes char, ash, catalyst

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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. Char, 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, char and catalyst fines are removed from the vapor phase product (e.g., the partially deoxygenated hydropyrolysis product). Any ash present may also be removed at this stage.

[0043] In certain embodiments, the hydropyrolysis reactor **14** may include solid separation equipment (e.g., cyclones), for example above a dense bed phase, to mitigate the entrainment of solid particles above a certain particle size. In addition, or alternatively, the solid separation equipment may be positioned downstream from the hydropyrolysis reactor **14** that removes the char and other solids in the output **30** to generate a vapor phase product **40**. For example, as illustrated in **FIG. 1**, the output **30** is fed to a solid separator **42** that separates/removes the solids (e.g., char, ash, and catalyst fines **46**) from the output **34**. The char and catalyst fines **46** may be removed from the output **34** by cyclone separation, swirl separator, filtering, electrostatic precipitation, inertial separation, magnetic separation, or any other suitable solid separation technique and combinations thereof. For example, char may be removed by filtration from the vapor stream (e.g., the output **30**) or by way of filtering from a wash step-ebullated bed. Back pulsing may be employed in removing char and other solids from the filters as long as hydrogen used in the disclosed process sufficiently reduces the reactivity of the pyrolysis vapors and renders the char free-flowing.

[0044] In one embodiment, the solid separator **42** includes one or more cyclones. In certain embodiments, the solid separator **42** includes a candle filter (e.g., a blow back candle filter). The candle filter receives the output **34** from the hydropyrolysis reactor **14** and separates the char and catalyst fines **46** the output **34** at a removal efficiency of at least 99% to generate the vapor phase product **40**. In other embodiments, the solid separator **36** includes one or more filters or a combination of cyclones, filters, and other suitable solid separation equipment to remove the entrained solids from the output **30**. For example, the char **38** and other solids may be removed by cyclone separation followed by hot gas filtration. The hot gas filtration removes fines not

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removed in the cyclones. In this embodiment, the dust cake caught on the filters is more easily cleaned compared to the char removed in the hot filtration of the aerosols produced in conventional fast pyrolysis because the hydrogen from the hydrolysis step stabilizes the free radicals and saturated the olefins. In accordance with another embodiment of the present disclosure, cyclone separation followed by trapping the char and catalyst fines **46** in a high-porosity solid adsorbent bed is used to remove the char and catalyst fines **46** from the output **34**. By way of non-limiting example, high-porosity solid adsorbents suitable for trapping the char and catalyst fines **46** include alumina silicate materials. Inert graded bed and/or filter materials may also be used to remove the char and catalyst fines **46** from the output **34** to generate the vapour phase product **40**.

[0045] In other embodiments, the solid separator **40** includes a combination of cyclones and swirl tube separators. In this particular embodiment, the cyclone receives the output **34** from the hydrolysis reactor **14** to generate an intermediate product having a reduced char and catalyst fines content compared to the output **34**. The intermediate product is fed to a swirl tube separator downstream of the cyclones to remove additional char and catalyst fines not removed by the cyclones, thereby generating the vapor phase product **40** and the char and catalyst fines **46**. The combined cyclone and swirl tube separators of the solid separator **42** remove greater than 99.99% of the char and catalyst fines **46** from the output **34**.

[0046] The char and catalyst fines **46** may also be removed by bubbling the first stage product gas (e.g., the output **34**) through a re-circulating liquid. The re-circulated liquid includes a high boiling point portion of a finished oil from this process (e.g., from the second stage **24**) and is thus a fully saturated (hydrogenated), stabilized oil having a boiling point above approximately 370 °C. In certain embodiments, the finished oil may be a heavy oil generated in a separate process. The char or catalyst fines **46** from the first stage **20** are captured in this liquid. A portion of the liquid may be filtered to remove the fines **46** and a portion may be re-circulated back to the hydrolysis reactor **14**. By using a re-circulating liquid, the temperature of the char-laden process vapors from the first stage **20** is lowered to a temperature suitable for the hydroconversion step in the second stage **24**, while also removing fine particulates of char and catalyst. Additionally, employing liquid filtration avoids the use of hot gas filtration.

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[0047] In accordance with another embodiment of the present disclosure, large-size NiMo or CoMo catalysts, deployed in an ebullated bed, are used for char removal to provide further deoxygenation simultaneous with the removal of fine particulates. Particles of this catalyst should be large, preferably in the range of from 15 to 30 mm in size, thereby rendering them easily separable from the fine char carried over from the hydropyrolysis reactor **14**, which is generally less than 200 mesh (smaller than 70 micrometers (μm)).

Second Stage

[0048] Following removal of the char and catalyst fines **46**, the vapor phase product **40** (e.g., the partially deoxygenated hydropyrolysis product) together with the H_2 , CO, CO_2 , H_2O , and $\text{C}_1 - \text{C}_3$ 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 **40** undergoes hydroconversion in the presence of a hydroconversion catalyst to generate a fully deoxygenated hydrocarbon product **50**. 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 **50** 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 .

[0049] 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

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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 **46**) 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 catalyst.

[0050] 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 MoO₃) 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.

[0051] Following the hydroconversion step, the fully deoxygenated hydrocarbon product **42** is fed to one or more condensers that condenses the hydrocarbon product **50**. The condensed hydrocarbon product **50** is fed to a gas-liquid separator **52** to provide a liquid phase product **56** having substantially fully deoxygenated C₄₊ 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 **56** (e.g., the substantially fully deoxygenated hydrocarbon C₄₊ 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 **56** (e.g., less than 2 wt%). Therefore, due, in part, to the lower oxygen content of the liquid phase product **56**, 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.

[0052] The hydrocarbon product **50** undergoes a separation process in the gas-liquid separator **52** that separates and removes the aqueous material from the substantially fully deoxygenated C₄₊ hydrocarbon liquid. Any suitable phase separation technique may be used to separate and remove the aqueous material from the substantially fully deoxygenated C₄₊ hydrocarbon liquid, thereby generating the liquid phase product **56** having the substantially fully deoxygenated C₄₊ hydrocarbon and non-condensable gases **58**. The non-condensable gases **58** includes mainly H₂, CO, CO₂, and light hydrocarbon gases (typically C₁ to C₃ and may also contain some C₄₊ hydrocarbons).

[0053] In certain embodiments, the non-condensable gases **58** are fed to a gas clean-up system **60**. The gas clean-up system **60** removes H₂S, NH₃ and trace amounts of organic sulfur-

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containing compounds, if present, as by-products of the process, thereby generating a hydrocarbon stream **64** having CO, CO₂, H₂ and the light hydrocarbon gases. The gas clean-up system **60** includes one or more process units that remove H₂S **68** and NH₃ **70** from the non-condensable gases **58** as by-products of the process. The hydrocarbon stream **64** may be sent to a separation, reforming, and water-gas shift section **74** where hydrogen **28** is produced from the light hydrocarbon gases in the hydrocarbon stream **64** and renewable CO₂ **78** 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 **74** is equal to or greater than the hydrogen required to maintain fluidization and sustain chemical consumption of hydrogen in the process.

[0054] The liquid phase product **56** recovered from the gas-liquid separator **52** is fed to a product recovery section **80**. In the product recovery section **80**, aqueous product **82** is removed from the liquid phase product **56** to generate an intermediate liquid phase product **84**. The intermediate liquid phase product **84** may undergo distillation to separate the substantially fully deoxygenated C₄+ hydrocarbon liquid into fractions according to ranges of the boiling points of the liquid products contained in the intermediate liquid phase product **84**. For example, the substantially fully deoxygenated C₄+ hydrocarbon liquid in the intermediate liquid phase product **84** includes naphtha range hydrocarbons, middle distillate range hydrocarbons (e.g., gas oil, diesel) and vacuum gasoil (VGO) range hydrocarbons.

[0055] For the purpose of clarity, “middle distillates” as used herein are hydrocarbons or oxygenated hydrocarbons recovered by distillation between an atmospheric-equivalent initial boiling point (IBP) and a final boiling point (FBP) measured according to standard ASTM distillation methods. ASTM D86 initial boiling point of middle distillates may vary from between approximately 150 °C to approximately 220 °C. Final boiling point of middle distillates, according to ASTM D86 distillation, may vary from between approximately 350 °C to approximately 380 °C. “Naphtha” as used herein is one or more hydrocarbons or oxygenated hydrocarbons having four or more carbon atoms and having an atmospheric-equivalent final boiling point that is greater

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than approximately 90 °C but less than approximately 200 °C. A small amount of hydrocarbons produced in the process (approximately less than 3 wt% of total C₄₊ hydrocarbons, and preferably less than 1 wt% of total C₄₊ hydrocarbons) boil at temperatures higher than those for the middle distillates as defined above. That is, these hydrocarbons have a boiling range similar to vacuum-gas oil produced by distillation of petroleum. Gasoline is predominantly naphtha-range hydrocarbons and is used in spark-ignition internal combustion engines. In the United States, ASTM D4814 standard establishes the requirements of gasoline for ground vehicles with spark-ignition internal combustion engines. Gas oil (GO)/diesel is predominantly middle-distillate range hydrocarbons and is used in compression-ignition internal combustion engines. In the United States, ASTM D975 standard covers the requirements of several grades of diesel fuel suitable for various types of diesel engines.

[0056] Accordingly, in the illustrated embodiment, the intermediate liquid product **84** is fed to a distillation unit **86** to recover gasoline product **90** and a distillate product **92** (e.g., a middle distillate). In certain embodiments, kerosene/jet fuel **94** are recovered as separate streams from the distillation unit **86**. The distillate product **92** (e.g., the middle distillate) contains gas oil (GO), for example biodiesel, and is substantially fully free from oxygen, sulfur, and nitrogen. In certain embodiments, the oxygen content of the distillate product **92** is less than approximately 1.50 wt %. For example, the oxygen content may be approximately 1.40 wt %, 1.25 wt %, 0.50 wt %, 0.25 wt %, or 0.10 wt % or less. In one embodiment, the sulfur content is less than 100 ppmw. For example, the sulfur content may be approximately 75 ppmw, 50 ppmw, 25 ppmw, 10 ppmw, 5 ppmw, 1 ppmw or less. Accordingly, the biodiesel obtained from the distillate product **92** is considered an ultra-low sulfur diesel (ULSD), which generally has less than 10 ppmw sulfur. Regarding the nitrogen content, in certain embodiments, the nitrogen content of the substantially fully deoxygenated C₄₊ hydrocarbon liquid is less than 1000 ppmw. For example, the nitrogen content may be approximately 750 ppmw, 500 ppmw, 250 ppmw, 100 ppmw, 75 ppmw, 50 ppmw, 25 ppmw, 10 ppmw, or 1 ppmw or less.

[0057] As discussed above, hydrocarbon liquid products such as the distillate product **92** generated from hydroprocessing of solid biomass feedstock (e.g., the solid feedstock **18**) generally requires additional processing to upgrade and improve product properties such as cetane number,

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reduced density, reduced sulfur and/or nitrogen content, reduced benzene content (e.g., as a result of selective saturation), among others, and facilitate tailoring the overall hydrocarbon product to certain location and market specifications, among other benefits. However, the additional processing to upgrade the distillate product **92** introduces complexity to the process, while also increasing the overall cost of producing commercially viable biodiesel fuels having the desired specifications set forth by various fuel regulations. However, it has been recognized that by blending the distillate product **92** with a hydrotreated ester and/or fatty acid (HEFA), the product properties (e.g., cetane number, density) are improved without requiring additional processing to upgrade the distillate product **92**. Therefore, in accordance with an embodiment of the present disclosure, the distillate product **92**. The distillate product **92** may be further processed in a third stage of the hydroprocessing system **10** to upgrade the distillate product **92** into a commercially viable biodiesel fuel. In other embodiments, the distillate product **92** may be combined with other hydrocarbons (e.g., fossil-derived hydrocarbons and/or biorenewable-derived biodiesel) to yield a commercially viable biodiesel blend that does not require upgrading in the third stage.

Solid Feedstock System

[0058] As discussed above, the solid feedstock system **12** provides the solid feedstock **18** to the reactor **14** in a manner that does not require a pressurized gas and large volume vessels compared to lock hopper feeding systems, and does not result in compaction of the solid feedstock **18**. **FIG. 2** illustrates an arrangement of the piston feeder **30** and the dosing tank **32** of the solid feedstock system **12**, in accordance with an embodiment of the present disclosure. The solid feedstock system **12** may have an axial axis or direction **96**, a radial axis or direction **98** away from axis **96**, and a circumferential axis or direction **100** around the axis **96**. The piston feeder **30** includes multiple pistons arranged in a manner that allow the solid feedstock **18** to move through the piston feeder **30** and into the dosing tank **32** while maintaining a desired pressure within each chamber of the piston feeder **30**. For example, in the illustrated embodiment, the piston feeder **30** includes a first piston **102**, a second piston **104**, a third piston **106**, and a fourth piston **108**. The piston feeder **30** also includes a first chamber **110**, a second chamber **112**, and a conduit **114** extending between and fluidly coupling the chambers **110**, **112**. Each piston **102**, **104**, **106**, **108** includes a respective barrel **116**, **117**, **118**, and **119**. The barrel **116**, **117**, **118**, **119** translocates

within a respective chamber to facilitated movement of the solid feedstock **18** through the piston feeder **30** and into the dosing tank **32**, as discussed in further detail below.

[0059] In addition, the piston feeder **30** includes an inlet **120** positioned adjacent to and extending in the axial direction **96** away from the first piston **102** and the first chamber **110**, a feed chamber **122** disposed within the first chamber **110** and fluidly coupled to the inlet **120**, and an outlet **124** positioned adjacent to and extending axially **96** away from the fourth piston **108** and the second chamber **112**. However, the inlet **120** and the outlet **124** may be arranged in any other suitable manner than allows a flow of the solid feedstock **18** into and out of the piston feeder **30**.

[0060] At least a portion of the barrel **116** of the first piston **102** is disposed within the first chamber **110** and moves (e.g., translocates) along a length of the first chamber **110**, for example, in the radial direction **98** to move the solid feedstock **18** from the first chamber **110** and into the conduit **114**. Similar to the first piston **102**, at least a portion of the barrel **117** of the second piston **104** is disposed within the second chamber **112** and moves (e.g., translocates) along a length of the second chamber **112** to move the solid feedstock **18** from the second chamber **112** and into the dosing tank **32**. In the illustrated embodiment, a portion of the conduit **114** is slanted relative to the axial axis **96**. However, in certain embodiment, the conduit **114** may be parallel to the axial axis **96**.

[0061] In the illustrated embodiment, the first piston **102** and the second piston **104** radially extend along the radial axis **98** and are positioned parallel to one another. The third piston **106** and the fourth piston **108** extend axially along the axial axis **96** and are parallel to one another and orthogonal to the pistons **102**, **104**. However, in other embodiments, the pistons **102**, **104** are not positioned parallel to one another. For example, **FIG. 3** illustrates an embodiment of the piston feeder **30** in which the piston **104** is oriented at an acute angle α relative to a centerline axis **126** of the piston **108** and orthogonal to a centerline axis **128** of the piston **106**. Consequently, the second chamber **112** of the piston feeder **30** is also oriented at the acute angle α relative to the centerline axis **126** of the piston **108**. By arranging the piston **104** and the second chamber **112** in this way, the solid feedstock may move along the second chamber **112** easily due, in part, to gravitational forces and eroding of an interior surface of the second chamber **112** may be mitigated. For example, the solid feedstock may be abrasive and scratch, or otherwise erode, the interior

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surface of the second chamber **112** as the barrel **117** of the piston **104** pushes the solid feedstock toward the fourth piston **108** and into the dosing tank **32**. Such movement of the solid feedstock may, overtime, wear away the interior surface of the second chamber **112**. In addition, the solid feedstock may lodge between the interior surface of the second chamber **112** and the outer surface of the barrel **117**. As such, the barrel **117** may be unable to properly move within the second chamber **112** and transfer the solid feedstock into the dosing tank **32**. The slanted, or angled, configuration of the second piston **104** and the second chamber **112** may mitigate wear of the piston feeder surfaces (e.g., the interior surface of the second chamber **112** and the outer surface of the piston **106**) and lodging of the solid feedstock between the interior surface of the second chamber **112** and the outer surface of the piston **104**.

[0062] Returning to **FIG. 2**, the outlet **124** couples (e.g., connects) the piston feeder **30** to the dosing tank **32** such that the solid feedstock **18** may be transferred from the second chamber **112** to the dosing tank **32**. In operation, the first chamber **110** and the conduit **114** are maintained at ambient pressure (e.g., approximately 0.1 MPa (1 bara)) and the second chamber **112** and the dosing tank **32** are pressurized according to the pressure within the reactor **14**. For example, the second chamber **112** and the dosing tank **32** may be at a pressure of between approximately 0.1 megapascal (MPa) to approximately 5 MPa (approximately 1-50 bara). As discussed in further detail below, the third piston **106** may be used to maintain the different pressures within the chambers **110**, **112** and mitigate flow back of the solid feedstock **18** from the dosing tank **32** back into the piston feeder **30** due to pressure differentials between, for example, a feedstock storage tank and the dosing tank **32**.

[0063] The piston feeder **30** includes various valves and seals that facilitate a flow of the solid feedstock **18** through the chambers **110**, **112** and the conduit **114**, and mitigate flow back of the solid feedstock **18** from the dosing tanks **32** and/or reactor **14** back into the piston feeder **30**. For example, the piston feeder **30** includes a seal **130** and **132** at an end of the barrels **116**, **117**, respectively. The piston feeder **30** also includes pressure seals **134** and **136** at an end of the barrels **118**, **119**, respectively. In operation, the pressure seal **136** provides a seal between the dosing tank **32** and the second chamber **112** such that when the second chamber **112** receives the solid feedstock **18** from the first chamber **110**, which is at atmospheric pressure (e.g., 0.1 MPa (1 bara)),

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the solid feedstock **18** in the dosing tank **32**, which is at a higher pressure than the chamber **110**, **112** (e.g., at a pressure of between 0.6 MPa (6 bara) and 5 MPa (50 bara)), does not flow back into the piston feeder **30**. Similarly, the pressure seal **134** provides a seal between the chambers **110**, **112** such that when the second chamber **112** is pressurized to equal the pressure within the dosing tank **32**, the solid feedstock **18** does not flow back into the first chamber **110** and the conduit **114**, which are at atmospheric pressure. Once the second chamber **112** is isolated from the first chamber **110**, conduit **114**, and dosing tank **32**, the second chamber **112** may be filled with H₂ and pressurized to the pressure within the dosing tank **32** and the reactor **14**. For example, the piston feeder **30** may have a purge valve **140** and a bypass valve **142** that allow the second chamber **112** to be filled with the H₂ and pressurized the chamber **112**. During pressurization of the second chamber **112**, the valves **140**, **142** are open to allow the air within the chamber **112** to be displaced by the H₂. After some time, the purge valve **140** is closed and the bypass valve **142** remains open such that the chamber **112**, that is filled with H₂, may be pressurized to the desired pressure. Once the second chamber **112** is at the desired pressure, the bypass valve **140** is closed and the third piston **108** moves in the axial direction **96** away from the outlet **24** to release the seal and allow fluid communication between the second chamber **112** and the outlet **124**.

[0064] As discussed above, certain existing piston feeders use an o-ring to provide a seal and maintain pressure in a respective chamber. However, the force exerted on the o-ring by the continuous motion of the piston results in creep of the o-ring and, over time, damage. As such, the o-ring may be unable to seal and maintain the desired pressure within the respective chamber. Therefore, the pressure seal **134**, **136** disclosed herein is configured in a such a way to mitigate damage resulting from the forces exerted by the piston **106**, **108**. For example, **FIGS. 4** and **5** are perspective views of an end portion **150** of the piston **106**, **108** having the disclosed pressure seal **134**, **136**. In addition to the pressure seal **134**, **136**, the end portion **150** includes a top plate **152**, a bottom plate **154**, a middle plate **156**, and an insert **160**. The pressure seal **134**, **136** has an annular ring **162** that is positioned between the plates **152**, **156**. The end portion also includes an o-ring **164** between the bottom plate **154** and the insert **160**. The plates **152**, **154**, **156**, the insert **160**, the pressure seal **134**, **136**, and the o-ring **164** are held together by bolts **168**, thereby forming the end portion **150**, as shown in **FIG. 6**.

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[0065] FIG. 7 is a cross-sectional view of the end portion 150 along line 7-7. As shown in the illustrated embodiment, the annular ring 162 of the pressure seal 134, 136 has recesses 172 and protrusions 174 such that the annular ring 162 has a T-shaped cross-section. For example, the annular ring 162 has a first wall 175 extending between a first side 176a and a second side 176b of the annular ring 162, the second side 176b being substantially opposite (e.g., 180 degrees) from the first side 176a. The annular ring 162 also has a second wall 177 extending from and orthogonal to the first wall 175. The second wall 177 forms part of the first side 176a and the second side 176b. A portion of the first wall 175 extends (or protrudes out) from a surface of the first side 176a to form the protrusion 174a and recess 172a, and another portion of the first wall 175 extends (or protrudes out) from a surface of the second side 176b to form the protrusion 174b and recess 172b, thereby giving the annular ring 162 the T-shaped cross-sectional geometry. In certain embodiments, a flat ring may be disposed between the protrusion 174a and an inner surface of the plate 152 such that the terminal end of the protrusion 174a is not against and abuts the inner surface of the plate 152. In the illustrated embodiment, the protrusions 174 have a rectangular or square geometry. However, the protrusions 174 may have any other suitable geometry such as trapezoidal, triangular, polygonal, and combinations thereof. For example, in certain embodiments, protrusion 174a may have one cross-sectional geometry and the other protrusion 174b may have another cross-sectional geometry that is different from the cross-sectional geometry of the protrusion 174a.

[0066] As discussed in further detail below, the T-shape of the annular ring 162 facilitates coupling of the pressure seal 134, 136 to the end portion 150 and mitigates damage that may be caused by the forces exerted on the seal 134, 136 by the plates 152, 154 during operation of the piston feeder 30. For example, during operation, the second wall 177 of the seal 134, 136 expands in a linear direction 179 toward an inner surface of a respective piston chamber housing the barrels of the piston 106, 108 (e.g., the barrels 118, 119), thereby creating the seal. In addition to creating the seal, the liner movement (i.e., expansion) of the second wall 177 cleans the sealing surface during movement of the piston 106, 108 by removing feedstock that may be lodged between the barrel of the piston 106, 108 and the inner surface of the piston chamber. When the seal 134, 136 is deactivated, the second wall 177 retracts and returns to its original shape. Unlike o-ring shaped seals, the first wall 175 (e.g., the T-bar) forces the second wall 177 back to its original shape as

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the first wall **175** is held in place by the plates **152**, **156** and is unable to move. As such, the first wall **175** pulls the second wall **177** back to its original shape and mitigates wear on the seal **134**, **136** that may be caused by frictional forces exerted by the inner surface of the piston chamber onto the second wall **177**. The T-shape of the annular ring **162** blocks, or otherwise mitigates, the pressure seal **134**, **136** from creeping and allows it to maintain its original diameter. Additionally, narrow tolerances of the T-shape mitigate extrusion of portions of the seal **134**, **136** as it is compressed during operation, which would change its shape and available material resulting in loss of sealing effectiveness. The annular ring **162** may be formed from an elastic incompressible material such that the annular ring may expand and contract to return to its original shape after application and removal of forces exerted by the plates **152**, **154**, **156**. By way of non-limiting example, the thermoplastic material may be selected from polyurethane materials and the like. As used herein, the term “elastic incompressible material” denotes a material that maintains its density (i.e., it is incompressible) but not necessarily its shape (i.e., the material deforms) when a force is applied, and returns to its original shape when the force is removed.

[0067] To facilitate discussion of the pressure seal **134**, **136**, reference will be made to **FIG. 8**, which is an exploded view of a section of the end portion **150**. As shown in the illustrated embodiment, the T-shape cross-sectional geometry of the annular ring **162** facilitates retaining the pressure seal **134**, **136** in the end portion **150**. For example, the plates **152**, **156** each have a lip **178**, **180**, respectively, that form a rim around an outer circumference of the plates **152**, **156**. The plates **152**, **156** also have a recessed wall **184**, **186** (e.g., annular recesses wall) sized and shaped to receive the protrusions **174a**, **174b**, respectively, of the pressure seal **134**, **136**. When assembled, the pressure seal **134**, **136** does not abut a top plate outer surface **190** and a middle plate outer surface **192**. For example, as shown in the illustrated embodiment, there is a gap **188a** between a first seal outer surface **194a** and the top plate outer surface **190**, and a gap **188b** between a second seal outer surface **194b** and the middle plate outer surface **192**. The gap **188** extends circumferentially around the end portion **150** when the seal is not activated. Additionally, a terminal end **191** of the second wall **177** is positioned entirely within the lips **178**, **180** such that the terminal end **191** does not protrude away from or is flush with the outer surfaces of the end portion **150**. That is, the terminal end **191** is nested within the plates **152**, **156**. This seal configuration keeps the seal **134**, **136** from rubbing against an inner surface of the respective piston

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feeder chamber the piston during movement of the piston, thereby mitigating creep and damage to the seal during operation. Additionally, it allows for the second wall 177 to expand and create the seal when pressure is applied by the plates 152, 156 as described in further detail below with reference to FIG. 9. Unlike the surfaces 194 of the second wall 177, portion 198a, 198b of seal outer surface 197a, 197b of the sides 176a, 176b abuts a top plate surface 200 and middle plate surface 204, respectively. That is, there is no gap between the outer surface 197 of the pressure seal 134, 136 and the respective plate surfaces 220, 204. In addition, the middle plate 156 includes an interior wall 208 adjacent to the recessed wall 186 and extending from the middle plate surface 204. An outer portion 210 of the first wall 175 abuts an outer surface 214 of the interior wall 208.

[0068] A second gap 218 between a top plate inner surface 220 and a terminal end 224 of the interior wall 208 allows for the top plate 152 to exert a force 226 on the pressure seal 134, 136 when the piston (e.g., the piston 106, 108) translocates to isolate the chamber (e.g., the second chamber 112) and/or the outlet (e.g., the outlet 124) such that a pressure differential between the dosing tank (e.g., the dosing tank 32) and piston chambers at atmospheric pressure (e.g., the first chamber 110) does not result in flow back of the solid feedstock (e.g., the solid feedstock 18) from the dosing tank back into the piston feeder (e.g., the piston feeder 30). For example, as the piston 106, 108 moves in a direction towards the outlet 124 the bottom plate 154 abuts against a terminal end of the chamber it is in causing the bottom plate 154 and the middle plate 156 to move in a direction opposite to the direction the piston 106, 108 is moving. Consequently, the gap 218 is decreased causing the top plate 152 to exert the force 226 on the pressure seal 134, 136. The bottom plate 154 also exerts a force counter to the force 226, which pushes against the pressure seal 134, 136, thereby causing a portion of the annular ring 162 to compress and pushing it towards an inner wall of the chamber, as explained in further detail below. The compression of the annular ring 162 creates a seal within the chamber and blocks fluid communication between a space of the piston feeder or chamber adjacent to (or above) the top plate 152 and a space of the piston feeder or chamber adjacent to (or below) the bottom plate 154.

[0069] For example, FIG. 9 is cross-sectional view of a portion of the piston feeder 30 having the pressure seal 134, 136 of the present disclosure in an activated configuration. In the illustrated embodiment, the end portion 150 of the piston 106, 108 is positioned within a chamber

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230 of the piston feeder **30** such that the bottom plate **154** abuts against a portion of an inner chamber wall **232**. The bottom plate **154** has a beveled terminal end **234** having a slanted wall **236** that forms an angle θ of between approximately 30° and 50° . A portion **240** of the beveled terminal end **234** contacts the inner chamber wall **232** such that the inner chamber wall **232** exerts a force **246** against the bottom plate **152**. Consequently, the gap **218** decreases, thereby exerting the force **226** and a counter force **250** onto the pressure seal **134**, **136** causing the annular ring **162** compress and the second wall **177** to expand, thereby closing the gap **188** and pushing the terminal end **191** out toward an inner surface **252** of the chamber **230** to provide the seal. The T-shape configuration of the annular ring **162**, in combination with the beveled terminal end **234** of the bottom plate **154**, mitigate damage to the annular ring **162** that may be caused by creep, as discussed above.

[0070] **FIG. 10** illustrates an alternative embodiment of the end portion **150** of the piston **106**, **108** in which the end portion includes a spring and an o-ring between the plates **152**, **154**. For example, in the illustrated embodiment, an end portion **254** includes a spring **256** within a void **258** that forms between the plates **152**, **156** of the end portion **254**. Unlike the end portion **150**, the end portion **254** does not include a separate middle plate (e.g., the middle plate **156**). Rather, the bottom plate **154** of the end portion **254** is combined with the middle plate (e.g. the middle plate **156**) such that the bottom plate **154** and the middle plate form a single unitary structure. In the illustrated embodiment, coupled to the bottom plate **154** is a volume dispenser **255** having a concave configuration. The volume dispenser **255** facilitates movement of the solid feedstock through the piston feeder, the dosing tank, and/or the reactor.

[0071] As discussed above, the seal **134**, **136** expands when activated, forcing the second wall **177** toward the inner surface of the piston chamber (e.g., the inner surface **252**) to create the seal. When the seal **134**, **136** is deactivated (e.g., when the seal is broken), the second wall **177** is pulled toward the first wall **175** and the seal **134**, **136** returns to its original shape. The spring **256** facilitates pulling the second wall **177** toward the first wall **175** after the forces **226**, **250** are released by overcoming the friction forces exerted on the second wall **177** by the surface **190**, **192** of the plates **152**, **156**, respectively. In addition to facilitating retraction of the second wall **177** when the seal **134**, **136** is deactivated, the spring **256** mitigates wear of the terminal end **191**

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resulting from friction forces exerted by the inner surface of the piston chamber against the terminal end **191** when the second wall **177** does not retract to its original shape once deactivated. For example, once the seal **134, 136** is deactivated, the piston **106, 108** moves in a direction away from an end of the chamber (e.g., in a direction that is substantially the same as the counter force **250**). If the second wall **177** of the seal **134, 136** does not retract to its original shape, the terminal end **191** may rub against the inner surface of the chamber. This rubbing (i.e., friction) may wear the seal **134, 136** over time causing leakage and feedstock to get trapped between the piston and the inner surface of the chamber. The spring **256** may be any spring suitable for overcoming the friction forces of the seal **134, 136**. The spring **256** has an annular configuration and may be made from materials such as, but not limited to, steel, metal alloys, or the like. The end portion **254** may have any number of springs **256**. For example, the end portion **254** may have 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more springs **256**.

[0072] In addition to the spring **256**, the end portion **254** includes a backup ring **258** between the recessed wall **184** and the outer surface **197a** of the pressure seal **134, 136**. The backup ring **258** mitigates extrusion of the first wall **175**, for example, when there is a gap between the recessed wall **258** and the outer surface **197a** of the seal **134, 136**. The backup ring **258** may be made of any suitable material with sufficient durability and elastomeric properties to withstand the forces **226, 250** and block extrusion of the first wall **175** during operation of the piston feeder. By way of non-limiting example, the backup ring **258** may be a nylon ring or the like.

[0073] FIG. 11 illustrates another embodiment of the end portion **150** of the piston **106, 108** in which the end portion includes a pressure assisted seat **253**. The pressure-assisted seat **253** works by balancing of process pressure **255** (e.g., the pressure below the end portion **150**) against seat pressure **257** (e.g., the pressure inside of the piston for de-activating the seal function). The seat pressure **257** is maintained higher than the process pressure **255**. For example, the seat pressure **257** is maintained at between approximately 0.5% and 25% higher than the process pressure **255**. By way of non-limiting example, the seat pressure **257** may be between approximately 1 and 15 bar higher than the reactor pressure, and the process pressure **255** may be between approximately 1 and 10 bar higher than reactor pressure. In this way, it is ensured that the pressure on the seal **134, 136** may be released when the piston (e.g., the piston **106, 108**) is

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retracted independently of the operating pressure. An advantageous aspect of this design is that having a higher seat pressure **257** compared to the process pressure **255** secures the retraction of the seal **134**, **136** when removing pressure from the pressure-assisted seat **253** when the piston moves away from the outlet (e.g., the outlet **124**) of the piston feeder or of the chamber in which the piston is housed. Additionally, bearings may be positioned adjacent to seal **134**, **136** (e.g., adjacent to and abutting the first wall **175** of the T-shaped annular ring **162**) to control the concentricity of the pressure-assisted seat **253**. The bearings ensure that the seat can move axially without damaging surfaces of the end portion **150** and the piston chamber. The bearings **259** may be made from a material having a hardness that is different from a hardness of the pressure-assisted seat **253**. By way of non-limiting example, the bearings may be bronze or any other material that is softer than the material of the pressure-assisted seat **253**. A central part **263** sets the precompression of the seal **134**, **136** when no pressure is set on a metal-metal seat **265**. The central part **263** of the end portion **150** of the piston is pressurized by an external source of inert gas through a pipe in the piston. By maintaining a higher pressure in the piston than in the process it is ensured that all leaks will be from the inside and out and thereby avoiding dust or foreign matters from entering the moving parts of the seat construction. For example, the higher pressure in the metal-metal seat **265** compared to the process pressure ensures that dust does not accumulate and, in case there is a leak due to a damaged O-ring, gas will not flow into the equipment which may otherwise cause damage and impact performance.

[0074] As discussed above, the disclosed piston feeder (e.g., the piston feeder **30**) provides solid feedstock (e.g., the solid feedstock **18**) to the dosing tank **32**. The dosing tank **32** may include additional features such as agitators and screw conveyors that keep the solid feedstock **18** in motion, mitigate compaction, and facilitate dosing the solid feedstock **18** into the reactor **14**. FIG. **12** is a cross-sectional view of an embodiment of the dosing tank **32**. The dosing tank **32** includes the body **260**, inlets **262**, and outlet **264**. While in the illustrated embodiment, the dosing tank **32** has a single outlet **264**, the dosing tank **32** may have multiple outlets. The body **260** defines a housing **270** (e.g., vessel) of the dosing tank **32** that contains a desired volume of feedstock (e.g., the solid feedstock **18**). For example, the housing **270** may contain a volume of solid feedstock that is between approximately 10 m³ to 130 m³. As such, dimensions of the housing **270** may be between approximately 2 m (meters) diameter x 4 m length and 4 m diameter x 10 m length.

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However, as should be appreciated, the housing **270** may be any size suitable for containing the desired amount of solid feedstock. The housing **270** has a longitudinal axis **272** that extends from a first end **276** to a second end **278** of the dosing tank **32**. In embodiments having multiple outlets **264**, one or more outlets **264** are positioned at the first end **276** and one or more outlets **264** are positioned on the second end **278**. The outlets **264** may feed the solid feedstock (e.g., the solid feedstock **18**) into the reactor (e.g., the reactor **14**) symmetrically (e.g., each outlet feeding the solid feedstock into the reactor simultaneously) or in series (e.g., one outlet feeds the solid feedstock into the reactor followed by the other outlet feeding the feedstock into the reactor). Each outlet **264** may dose the same or different amounts of the solid feedstock into the reactor. In certain embodiments, each outlet **264** may be fluidly coupled to separate reactors such that one dosing tank **32** may feed the solid feedstock into multiple reactors.

[0075] As shown in **FIG. 12**, along the longitudinal axis **272** are multiple agitators **274** that move the solid feedstock entering the housing **270** toward a center **280**. The agitators **274** include a shaft **282** having a plurality of blades **284** that maintain movement of the solid feedstock **18** within the dosing tank **32**. In operation, the agitators **274a** and **274c** move in a first direction along the longitudinal axis **272** such that the respective blades **284** move a first portion of the solid feedstock **18** toward the center **282**, and the agitators **274b** and **176d** move in a second direction opposite the first direction along the longitudinal axis **272** such that the respective blades **284** move a second portion of the solid feedstock **18** toward the center **280**.

[0076] The housing **270** also includes one or more troughs **286** into which the solid feedstock enters through an opening **288** at the center **280** of the housing **270**. The troughs **286** extend along the longitudinal axis **272** from the first end **276** to the second end **278** and terminate at the respective outlet **264**. In embodiments having multiple troughs **286**, the troughs **286** are adjacent to one another and separated by a partition such that the solid feedstock in one trough **286** is separated from the solid feedstock in an adjacent trough **286**. Each trough **286** includes a solid feed transport device **290** that moves and doses the solid feedstock in the trough **286** to the reactor (e.g., the reactor **14**). By way of non-limiting example, the solid feed transport device **290** is a screw conveyor type, pneumatic transport system, or any other suitable solid feed transport device. The dosing tank **32** may include one or more control device **292** that control and facilitate

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movement of the agitator **274** and the solid feed transport device **290**. The agitators **274** and the solid feed transport device **290** operate independently from one another. Therefore, the agitator **274** and the solid feedstock transport device **290** each have their own control device **292**. However, in certain embodiment, the agitator **274** and the solid feedstock transport device **290** are independently operated using the same control device **292**. As should be appreciated, the dosing tank **32** may be used in combination with the disclosed piston feeder. It may be positioned upstream or downstream of the piston feeder. In certain embodiments, the dosing tank **32** may be integral with the piston feeder. In other embodiments, the dosing tank **32** is a standalone unit that is separate from and removably coupled to the piston feeder. By having the dosing tank **32** as a standalone unit, it may be retrofit into existing reactor system and allows flexibility in adjusting the solid feedstock feeding system configuration (e.g., move the dosing tank from a downstream position to an upstream position relative to the piston feeder, remove the dosing tank from a solid feedstock feeding system already in place, or add the dosing tank to a solid feedstock feeding system already in place).

[0077] Present embodiments also include a method of feeding a solid feedstock (e.g., the solid feedstock **18**) to a reactor (e.g., the reactor **14**). For example, **FIG. 13** is a flow diagram of a method **300** that may be used to feed the solid feedstock into the reactor using the disclosed piston feeder (e.g., the piston feeder **30**), while also avoiding flow back of the solid feedstock from the dosing tank (e.g., the dosing tank **32**) back into the piston feeder. To facilitate discussion of the acts of the method **300**, reference will be made to **FIG. 14-18**. The method **300** includes providing the solid feedstock to a first chamber of the piston feeder at ambient pressure (block **304**).

[0078] For example, with reference to **FIG. 14**, the piston feeder **30** receives the solid feedstock **18** from a solid feedstock storage tank through the inlet **120**. As shown in the illustrated embodiment, the inlet **120** is fluidly coupled to the feed chamber **122**. The feed chamber **122** is aligned with the inlet **120** and receives the solid feedstock **18** from the solid feedstock storage tank disposed upstream of the piston feeder **30**. In the illustrated embodiment, the fourth piston **108** is positioned such that the chambers **110**, **112**, **122** and the conduit **114** are isolated from the outlet **124** and the dosing tank (e.g., the dosing tank **32**) to avoid flow back of the solid feedstock **18** that

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may be in the dosing tank. For example, as discussed above the dosing tank is at a pressure of between approximately 0.6 MPa (6 bara) and 5 MPa (50 bara), which is the pressure within the reactor (e.g., the reactor **14**). In contrast, the pressure within the chambers **110**, **112**, **122** and the conduit **114** is at ambient (e.g., approximately 0.1 MPa (1 bara)). The pressure differential between the piston feeder **30** and the dosing tank may cause flow back of the solid feedstock **18** back into the piston feeder **30** if an exit **206** of the second chamber **112** is not blocked and isolated from the outlet **124**. Therefore, while in this position, the end portion **150** of the fourth piston **108** abuts the inner chamber wall **232** of the chamber **230b**, thereby exerting a force on the pressure seal **136** causing it to compress, which forces it out against an inner surface of the chamber **230b**. In this way, the pressure seal **136** provides a seal and isolates the outlet **124** from the chambers **110**, **112**, **122** and the conduit **114** to maintain the pressuring at the outlet **124** substantially the same as the pressure within the dosing tank.

[0079] Returning to **FIG. 13**, the method **300** also includes transferring the solid feedstock from the feed chamber into the second chamber (block **310**). For example, as shown in **FIG. 15** the first piston **102** moves towards a terminus **312** of the first chamber **110** to align the feed chamber **122** with an opening **316** of the conduit **114**. Once the feed chamber **122** is aligned with the opening **316**, the solid feedstock **18** flows through the conduit **114** and into the second chamber **112**. The fourth piston **108** remains in place to continue isolating the outlet **124** and blocking fluid communication between the chambers **110**, **112**, **122** and the conduit **114** and the dosing tank, thereby mitigating flow back of the solid feedstock **18** already in the dosing tank.

[0080] Once again returning to **FIG. 13**, following transfer of the solid feedstock to the second chamber in accordance with the acts of block **310**, the method **300** includes pressurizing the second chamber (block **318**). For example, the third piston **106** moves toward the second chamber **112**, thereby blocking fluid communication between the chambers **110**, **122** and the conduit **114** and the second chamber **112**, as shown in **FIG. 16**. The second chamber **112** is isolated from the conduit **114** (and anything upstream of the conduit **114**) and the outlet **124** of the piston feeder **30**. Similar to the fourth piston **108**, the end portion **150b** of the third piston **106** abuts an inner wall **320** of a chamber inlet **324** associated with the second chamber **112**, thereby exerting a force on the pressure seal **134** causing it to compress, which forces it out against an

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inner surface of a second conduit **326** that houses the barrel **118** of the third piston **106**. The fourth piston **108** remains in position blocking fluid communication between the second chamber **112** and the outlet **124**. In this way, the pressure seal **134** provides a seal and isolates the second chamber **112** from the conduit **114** and upstream of the conduit **114**, and the pressure seal **136** seals and isolates the second chamber **112** from the outlet **124** to allow the second chamber **112** to be pressurized to a pressure that is substantially the same as the pressure within the dosing tank.

[0081] For example, a pressure of the second chamber **112** is at ambient. Therefore, the second chamber **112** is pressurized according to block **312** of the method **300** such that the pressure within the second chamber **112** is approximately equal to the pressure within the dosing tank. Pressurizing the second chamber **112** before feeding the solid feedstock **18** into the dosing tank mitigates flow back of the solid feedstock **18** within the dosing tank that may be caused due to the pressure differential between the second chamber **112** and the dosing tank. As discussed above, the second chamber **112** includes the bypass valve **140** through which H₂ gas may be injected into the second chamber **112**. The purge valve **142** is opened such that the air within the second chamber **112** may be displaced by the H₂ gas. Once the air within the second chamber **112** is displaced, the purge valve **142** is closed and the H₂ gas continues to fill the second chamber **112** until the desired pressure is reached. For example, the dosing tank may be at a pressure of between approximately 0.6 MPa (6 bara) and 5 MPa (5 bara). Accordingly, the second chamber **112** is pressurized to a pressure of 0.6 MPa (6 bara) and 5 MPa (5 bara).

[0082] Returning to **FIG. 13**, the method includes feeding the solid feedstock to a dosing tank (block **330**). To feed the solid feedstock **18** into the dosing tank (e.g., the dosing tank **32**), the fourth piston **108** moves away from the outlet **124** while the third piston **106** remains in place to maintain the second chamber **112** isolated from the first chambers **110**, **122** and the conduit **114**, as shown in **FIG. 17**. Movement of the fourth piston **108** in the direction **332** releases the force (e.g., the forces **226**, **250**) from the pressure seal **136**, which opens and allows fluid communication between the second chamber **112** and the dosing tank via the outlet **124**. The barrel **117** of the second piston **104** moves within the second chamber **112** in a direction **334** toward outlet **124** to move the solid feedstock **18** into the dosing tank. As should be noted, the pistons **104**, **108** may move simultaneously or in series. For example, in one embodiment, the third piston **106** moves in

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the direction **334** as the fourth piston **108** moves in the direction **332**. In other embodiments, the fourth piston **108** moves in the direction **332** first to allow fluid communication between the second chamber **112** and the outlet **124**, followed by movement of the second piston **104** in the direction **334** to feed the solid feedstock **18** into the dosing tank.

[0083] Once the solid feedstock **18** is fed to the dosing tank, the piston feeder **30** may receive another batch of the solid feedstock **18**. For example, returning to **FIG. 13**, the method **300** includes aligning the feed chamber with the inlet of the piston feeder (block **340**). The step may be done after or during the acts of block **330**. In certain embodiments, the acts of block **340** may be done simultaneously with the acts of block **318**. During alignment of the feed chamber **122** and the inlet **124**, the first piston **102** moves in a direction **342** away from the terminus **312** of the first chamber **110** and toward the inlet **124** (see **FIG. 18**). The pistons **104**, **106**, **108** remain in place to keep the first chamber **110** and the conduit **114** isolated from the second chamber **112**, the outlet **124**, and the dosing tank. In this way, flow back of the solid feedstock **18** in the dosing tank may be mitigated.

[0084] Following alignment of the feed chamber **122** with the inlet **124**, the solid feedstock **18** is provided to the feed chamber **122** in accordance with the acts of block **304**. The method **300** may be repeated for each batch of solid feedstock that is fed to the dosing tank. Before, during, or after each batch of solid feedstock **18** is provided to the feed chamber **122**, the second piston **104** may move away from the fourth piston **108** and the outlet **124** in a direction substantially opposite from the direction **334** and the fourth piston **108** may move toward the outlet **124** in a direction substantially opposite from the direction **332**. The third piston **106** remains in place such that the second chamber **112** remains isolated from the first chamber **110** and the conduit **114**. The configuration of the pistons **106** and **108** block fluid communication between the second chamber **112** and the first chamber **110** and the outlet **124**, respectively. While in this configuration, the purge valve **142** may be opened to release the H₂ and depressurized the second chamber **112**. Once depressurized, the third piston **106** may move away from the second chamber **112** in a direction **346** to allow fluid communication between the first chamber **110** and the second chamber **112** (see **FIG. 18**). As should be noted, based on the arrangement of the pistons **106** and **108**, the directions **332**, **346** may be the same or different.

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[0085] A piston having the seal and end portion configuration disclosed herein was tested for leakage. The leakage test was performed by pressurizing the piston and maintaining the pressure over a period of time. A reduction in pressure was measured during that time period, and the leakage rate was determined from the rate of pressure decrease. For example, the piston was pressurized to 41.5 bar. After 45 seconds, the pressure was measured every second for 300 seconds. A slope of a linear regression of the measured pressure was determined and the leak flow was calculated from the slope. The leakage test provides a good indication as to whether the piston maintains a seal for a desired number of cycles. The experimental setup included a piston having an end portion similar to that shown **FIG. 10** and disposed in a housing. The piston was moved in cycles, each cycle including a downward movement (e.g., toward a sealing area adjacent to an outlet/terminal end of the housing) to activate the seal (e.g., cause the seal to linearly expand) and an upward movement (e.g., away from the sealing area and toward a housing opening opposite to the terminal end) to deactivate the seal (e.g., cause the seal to linearly retract). A pressure vessel pressurized with inert gas (e.g., nitrogen (N₂) or helium (He)) was positioned below the piston to measure the sealing ability of the seal. A pressure of the pressure vessel was observed for a period of time to estimate a leak rate of the inert gas and changes to the leak rate during the test. **FIG. 19** is a plot **350** of number of cycles **352** as a function of leak flow **354** in normal liters/hour (NL/h) of a piston having the spring loaded end portion and seal disclosed herein (e.g., as shown in **FIG. 10**). As shown in the illustrated embodiment, the end portion and seal configuration disclosed herein maintained the seal for over 500,000 cycles without degradation and/or wear of the seal. The leakage flow was maintained between approximately 1NL/h and approximately 6 NL/h, which is within specifications, and remained fairly steady throughout the 500,000 cycles. Conventional o-ring type seals that do not have the T-bar configuration of the seal disclosed herein begin to degrade/wear after approximately 20 cycles. In contrast the seal disclosed herein may go through 500,000 cycles or more without any observable degradation/wear and changes in leak rate.

[0086] As discussed above, the solid feedstock system disclosed herein may be used to provide a solid feedstock (e.g., biomass) to a reactor (e.g., a hydroprocessing reactor) in a manner that does not require large vessels and pressurized gas compared to lock hopper feeding systems used in commercial applications. The disclosed system and methods may also mitigate compaction of the solid feedstock that may affect the overall efficiency of hydroprocessing

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techniques and cost. The disclosed system and method use a unique configuration of pistons that transfer the feed through different chambers and into a dosing tank. Certain pistons of the piston feeder provide a seal that isolates chambers to facilitate pressurizing and mitigate flow back of the solid feedstock back into the piston feeder. The disclosed seal is designed in such a manner that mitigates damage caused by creep that may result in undesirable leakage and flow back of the solid feedstock from the dosing tank to the piston feeder. Additionally, the terminal end of the pistons having the disclosed seal have a beveled terminus such that the force applied by the terminus of the piston to the seal minimizes damage to the seal overtime.

[0087] 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 hydroprocessing of a solid feedstock, comprising:

a hydropyrolysis reactor having one or more inlets configured to receive the solid feedstock and to generate a product stream comprising partially deoxygenated hydropyrolysis product, H₂O, H₂, CO₂, CO, C₁-C₃ gases, char, and fines, wherein the hydropyrolysis reactor comprises one or more deoxygenation catalysts;

a solid feedstock feeding system disposed upstream from and fluidly coupled to the hydropyrolysis reactor, wherein the solid feedstock feeding system comprises a piston feeder comprising an inlet, an outlet, at least one piston disposed between the inlet and the outlet, wherein the at least one piston comprises:

a chamber; and

a barrel disposed in and configured to translocate within the chamber, wherein the barrel comprises a terminal end having a seal, and wherein the seal comprises an annular ring having a first wall and a second wall, wherein the second wall is orthogonal to and extends from the first wall such that a first portion of the first wall protrudes away from the second wall in a first direction and a second portion of the first wall protrudes away from the second wall in a second direction that is substantially opposite from the first direction.

2. The system of claim 1, wherein the terminal end comprises a first plate, a second plate, and a third plate, wherein the third plate forms the terminus of the terminal end, wherein the seal is disposed between the first plate and the second plate, and wherein the terminal end is configured to apply one or more forces on the seal to push at least a portion of the seal toward an inner surface of the chamber.

3. The system of claim 2, wherein the first plate comprises a first surface, a first recessed wall, and a lip adjacent to the first recessed wall, the first recessed wall is circumferentially around the first surface and the first lip is around a circumference of the first plate, and wherein the second

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plate comprises a second surface, a second recessed wall, a second lip, and an interior wall extending from the second surface and positioned parallel to the second lip, the second recessed wall is disposed between the second lip and the interior wall and is circumferentially around the second surface.

4. The system of claim 3, wherein the first portion of the first wall of the seal is disposed within the first recessed wall, the second portion of the first wall of the seal is disposed within the second recessed wall, the first wall abuts the interior wall, and the second wall is disposed between the first lip of the first plate and the second lip of the second plate.

5. The system of claim 2, wherein the third plate has a beveled end, and wherein an angle of the bevel is between approximately 35° and 50°.

6. The system of claim 2, wherein the seal is an elastic incompressible material.

7. The system of claim 2, wherein a cross-sectional geometry of the seal is T-shaped.

8. The system of claim 2, comprising a second piston disposed upstream from the at least one piston, wherein the second piston comprises a second chamber and a second barrel disposed and configured to translocate within the second chamber, wherein the second barrel comprises a second terminal end having a top plate, a middle plate, a bottom plate, and a second seal disposed between the top plate and the middle plate, and wherein the second seal has a cross-sectional geometry that is T-shaped.

9. The system of claim 2, comprising a dosing tank disposed downstream from and fluidly coupled to the piston feeder, wherein the dosing tank comprises a housing having one or more inlets, and one or more outlets.

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10. The system of claim 9, wherein at least one inlet of the one or more inlets is fluidly coupled to the outlet of the piston feeder and configured to receive the solid feedstock from the piston feeder, and wherein the at least one piston is positioned adjacent to the one or more inlets of the dosing tank and is configured to isolate a portion of the piston feeder from the dosing tank.

11. The system of claim 1 comprising a hydroconversion reactor disposed downstream from and fluidly coupled to the hydropyrolysis reactor, wherein the hydroconversion reactor is configured to receive the product stream, wherein the partially deoxygenated hydropyrolysis product in the product stream undergoes hydroconversion to generate a vapour phase product comprising substantially fully deoxygenated hydrocarbon product, H₂O, CO, CO₂, and C₁ – C₃ gases.

12. A system for hydroprocessing of a solid feedstock, comprising:

a hydropyrolysis reactor having one or more inlets configured to receive the solid feedstock and configured to generate a product stream comprising partially deoxygenated hydropyrolysis product, H₂O, H₂, CO₂, CO, C₁-C₃ gases, char, and fines;

a hydroconversion reactor disposed downstream from and fluidly coupled to the hydropyrolysis reactor, wherein the hydroconversion reactor is configured to receive the product stream, wherein the partially deoxygenated hydropyrolysis product in the product stream undergoes hydroconversion in the hydroconversion reactor to generate a vapour phase product comprising substantially fully deoxygenated hydrocarbon product, H₂O, CO, CO₂, and C₁ – C₃ gases; and

a solid feedstock feeding system disposed upstream from and fluidly coupled to the hydropyrolysis reactor, wherein the solid feedstock feeding system comprises a piston feeder comprising an inlet, an outlet, at least one piston disposed between the inlet and the outlet, wherein the at least one piston comprises a barrel disposed in and configured to translocate within a chamber and comprising a seal on a terminal end, wherein the seal comprises an annular ring having a T-shaped cross-sectional geometry.

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13. The system of claim 12, wherein the seal is disposed between a first plate and a second plate forming part of the terminal end, and wherein at least a portion of the seal is configured to protrude out from an exterior surface of the first and second plates when one or more forces are applied to the terminal end and to retract when the one or more forces are removed from the terminal end.
14. The system of claim 12, wherein the terminal end of the barrel has a beveled end.
15. The system of claim 14, wherein an angle of the bevel is between approximately 35° and 50°.
16. The system of claim 12, wherein the seal is an elastic incompressible material.
17. The system of claim 12, comprising a dosing tank disposed between and fluidly coupled to the piston feeder and the hydrolysis reactor.
18. The system of claim 17, wherein the dosing tank comprises a housing having one or more inlets, and one or more outlets, wherein at least one inlet of the one or more inlets is fluidly coupled to the outlet of the piston feeder and configured to receive the solid feedstock from the piston feeder, and wherein the piston is positioned adjacent to the one or more inlets of the dosing tank and is configured to isolate a portion of the piston feeder from the dosing tank.
19. The system of claim 12, comprising a second piston disposed upstream from the piston, wherein the second piston comprises a second barrel disposed and configured to translocate within a second chamber, wherein the second barrel comprises a second terminal end having a second seal.

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20. The system of claim 19, wherein the second seal has a cross-sectional geometry that is T-shaped.