(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
22 August 2024 (22.08.2024)

WIPO | PCT

(10) **International Publication Number**
WO 2024/173198 A2

(51) **International Patent Classification:**
C01B 3/36 (2006.01) *C10B 21/20* (2006.01)

(21) **International Application Number:**
PCT/US2024/015313

(22) **International Filing Date:**
12 February 2024 (12.02.2024)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
63/445,107 13 February 2023 (13.02.2023) US

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(54) Title: CONTROL OF SCRUBBING OPERATION IN GASIFICATION

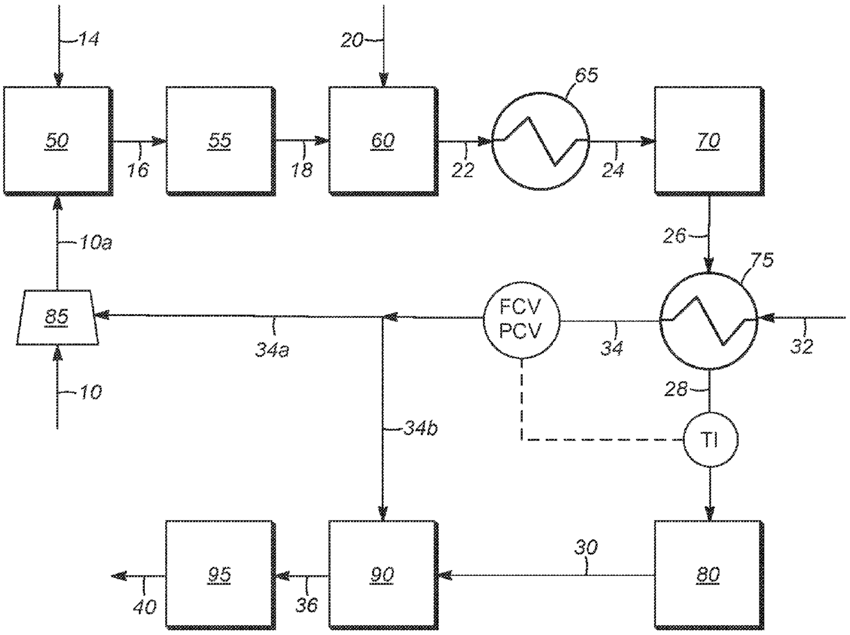

FIGURE 1

(57) **Abstract:** Gasification processes utilizing carbonaceous feeds and preferably biomass are disclosed, which can implement one or more strategies for controlling the temperature of the scrubber operation used to remove water-soluble contaminants from the gasifier effluent. Temperature of the scrubber feed (*e.g.*, the un-scrubbed gasifier effluent or portion thereof that directly enters the scrubber) may be controlled by removing heat from a heated scrubber feed, such as by steam generation that may be further integrated within the overall process. Suitable equipment for transferring heat from a hot gasifier effluent stream can include a boiler that utilizes convective heat exchange, such as in the case of a kettle boiler that generates low to medium pressure steam, thereby improving the overall thermal efficiency of the process.

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[Continued on next page]

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

— *of inventorship (Rule 4.17(iv))*

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

CONTROL OF SCRUBBING OPERATION IN GASIFICATION

CROSS REFERENCE TO RELATED APPLICATIONS

[01] This application claims the benefit of priority to U.S. Provisional Application No. 63/445,107, filed February 13, 2023, which is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

[02] Aspects of the invention relate to gasification processes, and more particularly temperature control of unit operations in such processes, such as a scrubbing operation used to remove water-soluble contaminants from a gasifier effluent.

DESCRIPTION OF RELATED ART

[03] The gasification of coal has been performed industrially for over a century in the production of synthesis gas (syngas) that can be further processed into transportation fuels. More recent efforts toward developing energy independence with reduced greenhouse gas emissions have led to a strong interest in using biomass as a gasification feed, and thereby an alternative potential source of synthesis gas, as well as its downstream conversion products. Generally, biomass gasification is performed by partial oxidation in the presence of a suitable oxidizing gas containing oxygen and other possible components such as steam. Gasification at elevated temperature and pressure, optionally in the presence of a catalytic material, produces an effluent with hydrogen and oxides of carbon (CO, CO_2), as well as hydrocarbons such as methane. This effluent, which is often referred to as synthesis gas in view of its H_2 and CO content, must be cooled significantly and also treated to remove a number of undesired components that can include particulates, alkali metals, halides, and sulfur compounds, in addition to byproducts of gasification that are generally referred to as tars and oils. Furthermore, downstream conversion of the synthesis gas to value-added products often requires its hydrogen content to be increased, relative to that obtained from gasification alone.

[04] The economics of biomass gasification and the effective utilization of the produced synthesis gas for obtaining desired end products are impacted by a number of complex and interacting processing objectives, as well as the associated equipment requirements. For increasing the H_2:CO molar ratio of the synthesis gas for its subsequent use in a number of reactions, the exothermic water-gas shift (WGS) reaction gas according to:

$$CO + H_2O \leftrightarrow H_2 + CO_2$$

is widely exploited. The thermodynamics of this reaction govern an equilibrium shift toward hydrogen production at lower temperatures, which are generally unfavorable from the standpoint of reaction kinetics.

[05] Operations conducted to purify the gasifier effluent, or synthesis gas, in preparation for the catalytic WGS reaction, include scrubbing to remove water-soluble contaminants, which requires a significant reduction in temperature, relative to the temperatures used in the upstream gasification and tar removal operations. Efforts to recover valuable heat while achieving an acceptable degree of cooling for the scrubbing operation have involved integration with biomass drying equipment and the use of air fans to maintain scrubber temperatures. This, however, requires interdependency between processing equipment that is often used for heating/cooling objectives that are not necessarily aligned and even widely unbalanced. Such a situation can arise, for example, in the case of using biomass hot water loops to provide scrubber cooling, in which case the temperature exchange between large quantities of circulating hot water for biomass drying and water being fed to the scrubber can introduce processing complexities that are not easily managed. The equipment and instrumentation associated with the control loops in such heat exchange schemes can ultimately prove unreliable and inefficient. Overall, the present state of the art would benefit from improvements in gasification technology, relating to the scrubber temperature management requirements.

SUMMARY OF THE INVENTION

[06] Aspects of the invention are associated with the discovery of gasification processes utilizing carbonaceous feeds and preferably biomass, which can implement one or more strategies for controlling the temperature of the scrubber operation used to remove water-soluble contaminants from the gasifier effluent. Particular aspects relate to controlling the temperature of the scrubber feed (*e.g.*, the un-scrubbed gasifier effluent or portion thereof that directly enters the scrubber), by removing heat from a heated scrubber feed, such as by steam generation that may be further integrated within the overall process. Suitable steam generation equipment upstream of the scrubber can include, for example, a boiler that utilizes convective heat exchange, such as in the case of a kettle boiler. In any event, heat present in the gasifier effluent leading to the scrubber (*e.g.*, un-scrubbed gasifier effluent) may be transferred to boiler feed water to produce, for example, low to medium pressure steam, thereby improving thermal efficiency. According to a specific embodiment, a hot, filtered gasifier effluent provided from a filtration operation is used as a source of heat for steam generation, prior to this gasifier effluent being fed to the scrubber.

[07] Advantageously, temperature control of the scrubber operation may be decoupled from preparation steps involving the carbonaceous feed (*e.g.*, biomass drying). In this manner, complex temperature control loops may be replaced by a simplified, single loop flow control valve or pressure control valve. The requirements for cooling of the scrubber are thereby streamlined and the temperature control of this operation is made more reliable. For example, the possibility of overheating of the scrubber may be greatly reduced, such that its performance (*e.g.*, in terms of ammonia removal) is made more robust and consistent, particularly in the face of upstream and/or downstream operational disturbances. Further benefits reside in the availability of an additional form of heat recovery and improvements over conventional processes, in terms of how this heat recovery may be controlled and manipulated to facilitate operation of the scrubber. Other advantages can include the reduction or elimination of boiler feed water flow to the scrubber for temperature control, thereby improving overall process economics, through a net savings of high-quality makeup water.

[08] Representative processes may therefore comprise controlling a temperature of the scrubber feed by steam generation from heat in a heated scrubber feed (*e.g.*, with this heated scrubber feed being upstream of a boiler and having a higher temperature, relative to that of the scrubber feed). Both this scrubber feed and heated scrubber feed may comprise, or in some embodiments may equate to, an un-scrubbed gasifier effluent, from which water-soluble contaminants are removed by the scrubbing operation. With respect to this temperature control, the steam generation may remove a varying amount of the heat from the heated scrubber feed to provide generated steam that varies in quantity and/or in quality (*e.g.*, pressure). According to one embodiment, a setpoint temperature of the scrubber feed may be maintained according to the quantity of steam generated at a fixed pressure, with this pressure bearing a relationship to both the corresponding steam saturation temperature (*e.g.*, according to a standard steam table) of the generated steam and the setpoint temperature. For example, in response to a positive deviation of the temperature of the scrubber feed above a setpoint temperature, the generated steam may be increased in quantity (flow rate), thereby removing a larger quantity of heat from the heated scrubber feed for increased cooling. Conversely, in response to a negative deviation of the temperature of the scrubber feed below the setpoint temperature, the generated steam may be decreased in quantity (flow rate), thereby removing a smaller quantity of heat from the heated scrubber feed for decreased cooling. According to a specific embodiment, therefore the controlling of the temperature of the scrubber feed comprises feedback control that varies the flow rate of the generated steam, in response to such positive or negative deviation. However, it is also possible to vary the pressure of the generated steam, which bears a relationship to its temperature, as noted above, and therefore also to the quantity of heat removed upstream of the scrubber, with higher steam pressures/temperatures corresponding to lower heat removal from the scrubber feed. Therefore, steam pressure may be increased or decreased in response to positive or negative deviations, respectively, as described above.

[09] These and other embodiments, aspects, and advantages relating to the present invention are apparent from the following Detailed Description.

BRIEF DESCRIPTION OF THE DRAWING

[10] A more complete understanding of the exemplary embodiments of the present invention and the advantages thereof may be acquired by referring to the following description in conjunction with the accompanying Figure.

[11] The Figure depicts a flowscheme illustrating an embodiment of a process for the gasification of a carbonaceous feed, which process employs various aspects as described herein for improving temperature control of a scrubbing operation, such as by steam generation. For the sake of simplicity, multiple features are illustrated and described in the single Figure, with the understanding that not all features (*e.g.*, not all individual operations and their associated process streams and equipment) are required and that various specific features, such as control of the temperature of the scrubber feed and the utilization of generated steam for various purposes (*e.g.*, drying of the carbonaceous feed and/or increasing the moisture level of a water-gas shift (WGS) operation), can be implemented independently of others.

[12] In order to facilitate explanation and understanding, the Figure provides an overview of these and other features for implementation in gasification processes. Some associated equipment such as certain vessels, heat exchangers, valves, instrumentation, and utilities, are not shown, as their specific description is not essential to the implementation or understanding of the various aspects of the invention. Such equipment would be readily apparent to those skilled in the art, having knowledge of the present disclosure. Other processes for producing syngas and/or its conversion products such as renewable liquids, according to other embodiments within the scope of the invention and having configurations and constituents determined, in part, according to particular processing objectives, would likewise be apparent.

DETAILED DESCRIPTION

[13] The expressions "wt-%" and "mol-%," are used herein to designate weight percentages and molar percentages, respectively. The expressions "wt-ppm" and "mol-ppm" designate weight and molar parts per million, respectively. For ideal gases, "mol-%" and "mol-ppm" are equal to percentages by volume and parts per million by volume, respectively. The terms "barg" and "psig" are used herein to designate gauge pressures (*i.e.*, pressure in excess of atmospheric pressure) in units of bars and pounds per square inch, respectively, whereas the terms "bar" and "psi" are used herein to designate absolute pressures. For example, gauge pressures of 0 barg and 0 psig are approximately equivalent to absolute pressures of 1 bar and 14.5 psi, respectively.

[14] The term "substantially," as used herein, refers to an extent of at least 95%. For example, the phrase "substantially all" may be replaced by "at least 95%." The phrases "all or a portion" or "at least a portion" are meant to encompass, in certain embodiments, "at least 50% of," "at least 75% of," "at least 90% of," and, in preferred embodiments, "all." Likewise, designated portions, such as a "first portion" or "second portion" may represent these percentages (but not all) of the total, and particularly these percentages (but not all) of the total process stream to which they refer.

[15] Reference to any starting material, intermediate product, or final product, which are all preferably process streams in the case of continuous processes, should be understood to mean "all or a portion" of such starting material, intermediate product, or final product, in view of the possibility that some portions may not be used, such as due to sampling, purging, diversion for other purposes, mechanical losses, *etc.* Therefore, for example, the phrase "scrubber feed…is fed to a scrubbing operation" should be understood to mean "all or a portion of the scrubber feed…is fed to a scrubbing operation." As in the case of "all or portion" being expressly stated, when "all or a portion" is the understood meaning, this phrase is should further be understood to encompasses certain and preferred embodiments as noted above.

[16] Representative processes described herein for the gasification of a carbonaceous feed may comprise a number of unit operations, with one of such operations stated as being performed or carried out "before," "prior to," or "upstream of" another of such operations, or with one of such operations being performed or carried out “after,” “subsequent to,” or “downstream of,” another of such operations. These quoted phrases, which refer to the order in which one operation is performed or carried out relative to another, are in reference to the overall process flow, as would be appreciated by one skilled in the art having knowledge of the present specification. More specifically, the overall process flow can be defined by the bulk gasifier effluent flow, including bulk flows of both the un-scrubbed gasifier effluent and scrubbed gasifier effluent, as well as the bulk WGS product flow, as such flow(s) is/are subjected to operations as defined herein. Insofar as the quoted phrases are used to designate order, in specific embodiments these phrases mean that one operation immediately precedes or follows another operation, whereas more generally these phrases do not preclude the possibility of intervening operations. Therefore, for example, one or more “operations downstream of the gasifier” can refer, according to a specific embodiment, an operation that immediately follows the gasifier, such as in the case of a tar removal operation according to the embodiment illustrated in the Figure. However, this phrase more generally, and preferably, refers to any of, or any combination of, operations that follow the gasifier, whether or not intervening operations are present, such as in the case of any one or more of a quenching operation, a convective syngas cooler (CSC) or radiant syngas cooler (RSC), and/or a filtration operation that follow the tar removal operation, as an intervening operation, according to the embodiment illustrated in the Figure. Therefore, to the extent that representative processes described herein are defined as including certain unit operations, unless otherwise stated or designated (*e.g.*, by using the phrase “consisting of”), such processes do not preclude the use of other operations, whether or not specifically described herein.

[17] Specific processes described herein are defined by a gasifier, a scrubbing operation (*e.g.*, wet scrubber) downstream of the gasifier, and a WGS operation downstream of the scrubbing operation. The gasifier provides a “gasifier effluent” and the WGS operation provides a “WGS product.” The term “gasifier effluent” is a general term that refers to the effluent of the gasifier, whether or not having been subjected to one or more operations downstream of the gasifier and upstream of the WGS operation. The “gasifier effluent” may be more particularly designated as an “un-scrubbed gasifier effluent” or a “scrubbed gasifier effluent,” which are also general terms but add specificity in terms of characterizing the gasifier effluent depending on whether or not it has been subjected to the scrubbing operation.

[18] The terms “gasifier effluent” and “un-scrubbed gasifier effluent” encompass more specific terms that designate (i) the effluent provided directly by the gasifier, *i.e.*, the “raw gasifier effluent,” (ii) the raw gasifier effluent having been subjected to at least a tar removal operation, *i.e.*, a “tar-depleted gasifier effluent,” having a lower concentration of tars and oils relative to the raw gasifier effluent, (iii) the raw gasifier effluent having been subjected to at least a dry quenching operation, *i.e.*, a “quenched gasifier effluent,” having a lower temperature and higher moisture (H_2O) concentration relative to the raw gasifier effluent, resulting from direct quenching (*e.g.*, partial quenching) with water, (iv) the raw gasifier effluent having been subjected to at least a convective syngas cooler (CSC) or at least a radiant syngas cooler (RSC), *i.e.*, a “cooled gasifier effluent” having a lower temperature relative to the raw gasifier effluent, resulting from heat transfer for external steam generation, (v) the raw gasifier effluent having been subjected to at least a filtration operation, *i.e.*, a “filtered gasifier effluent,” having a lower solid particle content relative to the raw gasifier effluent, and which may provide all or part of a “heated scrubber feed,” (vi) the raw gasifier effluent having been subjected to removal of heat, and which may provide all or part of a “scrubber feed,” having a lower temperature relative to the raw gasifier effluent, resulting from heat removal (*e.g.*, to generate steam), and (vii) the raw gasifier effluent having been subjected to any other operation upstream of the scrubbing operation, whether or not specifically described herein.

[19] Likewise, the terms “gasifier effluent” and “scrubbed gasifier effluent” encompass more specific terms that designate (viii) the raw gasifier effluent or un-scrubbed gasifier effluent having been subjected to a scrubbing operation to reduce its content of water-soluble contaminants (*e.g.*, chlorides), and (ix) the raw gasifier effluent or scrubbed gasifier effluent having been subjected to any other operation downstream of the scrubbing operation, whether or not specifically described herein. The terms “gasifier effluent,” “un-scrubbed gasifier effluent,” and “scrubbed gasifier effluent,” and any of the more specific examples (i)-(ix) of these terms, encompass products (*e.g.*, flow streams) that are upstream of, and optionally may be fed to, the WGS operation.

[20] The term “WGS product” is a general term that refers to a product of the WGS operation, all or a portion of which may, according to particular embodiments, be fed to a syngas conversion operation or a syngas separation operation to provide as a value-added product, a renewable syngas conversion product or a renewable syngas separation product. The term “WGS product” encompasses all or a portion of the product provided directly by the WGS operation, or otherwise such product after having been subjected to heating, cooling, pressurization, depressurization, and/or purification, such as acid gas removal. The term "syngas," or alternatively "synthesis gas product," insofar as they relate to streams comprising H_2 and CO, are used herein to generally refer to the gasifier effluent, whether an un-scrubbed gasifier effluent or a scrubbed gasifier effluent as defined above, or the WGS product.

[21] Particular examples of renewable syngas conversion products and renewable syngas separation products include both renewable liquid products (*e.g.*, liquid hydrocarbons or methanol) and renewable gaseous products (*e.g.*, renewable natural gas (RNG) or renewable hydrogen). The modifiers "syngas conversion" and "syngas separation," as well as the modifiers "conversion" and "separation," as used in the terms "renewable syngas conversion product," "renewable syngas separation product," "gaseous conversion byproduct," "liquid conversion byproduct," and "gaseous separation byproduct" are meant to more specifically designate the origin of these products and byproducts, as being obtained from either a syngas conversion operation (*e.g.*, comprising a Fischer-Tropsch reaction stage, a methanol synthesis reaction stage, or a methanation reaction stage) or a syngas separation operation (*e.g.*, comprising a hydrogen purification stage, such as in the case of syngas separation by pressure swing adsorption (PSA) and/or the use of a membrane). Any such syngas conversion operation or syngas separation operation is preferably performed on the WGS product that can yield an increased, and more favorable, H_2:CO molar ratio, in terms of efficiently performing the desired conversion or separation. The use of the modifiers "separation" and "conversion" in the terms noted above to modify products and byproducts does not preclude such products and byproducts being obtained from a combination of separation and conversion.

[22] Representative gasification processes described herein are defined by various possible operations, occurring downstream of the gasifier which may include a tar removal operation; operations for cooling, such as a quenching operation, a CSC, and/or an RSC; a filtration operation; steam generation, such as by using a boiler; a scrubbing operation; a WGS operation; and a syngas conversion operation. Certain possible features of the gasifier, as well as these downstream operations and their associated process streams and conditions, according to preferred embodiments and otherwise any embodiments as defined in the claims, as well as the embodiment illustrated in the Figure, are provided in the following description.

Gasifier

[23] Representative processes comprise, in a gasifier, contacting a carbonaceous feed with an oxygen-containing gasifier feed, under gasification conditions, to provide a gasifier effluent (*e.g.*, a raw gasifier effluent) comprising synthesis gas.

[24] The carbonaceous feed may comprise coal (*e.g.*, high quality anthracite or bituminous coal, or lesser quality subbituminous, lignite, or peat), petroleum coke, asphaltene, and/or liquid petroleum residue, or other fossil-derived substance. In a preferred embodiment, the carbonaceous feed may comprise biomass. The term "biomass" refers to renewable (non-fossil-derived) substances derived from organisms living above the earth's surface or within the earth's oceans, rivers, and/or lakes. Representative biomass can include any plant material, or mixture of plant materials, such as a hardwood (*e.g.*, whitewood), a softwood, a hardwood or softwood bark, lignin, algae, and/or lemna (sea weeds). Energy crops, or otherwise agricultural residues (*e.g.*, logging residues) or other types of plant wastes or plant-derived wastes, may also be used as plant materials. Specific exemplary plant materials include corn fiber, corn stover, and sugar cane bagasse, in addition to "on-purpose" energy crops such as switchgrass, miscanthus, and algae. Short rotation forestry products, such as energy crops, include alder, ash, southern beech, birch, eucalyptus, poplar, willow, paper mulberry, Australian Blackwood, sycamore, and varieties of paulownia elongate. Other examples of suitable biomass include vegetable oils, carbohydrates (*e.g.*, sugars), organic waste materials, such as waste paper, construction, demolition wastes, digester sludge, and biosludge. Representative carbonaceous feeds therefore include, or comprise, any of these types of biomass. Particular carbonaceous feeds comprising biomass include municipal solid waste (MSW) or products derived from MSW, such as refuse derived fuel (RDF). Carbonaceous feeds may comprise a combination of fossil-derived and renewable substances, including those described above. A preferred carbonaceous feed is wood (*e.g.*, in the form of wood chips).

[25] In the gasifier (or, more particularly, a gasification reactor of this gasifier), the carbonaceous feed is subjected to partial oxidation in the presence of an oxygen-containing gasifier feed, added in an amount generally limited to supply only 20-70% of the oxygen that would be necessary for complete combustion. The oxygen-containing gasifier feed will generally comprise other oxygenated gaseous components including H_2O and/or CO_2 that may likewise serve as oxidants of the carbonaceous feed. The oxygen-containing gasifier feed can refer to all gases being fed or added to the gasifier, or otherwise can refer to gas that is separate from other gases being fed or added, whether subsequently combined upstream of, or within, the gasifier. For example, the oxygen-containing gasifier feed may be introduced to the gasifier, along with steam, or a portion of steam, generated elsewhere in the process (*e.g.*, CSC-generated steam) and used as a separate feed. Contacting of the carbonaceous feed with the oxygen-containing gasifier feed in the gasifier provides a gasifier effluent, and more particularly a raw gasifier effluent as the product directly exiting the gasifier. One or more reactors (*e.g.*, in series or parallel) of the gasifier may operate under gasification conditions present in such reactor(s), with these conditions including a temperature of generally from about 500°C (932°F) to about 1000°C (1832°F), and typically from about 816°C (1500°F) to about 1038°C (1900°F). Other gasification conditions may include atmospheric pressure or elevated pressure, for example an absolute pressure generally from about 0.1 megapascals (MPa) (14.5 psi) to about 10 MPa (1450 psi), and typically from about 1 MPa (145 psi) to about 3 MPa (435 psi), or from about 0.5 MPa (72 psi) to about 2 MPa (290 psi).

[26] Gasification reactor configurations include counter-current fixed bed ("up draft"), co-current fixed bed ("down draft"), and entrained flow plasma. Different solid catalysts, having differing activities for one or more desired functions in gasification, such as tar reduction, enhanced H_2 yield, and/or reduced CO_2 yield, may be used. Limestone may be added to a gasification reactor, for example, to promote tar reduction by cracking. Various catalytic materials may be used in a gasification reactor, including solid particles of dolomite, supported nickel, alkali metals, and alkali metal compounds such as alkali metal carbonates, bicarbonates, and hydroxides. Often, a gasifier is operated with a gasification reactor having a fluidized bed of particles of the carbonaceous feed (and optionally particles of solid catalyst), with the oxygen-containing gasifier feed, and optionally separate, fluidizing H_2O- and/or CO_2-containing feeds, being fed upwardly through the particle bed. Exemplary types of fluidized beds include bubbling fluidized beds and entrained fluidized beds.

[27] In addition to gasifier effluent tar, the raw gasifier effluent comprises CO, CO_2, and methane (CH_4) that are derived from the carbon present in the carbonaceous feed, as well as H_2 and/or H_2O, and generally both, together with other components in minor concentrations, as described below. According to the embodiment illustrated in the Figure, the raw gasifier effluent 16 may be obtained directly from gasifier 50, prior to further operations as described herein.

[28] The raw gasifier effluent, or any gasifier effluent having been subjected to one or more operations as described herein, may comprise synthesis gas, *i.e.*, may comprise both H_2 and

CO, with these components being present in various amounts (concentrations), and preferably in a combined amount of greater than about 25 mol-% (*e.g.*, from about 25 mol-% to about 95 mol-%), greater than about 50 mol-% (*e.g.*, from about 50 mol-% to about 90 mol-%), or greater than about 65 mol-% (*e.g.*, from about 65 mol-% to about 85 mol-%). With respect to any such combined amounts (concentrations), the H_2:CO molar ratio of the gasifier effluent may be suitable for use in downstream syngas conversion operations (reactions or separations), such as (i) the conversion to a renewable syngas conversion product comprising higher molecular weight hydrocarbons and/or alcohols of varying carbon numbers via Fischer-Tropsch conversion or (ii) the conversion to a renewable syngas conversion product comprising methanol via a catalytic methanol synthesis reaction, or (iii) the conversion to a renewable syngas conversion product comprising renewable natural gas (RNG) via catalytic methanation that increases the methane content in a resulting RNG stream, or (iv) the separation of a renewable syngas separation product comprising purified hydrogen. More typically, however, a WGS operation is needed to achieve a favorable H_2:CO molar ratio, and/or a favorable H_2 concentration, for these or other downstream syngas conversion and separation operations. For example, the WGS operation may include parameters (*e.g.*, reactor temperatures and/or catalyst types) for obtaining the highest yield/concentration of hydrogen, through consumption of CO present in the syngas upstream of this operation, in the case obtaining purified hydrogen as a renewable syngas separation product (*e.g.*, by utilizing one or more PSA and/or membrane separation stages).

[29] Independently of, or in combination with, the representative amounts (concentrations) of H_2 and CO above, the gasifier effluent may comprise CO_2, for example in an amount of at least about 2 mol-% (*e.g.*, from about 2 mol-% to about 30 mol-%), at least about 5 mol-% (*e.g.*, from about 5 mol-% to about 25 mol-%), or at least about 10 mol-% (*e.g.*, from about 10 mol-% to about 20 mol-%). Independently of, or in combination with, the representative amounts (concentrations) of H_2, CO, and CO_2 above, the gasifier effluent may comprise CH_4, for example in an amount of at least about 0.5 mol-% (*e.g.*, from about 0.5 mol-% to about 15 mol-%), at least about 1 mol-% (*e.g.*, from about 1 mol-% to about 10 mol-%), or at least about 2 mol-% (*e.g.*, from about 2 mol-% to about 8 mol-%). Together with any water vapor (H_2O), these non-condensable gases H_2, CO, CO_2, and CH_4 may account for substantially all of the composition of the gasifier effluent. That is, these non-condensable gases and any water may be present in the gasifier effluent in a combined amount of at least about 90 mol-%, at least about 95 mol-%, or even at least about 99 mol-%.

Tar Removal Operation

[30] The raw gasifier effluent, obtained directly from the gasifier, will generally comprise gasifier effluent tar, such that a tar removal operation is typically necessary for further processing. This gasifier effluent tar can include compounds that are referred to in the art as “tars” and “oils” and are more particularly hydrocarbons and oxygenated hydrocarbons having molecular weights greater than that of methane, which may be present in the gasifier effluent at concentrations ranging from several wt-ppm to several wt-%. Certain types of these compounds, having relatively high molecular weight, are further characterized by being problematic due to their tendency to condense at lower temperatures and coat internal surfaces of processing equipment, downstream of the gasifier, causing undesirable fouling, corrosion, and/or plugging. These compounds also interfere with subsequent processing steps, or syngas conversion operations, for upgrading synthesis gas to higher value products, which perform optimally (*e.g.*, from the standpoint of stability) with pure feed gases.

[31] Particular compounds that are undesirable for these reasons include hydrocarbons and oxygenated hydrocarbons having six carbon atoms or more (C_6^+ hydrocarbons and oxygenated hydrocarbons), with benzene, toluene, xylenes, naphthalene, pyrene, phenol, and cresols being specific examples. These compounds are typically present in the raw gasifier effluent in a total (combined) amount from 1-100 g/Nm^3. The removal (*e.g.*, by conversion) of these organic compounds is therefore generally necessary to avoid serious problems caused by their deposition over time. Other types of tars and oils, such as ethane, ethylene, and acetylene, will not condense from the gasifier effluent but will nonetheless “tie up” hydrogen and carbon, with the effect of reducing the overall yield of H_2 and CO as the desired components of synthesis gas.

[32] Depending on the specific tar removal operation, tars and oils in the raw gasifier effluent can be converted, either catalytically or non-catalytically, by oxidation, cracking, and/or reforming to provide, in the tar-depleted gasifier effluent, additional H_2 and CO. The tar conversion reaction(s) can utilize available O_2 or oxygen sources (*e.g.*, H_2O and/or CO_2) that are present in, and/or added to, the synthesis gas. In view of the gasifier effluent tar, together with methane, containing a significant portion of the energy of the raw gasifier effluent, the conversion of these compounds can increase the overall yield of synthesis gas substantially. The tar removal operation, which may therefore, according to certain embodiments, be more specifically a tar conversion operation, can effectively reduce the concentration of compounds present as tar in the raw gasifier effluent, having been produced in the gasifier.

In general, tar removal, and more particularly tar conversion reactions, may be performed under higher temperatures compared to those used in the gasifier, such that the tar-depleted gasifier effluent, obtained directly from the tar removal operation, may have a temperature of greater than about 1000°C (*e.g.*, from about 1000°C (1832°F) to about 1500°C (2732°F), such as from about 1204°C (2200°F) to about 1427°C (2600°F)).

[33] According to one embodiment, the tar removal operation may be used for the conversion (*e.g.*, reforming) of tar and methane through non-catalytic partial oxidation (Pox) in a reactor used for this operation. The efficiency of this specific operation can be promoted using hot oxygen burner (HOB) technology, according to which an excess of oxygen is mixed with a small amount of fuel (*e.g.*, natural gas, propane, or recycled synthesis gas). Combustion of this fuel within the reactor can result in a temperature increase to above 1100°C (2012°F), causing the combustion products and excess oxygen to accelerate to sonic velocity through a nozzle, thereby forming a turbulent jet that enhances mixing between the tar/methane containing synthesis gas and the reactive hot oxygen stream. An HOB-based system can effectively improve synthesis gas yields.

[34] In the case of a tar removal operation that utilizes catalytic conversion of tar and methane, this operation may include a reactor containing a bed of catalyst comprising solid or supported Ni, solid or supported Fe, and/or dolomite, for example in the form of a secondary fluidized bed downstream of the gasifier. Other catalysts for tar conversion include olivine, limestone, zeolites, and even metal-containing char produced from the gasification. As in the case of non-catalytic processes that may be performed in a tar removal operation, catalytic tar conversion may likewise include the introduction of supplemental oxygen and/or steam reactants, into a reactor used for this operation.

[35] According to other particular embodiments, the tar removal operation may utilize a suitable liquid or solid adsorbent, to selectively adsorb tars and oils from the raw gasifier effluent. For example, the tar removal operation may be performed with an oil washing system, whereby the raw gasifier effluent is passed through (contacted with) a liquid medium such as bio-oil liquor, to extract the tars and oils based on their preferential solubility. The liquid adsorbent may be combusted after it has become spent.

[36] Regardless of the particular method by which the tar removal operation is performed, the raw gasifier effluent may comprise tars and oils (*e.g.*, present as compounds described above) in an amount, or combined amount, from about 0.01 wt-% to about 5 wt-%, such as from about 0.1 wt-% to about 3 wt-% or from about 0.5 wt-% to about 2 wt-%. The tar removal operation may be effective to substantially or completely remove this gasifier effluent tar. For example, the tar-depleted gasifier effluent exiting, or obtained directly from, this operation, may comprise tars and oils in an amount, or combined amount, of less than about 0.5 wt-%, less than about 0.1 wt-%, or less than about 0.01 wt-%. Representative levels of removal of tars and oils (*e.g.*, by conversion), measured across the tar removal operation, may be at least about 90%, at least about 95%, or even at least about 99%, resulting in a tar-depleted gasifier effluent that may be substantially or completely free of tar.

Quenching Operation

[37] Hot gasifier effluent, for example the tar-depleted gasifier effluent exiting the tar removal operation, can be cooled by various techniques that include radiant and/or convective heat exchange. In representative embodiments, at least one quenching operation, and preferably a dry quenching operation, is used, in which water is added directly to the gasifier effluent and contributes to its overall moisture content, thereby favoring H_2 production via the equilibrium-limited WGS reaction (*i.e.*, to provide an increased H_2:CO molar ratio and an increased H_2 concentration). A dry quenching operation utilizes the sensible heat of the gasifier effluent to vaporize the injected water, which is sufficient for obtaining the resulting quenched gasifier effluent at a desired, cooler temperature. In the case of using dry quenching without the further use of an RSC, the quenched gasifier effluent may have a temperature from about 400°C (752°F) to about 900°C (1652°F), and preferably from about 538°C (1000°F) to about 816°C (1500°F) to allow for further processing. Representative processes can include, after sufficient further cooling (*e.g.*, using a CSC) a subsequent filtration operation (passage through a filter) to remove solid particles (*e.g.*, dust). In preferred embodiments, only a partial quench is used in the quenching operation, as opposed to a full quench, such that the quenched gasifier effluent exiting, or obtained directly from, the dry quenching operation is above its dewpoint, *i.e.*, not saturated. In general, the dry quenching operation can promote rapid and efficient cooling through direct contact between hot gasifier effluent and water or other aqueous quenching medium.

Convective Syngas Cooler (CSC) or Radiant Syngas Cooler (RSC)

[38] As described herein, according to preferred embodiments, a combination of a quenching operation characterized by direct contact of a synthesis gas (*e.g.*, the tar-depleted gasifier effluent exiting the tar removal operation) and a quenching medium such as water, together with a CSC, can provide effective cooling for further downstream operations. Alternatively, or in combination, an RSC may be utilized for effective removal of ash and formed slag. For example, a CSC or an RSC may be used to cool a quenched gasifier effluent exiting the quenching operation to provide a cooled gasifier effluent, with the quenched gasifier effluent optionally having a temperature within a range as described above and/or the cooled gasifier effluent having temperature from about 250°C (482°F) to about 600°C (1112°F), and preferably from about 275°C (527°F) to about 450°C (842°F) to allow for subsequent filtration. In some embodiments, a CSC or an RSC may be used to achieve such temperatures of a cooled gasifier effluent, in the absence of a quenching operation. In any event, a CSC or an RSC may operate by indirect heat transfer, such as in the case of having a shell and tube configuration, typically with the generation steam from some of the heat recovered from the gasifier and tar removal operation. According to more particular embodiments, a CSC or an RSC may operate as a boiler (*e.g.*, a fire tube boiler or water tube boiler) for the production of medium and/or high pressure steam.

Filtration Operation

[39] A filtration operation, using any suitable filter, may be used to remove solid particles (particulates) from the gasifier effluent, for example the cooled gasifier effluent as described above, exiting a CSC or an RSC. In the case of biomass gasification, these solid particles can include char, tar, soot, and ash, any of which can generally contain alkali metals such as sodium. Corrosive and/or harmful species such as chlorides, arsenic, and/or mercury may also be contained in such solid particles. A high temperature filtration, for example using bundles of metal or ceramic filters, may generally be sufficient to reduce the content of solid particles in the gasifier effluent, such as to provide a filtered gasifier effluent exiting, or obtained directly from, the filtration operation and having less than 1 wt-ppm, and possibly less than 0.1 wt-ppm of solid particles. In representative embodiments, the filtered gasifier effluent may have a temperature in a range as described above with respect to the cooled gasifier effluent.

[40] In some embodiments, a filtration operation may be performed upstream of (prior to) the tar removal operation to allow the latter to operate more effectively. The removal of solid particles of varying average particles sizes, using filtration or other techniques, may be performed at any of a number of possible stages within the overall process. For example, coarse solids removal by centrifugation may be performed directly downstream of the gasifier, and/or may even be performed *in situ* in the gasifier (*e.g.*, using internal cyclones, for removal of solid particles, positioned in a headspace above a fluidized particle bed).

[41] The filtration operation may be followed by, or integrated with, a supplemental cleaning operation to further purify the gasifier effluent, such as to further reduce its tar and overall hydrocarbon content, for example by contact with a solid "polishing" material such as a carbon bed. This can provide for more thorough removal of benzene, naphthalene, pyrene, toluene, phenols, and other condensable species that could otherwise be detrimental to downstream operations, such as by deposition onto equipment.

Steam Generation

[42] Steam may be generated from heat present in a gasifier effluent, such as the filtered gasifier effluent described above and exiting, or obtained directly from, the filtration operation. According to some embodiments, a boiler may be used (*e.g.*, a kettle boiler or other equipment that utilizes convective heat exchange) to carry out indirect heat exchange. For example, the boiler may more specifically perform cooling of a heated scrubber feed to provide the scrubber feed (or cooled scrubber feed) that is input directly the scrubber, in which case both the heated and cooled streams may comprise an un-scrubbed gasifier effluent, such as the filtered gasifier effluent. Such cooling may be accompanied by heating boiler feed water with the heat removed from the heated scrubber feed, thereby performing the steam generation and providing the generated steam, optionally for integration within the overall process. It can therefore be appreciated that, according to specific embodiments, the "heated scrubber feed" may correspond to, or may comprise, the "filtered gasifier effluent." Also, the heated scrubber feed/filtered gasifier effluent and the scrubber feed/cooled scrubber feed may be specific examples of an "un-scrubbed gasifier effluent."

[43] Immediately upstream of a boiler used for steam generation, the heated scrubber feed, such the filtered gasifier effluent, may have a temperature within the ranges given above with respect to this stream, for example a temperature corresponding to that of the cooled gasifier effluent, which may be from about 250°C (482°F) to about 600°C (1112°F), and preferably from about 275°C (527°F) to about 450°C (842°F). In representative embodiments, the scrubber feed, as a consequence of the steam generation, may be cooled from a temperature within a range as described above to a temperature from about 100°C (212°F) to about 225°C (437°F), and preferably from about 105°C (221°F) to about 185°C (365°F). Such temperature may correspond to the scrubber gas inlet temperature or scrubber operating temperature, and any discreet temperature value within these ranges may serve as a control point, or setpoint temperature, for the scrubbing operation, which respect to its temperature. According to particular embodiments, the pressure of the generated steam may be constant and correspond to a desired steam saturation temperature. For example, by maintaining the pressure of the generated steam at 5.9 barg (85 psig), this would provide a steam saturation temperature of about 169°C (337°F), representing the theoretically coolest temperature of the scrubber feed, with the actual temperature of this feed normally being somewhat higher, in view of the approach temperature characteristics of a given scrubber feed cooler/boiler. Maintaining the pressure of the generated steam, in turn, allows for effective control of the temperature of syngas entering the scrubber, which, in preferred embodiments may be controlled at a temperature slightly above its dewpoint. This can provide a desired level of performance in terms of energy extraction from the heated scrubber feed, without the formation of water droplets that can damage equipment (*e.g.*, via corrosion). Embodiments of the invention are thereby directed to processes in which the temperature and flow rate of the heated scrubber feed to the scrubber feed cooler (*e.g.*, boiler such as a kettle boiler) can vary, but in which this cooler nonetheless maintains a controlled (*e.g.*, constant) temperature of the scrubber feed, according to a varying rate of steam production/heat removal at a given pressure of the generated steam.

Scrubbing Operation

[44] A scrubbing operation may be used to remove water and water-soluble contaminants from an un-scrubbed gasifier effluent, such as the filtered gasifier effluent exiting the filtration operation, following the cooling of this stream by steam generation. For example, the filtered gasifier effluent may serve as a feed to a boiler that, following indirect heat exchange, provides a cooled effluent upstream of the scrubbing operation, all or at least a portion of which effluent may provide the scrubber feed to the scrubbing operation. The temperature of this scrubber feed may be controlled through varying of the amount of heat removed by the boiler, according to embodiments described herein. The scrubbing operation itself may provide further cooling of the scrubber feed. For example, the scrubber feed entering the scrubber following cooling for steam generation as described above, may have a temperature as also described above, which corresponds to the scrubber gas inlet temperature. The scrubbed gasifier effluent exiting the scrubber may have a temperature from about 35°C (95°F) to about 100°C (212°F), and preferably from about 38°C (100°F) to about 66°C (150°F).

[45] The scrubbing operation, such as wet scrubbing, may be effective for removing, as water-soluble contaminants, chlorides (*e.g.*, in the form of HCl), ammonia, and HCN, as well as fine solid particles (*e.g.*, char and ash). For example, in the case of using a wet scrubber, an un-scrubbed gasifier effluent, such as the scrubber feed obtained following cooling, may be fed to a trayed column to perform co-current or counter-current contacting with water or an aqueous solution. Further cooling in this column, such as to a temperature below 100°C (212°F) can aid in droplet condensation for improving the contaminant removal effectiveness. The scrubbing operation can be used to provide a scrubbed gasifier effluent exiting, or obtained directly from, this operation and having a combined amount of chloride, ammonia, and solid particles of less than 1 wt-ppm, and possibly less than 0.1 wt-ppm. The scrubbing operation also generally serves to remove water, such that the moisture content of the scrubbed gasifier effluent is reduced, relative to that of the scrubber feed.

WGS Operation

[46] The water gas shift (WGS) operation reacts CO present in a gasifier effluent, for example the scrubbed gasifier effluent immediately exiting the scrubbing operation, with steam to increase H_2 concentration (as well as CO_2 concentration). In this manner, the scrubbed gasifier effluent may be characterized as a feed to the WGS operation (WGS feed). Following the tar removal operation, filtration operation, and scrubbing operation, the scrubbed gasifier effluent/feed to the WGS operation may have favorable properties for use in this operation, in terms of its being free or substantially free of water-soluble contaminants as described above, as well as tars and particulates.

[47] According to some embodiments, the scrubbed gasifier effluent/feed to the WGS operation may be heated and/or supplemented with moisture (steam) to further improve its properties for kinetically and/or thermodynamically favoring the WGS reaction that desirably increases the H_2:CO molar ratio and/or H_2 concentration of the WGS product relative these characteristics of the WGS feed. For example, this feed may be heated to a temperature from about 225°C (437°F) to about 475°C (887°F), and preferably from about 260°C (500°F) to about 399°C (750°F), prior to its input to the WGS operation. The moisture content of this feed may be augmented utilizing a supplemental source steam, such as at least a portion of the generated steam provided from the steam generation (*e.g.*, using a boiler) as described above. For example, at least a portion of steam (*e.g.*, low or medium pressure steam) generated in the boiler may be fed or added to the WGS operation (*e.g.*, to one or more reactors used in this operation), thereby improving overall heat balancing/integration. In the

WGS operation, the use of steam in excess of the stoichiometric amount may be beneficial, particularly in adiabatic, fixed-bed reactors, for a number of purposes. These include driving the equilibrium toward hydrogen production, adding heat capacity to limit the exothermic temperature rise, and minimizing side reactions, such as methanation.

[48] Reactors used in a WGS operation may contain a suitable catalyst, such as those comprising one or more of Co, Ni, Mo, and W on a solid support, particular examples of which are Co/Mo and Ni/Mo catalysts that exhibit sulfur tolerance. Other catalysts for use in this operation (*i.e.*, contained within one or more WGS reactors) include those based on copper-containing and/or zinc-containing catalysts, such as Cu-Zn-Al; chromium-containing catalysts; iron oxides; zinc ferrite; magnetite; chromium oxides; and any combination thereof (*e.g.*, Fe_2O_3-Cr_2O_3 catalysts).

[49] In a typical WGS operation, two or more reactors with interstage cooling are used in view of the thermodynamic characteristics of the WGS reaction. For example, a high-temperature shift (HTS) reactor may operate with a temperature of the reactor inlet from about 310°C (590°F) to about 450°C (842°F), with more favorable reaction kinetics but a less favorable equilibrium conversion. The effluent from the HTS may then be cooled to a temperature suitable for the reactor inlet of a low-temperature shift (LTS) reactor, such as from about 200°C (392°F) to about 250°C (482°F), for providing less favorable reaction kinetics but a more favorable equilibrium conversion, such that the combined effect of the HTS and LTS reactors results in a high conversion to H_2 with a favorable residence time. In some cases, it may be desirable to use three or more reactors, or catalyst beds, to perform the WGS reaction, again with cooling between consecutive reactors or catalyst beds.

[50] In this manner, the WGS operation may be used to provide an immediate WGS product exiting, or obtained directly from, this operation and having an increased H_2:CO molar ratio and increased H_2 concentration, relative to the feed to the WGS operation or the synthesis gas obtained from upstream operations (*e.g.*, filtered gasifier effluent or cooled gasifier effluent). For example, the immediate WGS product may have an H_2:CO molar ratio from about 0.5 to about 3.5, from about 1.0 to about 3.0, or from about 1.5 to about 2.5 and/or a hydrogen concentration of at least about 35 mol-% (*e.g.*, from about 35 mol-% to about 80 mol-%), at least about 40 mol-% (*e.g.*, from about 40 mol-% to about 70 mol-%), or at least about 45 mol-% (*e.g.*, from about 45 mol-% to about 65 mol-%). These characteristics of the immediate WGS product may be controlled by bypassing the WGS operation to a greater or lesser extent (*e.g.*, diverting a smaller or larger portion of the feed to this operation, around this operation to provide a portion of the immediate WGS product). The WGS operation may be further beneficial in terms of converting carbonyl sulfide (COS) to H_2S which can be recycled and more easily removed elsewhere in the process, such as in an acid gas removal operation or possibly, at least to some extent, in the scrubbing operation.

Syngas Conversion or Separation Operations

[51] In some embodiments, processes described herein may also include a syngas conversion operation or syngas separation operation to produce a respective renewable syngas conversion product or renewable syngas separation product, such as liquid hydrocarbons, methanol, or RNG as examples of conversion products, and purified hydrogen as an example of a separation product. In the case of liquid hydrocarbon production, the syngas conversion operation may comprise a Fischer-Tropsch (FT) reaction stage. One or more reactors in this stage are used to process the synthesis gas mixture of hydrogen (H_2) and carbon monoxide (CO) by successive cleavage of C–O bonds and formation of C–C bonds with the incorporation of hydrogen. This mechanism provides for the formation of hydrocarbons, and particularly straight-chain alkanes, with a distribution of molecular weights that can be controlled to some extent by varying the FT reaction conditions and catalyst properties. Such properties include pore size and other characteristics of the support material. The choice of FT catalyst and its active metals (*e.g.*, Fe or Ru) can impact FT product yields in other respects, such as in the production of oxygenates.

[52] In the case of methanol production, the syngas conversion operation may comprise a methanol synthesis reaction stage. One or more reactors in this stage are used to form methanol according to the catalytic reaction:

$$CO + 2H_2 \rightarrow CH_3OH \quad (1)$$

Representative catalysts for the synthesis of methanol by this route are characterized by "CZA," which is a reference to copper and zinc on alumina, or $Cu/ZnO/Al_2O_3$. Alternatively, or in combination, various other catalytic metals and their oxides may be used, including one or more of W, Zr, In, Pd, Ti, Co, Ga, Ni, Ce, Au, Mn, and their combinations.

[53] In the case of methane production as a syngas conversion operation to provide a renewable natural gas (RNG) product, one or more methanation reactors (*e.g.*, in series or parallel) may be used to react CO and/or CO_2 with hydrogen and thereby provide a hot methanation product having a significantly higher concentration of methane relative to that initially present (*e.g.*, in the WGS product). Catalysts suitable for use in a methanation reactor

include supported metals such as ruthenium and/or other noble metals, as well as molybdenum and tungsten. Generally, however, supported nickel catalysts are most cost effective. Often, a methanation reactor is operated using a fixed bed of the catalyst.

[54] In the case of purified hydrogen production, the syngas separation operation may comprise a renewable hydrogen separation stage that can utilize, for example, (i) an adsorbent in the case of separation by PSA or (ii) a membrane. Combinations of such stages may be used in a given syngas separation operation. In any such operation, a gaseous separation byproduct is also provided that is generally enriched in the non-hydrogen components of syngas, such as CO, CO_2, and/or H_2O. This byproduct may be, for example, a PSA tail gas or otherwise a membrane permeate or retentate, depending on the particular membrane used and consequently whether the renewable hydrogen separation product is recovered as the membrane retentate or permeate. This hydrogen, obtained as a result of utilizing a syngas separation operation downstream of the WGS operation, may, in some embodiments, be characterized as high purity hydrogen (*e.g.*, having a purity of at least about 99 mol-% or more, such as at least 99.9 mol-% or at least 99.99 mol-%).

Further exemplary embodiments of gasification processes

[55] The Figure depicts a flowscheme illustrating an embodiment of a process including operations as described above, and further utilizing control of the temperature of the scrubber feed by steam generation. With reference to the Figure, and with the understanding that embodiments disclosed herein do not necessarily require all of the illustrated features, such embodiments may be directed to a process for gasification of a carbonaceous feed (*e.g.*, wood) generally. The process may comprise, in gasifier 50, contacting carbonaceous feed 10 (or dried carbonaceous feed 10a, following dryer 85) with oxygen-containing gasifier feed 14 (and optionally a separate source of steam) under gasification conditions to provide an un-scrubbed gasifier effluent comprising H_2, CO, and water-soluble contaminants. Oxygen-containing gasifier feed 14 alone (or possibly in combination with a separate source of steam), may comprise H_2O and O_2, as well as optionally CO_2, in a combined concentration of at least about 90 mol-%, at least about 95 mol-%, or at least about 99 mol-%. The un-scrubbed gasifier effluent may be any process stream downstream of gasifier 50 and upstream of scrubbing operation 80, including raw gasifier effluent 16, tar-depleted gasifier effluent 18, quenched gasifier effluent 22, cooled gasifier effluent 24, filtered gasifier effluent 26, or scrubber feed 28.

[56] The process may further comprise feeding at least a portion of the un-scrubbed gasifier effluent, for example as scrubber feed 28, to scrubbing operation 80 to remove at least a portion of the water-soluble contaminants and provide scrubbed gasifier effluent 30. An un-scrubbed gasifier effluent or portion thereof may also be fed, for example as heated scrubber feed 26, to boiler 75 for steam generation from heat in this heated scrubber feed, and for providing scrubber feed 28 (which may also be referred to as a cooled scrubber feed). It can therefore be appreciated that either or both of heated scrubber feed 26 and scrubber feed 28 may correspond to, or may comprise, an un-scrubbed gasifier effluent, such as in the particular case of an un-scrubbed gasifier effluent, that, as a heated scrubber feed, is at a higher temperature relative to this un-scrubbed gasifier effluent, as a scrubber feed. The un-scrubbed gasifier effluent, as heated scrubber feed 26 and scrubber feed 28, may have the same composition. In exemplary embodiments, the un-scrubbed gasifier effluent, which is fed to boiler 75 as heated scrubber feed 26, may be a filtered gasifier effluent, having been subjected to filtration operation 70 to remove solid particles. More particularly, in addition to having been subjected to filtration operation 70, the filtered gasifier effluent may have been further subjected to one or more intervening operations downstream of gasifier 50 and upstream of filtration operation 70. For example, such intervening operations may include one or more of (i) tar removal operation 55 to remove at least a portion of gasifier effluent tar (*e.g.*, and provide tar-depleted gasifier effluent 18), (ii) quenching operation 60 comprising direct contact with quench water 20 (*e.g.*, and provide quenched gasifier effluent 22), and (iii) convective syngas cooler (CSC) 65 or radiant syngas cooler 65 (RSC) implementing heat-exchanging contact with CSC feed water or RSC feed water (*e.g.*, and provide cooled gasifier effluent 24).

[57] In achieving various benefits and advantages as described herein, a representative process may comprise controlling a temperature of scrubber feed 28 by steam generation from heat in a heated scrubber feed. This heated scrubber feed may correspond, for example, to filtered gasifier effluent 26 or optionally any other gasifier effluent upstream of boiler 75. The steam generation may remove a varying amount of the heat from the heated scrubber feed, such as from filtered gasifier effluent 26, to provide generated steam 34 of varying quantity and/or quality (*e.g.*, pressure). Steam generation may be performed (may occur or may be carried out) in boiler 75 positioned downstream of the heated scrubber feed (*e.g.*, filtered gasifier effluent 26) and upstream of scrubber feed 28. A suitable boiler may utilize convective heat exchange, such as in the case of a kettle boiler. However, more generally any suitable heat exchanger (*e.g.*, a shell and tube heat exchanger) may be used as a boiler. Regardless of the particular boiler, this equipment may perform steps of: (a) cooling the heated scrubber feed to provide the scrubber feed 28 (which may also be referred to as a cooled scrubber feed), with both of these streams comprising un-scrubbed gasifier effluent (*e.g.*, filtered gasifier effluent), and (b) heating boiler feed water 32 with the heat (removed) from the heated scrubber feed, to perform the steam generation and provide generated steam 34.

[58] A representative process may comprise, optionally following one or more intervening operations downstream of gasifier 50, feeding at least a portion of the un-scrubbed gasifier effluent, for example as heated scrubber feed 26, to boiler 75 for steam generation from heat in heated scrubber feed 26 and for providing scrubber feed 28 (which may also be referred to as a cooled scrubber feed). In addition, heat-exchanging contact of boiler feed water 32 with heated scrubber feed 26 in boiler 75 may be used to provide generated steam 34 of varying quantity and/or quality (*e.g.*, pressure), in response to a temperature of scrubber feed 28. Such temperature may be measured at various points, such as directly downstream of boiler 75, directly upstream of scrubbing operation 80, or any intervening point, which measurement may serve as a basis for control of scrubbing operation 80, or more particularly a scrubber used in this operation. According to one embodiment, the temperature of scrubber feed 28 is measured at the gas inlet of a scrubber used in scrubbing operation 80, which measurement serves as a basis for control. Regardless of the particular point of measurement, scrubber feed 28 is ultimately fed to scrubbing operation 80, or more particularly a scrubber used in this operation, to remove at least a portion of the water-soluble contaminants (*e.g.*, HCl and ammonia), and provide scrubbed gasifier effluent 30.

[59] According to specific embodiments for controlling the temperature of scrubber feed 28, a process may comprise steps in which: (a) in response to a positive deviation of this temperature above a setpoint temperature, generated steam 34 is increased in quantity and/or quality (thereby removing a greater amount of heat from heated scrubber feed 26), and (b) in response to a negative deviation of this temperature below the setpoint temperature, generated steam 34 is decreased in quantity and/or quality (thereby removing a lesser amount of heat from heated scrubber feed 26). In the particular case of increasing or decreasing the quality of generated steam 34 in response to these temperature deviations, the pressure of this generated steam 34 may be varied. In some embodiments, the controlling of the temperature of the scrubber feed comprises feedback control that varies the pressure of the generated steam.

[60] A representative control methodology may utilize flow control valve (FCV) or pressure control valve (PCV) that controls the flow or pressure, respectively, of generated steam 34, according to a temperature of scrubber feed 28 received from temperature indicator (TI), used to measure this temperature. The flow or pressure of generated steam 34 may be varied, as described above, in response to a deviation of this temperature from a setpoint temperature, thereby removing a larger or smaller quantity of heat from heated scrubber feed 26 to maintain this temperature. Regardless of any particular control methodology, the setpoint temperature of scrubber feed 28 may be any discreet value suitable for a given process and its associated configuration. In some embodiments, the setpoint temperature may be a discreet value within the range from about 100°C (212°F) to about 225°C (437°F), such as from about 105°C (221°F) to about 185°C (365°F). In some embodiments, the steam generation (*e.g.*, from boiler 75) provides generated steam having a pressure from about 0 barg (0 psig) to about 20 barg (290 psig), such as from about 0 barg (0 psig) to about 10 barg (145 psig), from about 0 barg (0 psig) to about 7.5 barg (109 psig), from about 0.5 barg (7 psig) to about 20 barg (290 psig), from about 0.5 barg (7 psig) to about 10 barg (145 psig), or from about 0.5 barg (7 psig) to about 7.5 barg (109 psig). Such ranges of steam pressures correspond to respective ranges of steam temperatures (based on steam saturation temperatures) from about 100°C (212°F) to about 215°C (419°F), such as from about 100°C (212°F) to about 184°C (363°F), from about 100°C (212°F) to about 173°C (343°F), from about 112°C (234°F) to about 215°C (419°F), from about 112°C (234°F) to about 184°C (363°F), or from about 112°C (234°F) to about 173°C (343°F). Accordingly, in some embodiments, generated steam may be considered low or medium pressure steam.

[61] In preferred embodiments, the setpoint temperature of the scrubber feed is higher than its dewpoint temperature, in order to obtain advantages described herein, relating to effective heat extraction with the avoidance of condensation. For example, the setpoint temperature may be from about 1°C (2°F) to about 15°C (27°F), from about 1°C (2°F) to about 10°C (18°F), or from about 1°C (2°F) to about 5°C (9°F) higher than the dewpoint temperature of the scrubber feed. In any event, the setpoint temperature of the scrubber feed has implications with respect to the pressure of the generated steam, in view of the relationship between this pressure and the saturation temperature of the generated steam. Such implications may be particularly relevant in embodiments in which the steam generation provides generated steam that is maintained (*e.g.*, fixed) at a given pressure, but is varied in terms of flow rate to vary the quantity of heat removed from the heated scrubber feed and thereby maintain the setpoint temperature. Given the approach temperature between the generated steam (acting as the cold fluid) and the scrubber feed (acting as the hot fluid), the steam generation may provide generated steam that is maintained (*e.g.*, fixed) at a pressure corresponding to a steam saturation temperature that equals, or that is at least within about 10°C (18°F), such as within about 5°C (9°F), of the setpoint temperature. For example, the steam saturation temperature may be equal to the setpoint temperature but may also be from about 1°C (2°F) to about 10°C (18°F), such as from about 1°C (2°F) to about 5°C (9°F), lower than the setpoint temperature.

[62] Regardless of any particular control methodology, generated steam 34 may be utilized for further integration within the process, either for direct input into a process stream or process equipment, or for utilization of its heat content, such as for heating and/or drying applications. For example, as shown in the Figure, steam generation from boiler 75 provides generated steam 34, at least a portion, such as first portion 34a, of which is fed to dryer 85 for drying of carbonaceous feed 10, thereby providing dried carbonaceous feed 10a for feeding to gasifier 50. The use of heat from first portion 34a of generated steam 34 may be particularly effective in drying particular types of biomass, such as wood. In this manner, temperature control of scrubbing operation 80 may be integrated with biomass drying, but without the reliance on such drying for establishing important parameters relating to the scrubber operation. Alternatively, or in combination with feeding a portion of generated steam 34 to dryer 85, representative processes may comprise feeding at least a portion, such as second portion 34b, of generated steam 34 to WGS operation 90, such as in the case of directly inputting such portion into a WGS reactor or combining such portion with a feed to WGS operation 90, such as scrubbed gasifier effluent 30. In either case, steam added to WGS operation 90 serves to drive the intended WGS reaction toward H_2 production, such that WGS product 36 has an H_2:CO molar ratio that is increased, relative to that of scrubbed gasifier effluent 30.

[63] According to a representative process, raw gasifier effluent 16 produced in gasifier 50 is fed to tar removal operation 55, to provide tar-depleted gasifier effluent 18, having a lower amount of tar relative to raw gasifier effluent 16. Generally, processes comprise recovering a synthesis gas product from tar-depleted gasifier effluent 16, with such synthesis gas product possibly including any of those downstream of tar-depleted gasifier effluent 16 as illustrated in the Figure. For example, the synthesis gas product may be recovered as water-gas shift (WGS) product 36 of WGS operation 90, optionally following one or more intervening operations performed on the gasifier effluent, downstream of the tar removal operation and upstream of the WGS operation. Such intervening operations can include one or more of (i) quenching operation 60 comprising direct contact of the gasifier effluent with quench water 20, (ii) convective syngas cooler (CSC) 65 or radiant syngas cooler (RSC) 65, implementing heat-exchanging contact of the gasifier effluent with CSC feed water or RSC feed water, (iii) filtration operation 70 to remove solid particles from the gasifier effluent, (iv) boiler to further remove heat from the gasifier effluent and control the temperature of the downstream scrubbing operation as described herein, and (v) scrubbing operation 80 to remove water-soluble contaminants from the gasifier effluent.

[64] As more particularly illustrated in the Figure, a representative process comprises, in quenching operation 60, which may be more particularly a partial dry quench (PDQ) operation, contacting (*e.g.*, by direct contact), tar-depleted gasifier effluent 18 with quench water 20. This provides quenched gasifier effluent 22, having a temperature that is decreased relative to that of tar-depleted gasifier effluent 18. The process may additionally comprise, in convective syngas cooler (CSC) 65 or radiant syngas cooler (RSC) 65, further cooling quenched gasifier effluent 22, such as by indirect, heat-exchanging contact with CSC feed water or RSC feed water. This provides cooled gasifier effluent 24, which may then be subjected to filtration operation 70, heat removal in boiler 75, and scrubbing operation 80, with particular details of these operations as described herein. Feeding at least a portion of scrubbed gasifier effluent 30, provided from scrubbing operation 80, to WGS operation 90, provides WGS product 36 having a H_2:CO molar ratio that is increased relative to that of raw gasifier effluent 16, and/or syngas exiting any of intervening operations, such as tar-depleted gasifier effluent 18, quenched gasifier effluent 22, cooled gasifier effluent 24, filtered gasifier effluent 26 exiting filtration operation 70, scrubber feed 18 to scrubbing operation 80, or scrubbed gasifier effluent 30 exiting scrubbing operation 80.

[65] Representative processes may further comprise feeding at least a portion of WGS product 36 to syngas conversion operation 95 or syngas separation operation 95 to provide respective renewable syngas conversion product 40 or renewable syngas separation product 40. According to more specific embodiments, for example, (i) syngas conversion operation 95 may comprise a Fischer-Tropsch reaction stage, such that renewable syngas conversion product 40 comprises liquid hydrocarbons and/or oxygenates (*e.g.*, alcohols) of varying carbon numbers, (ii) syngas conversion operation 95 may comprise a catalytic methanol synthesis reaction stage, such that renewable syngas conversion product 40 comprises methanol, or (iii) syngas conversion operation 95 may comprise a catalytic methanation reaction stage, such that renewable syngas conversion product 40 comprises RNG. According to other more specific embodiments, syngas separation operation 95 may comprise a renewable hydrogen separation stage, such that renewable syngas separation product 40 comprises purified hydrogen.

[66] Overall, aspects of the invention relate to gasification processes implementing control of a scrubbing operation used for water-soluble contaminant removal from the gasifier effluent, and more particularly control of the temperature of a scrubber used for this purpose. This can reduce process complexity while providing valuable pathways for heat integration and steam generation. Those skilled in the art, having knowledge of the present disclosure, will recognize that various changes can be made to these processes in attaining these and other advantages, without departing from the scope of the present disclosure. As such, it should be understood that the features of the disclosure are susceptible to modifications and/or substitutions, and the specific embodiments illustrated and described herein are for illustrative purposes only, and not limiting of the invention as set forth in the appended claims.

CLAIMS:

1. A process for gasification of a carbonaceous feed, the process comprising:

   in a gasifier, contacting the carbonaceous feed with an oxygen-containing gasifier feed, under gasification conditions, to provide an un-scrubbed gasifier effluent comprising H_2, CO, and water-soluble contaminants;

   feeding at least a portion of the un-scrubbed gasifier effluent, as a scrubber feed, to a scrubbing operation to remove at least a portion of the water-soluble contaminants, and provide a scrubbed gasifier effluent;

   controlling a temperature of the scrubber feed by steam generation from heat in a heated scrubber feed.

2. The process of claim 1, wherein said steam generation removes a varying amount of said heat from the heated scrubber feed to provide generated steam of varying quantity and/or quality.

3. The process of claim 1 or claim 2, wherein a setpoint temperature for said controlling of the temperature of the scrubber feed is from about 100°C (212°F) to about 225°C (437°F).

4. The process of claim 3, wherein the setpoint temperature is higher than a dewpoint temperature of the scrubber feed.

5. The process of claim 4, wherein the setpoint temperature is from about 1°C (2°F) to about 10°C (18°F) higher than the dewpoint temperature of the scrubber feed.

6. The process of any one of claims 1 to 5, wherein said steam generation provides generated steam having a pressure from about 0 barg (0 psig) to about 20 barg (290 psig).

7. The process of any one of claims 3 to 6, wherein said steam generation provides generated steam that is maintained at a pressure corresponding to a steam saturation temperature that equals, or that is within about 10°C (18°F) of the setpoint temperature.

8. The process of any one of claims 1 to 7, wherein said steam generation provides generated steam, and wherein at least a portion of said generated steam is fed to a dryer for drying of said carbonaceous feed.

9. The process of any one of claims 1 to 8, wherein the carbonaceous feed is wood.

10. The process of any one of claims 1 to 9, further comprising feeding at least a portion of the scrubbed gasifier effluent to a water-gas shift (WGS) operation, to provide a WGS product having an H_2:CO molar ratio that is increased, relative to that of the scrubbed gasifier effluent.

11. The process of claim 10, wherein said steam generation provides generated steam, and wherein at least a portion of said generated steam is fed to the WGS operation.

12. The process of any one of claims 1 to 11, wherein said controlling of the temperature of the scrubber feed comprises feedback control that varies a flow rate or a pressure of the generated steam.

13. The process of any one of claims 1 to 12, wherein said steam generation is performed in a boiler positioned downstream of the heated scrubber feed and upstream of the scrubber feed.

14. The process of claim 13, wherein the boiler utilizes convective heat exchange.

15. The process of claim 13, wherein the boiler is a kettle boiler.

16. The process of claim 13, wherein said boiler performs steps of:

cooling the heated scrubber feed to provide the scrubber feed, wherein the heated scrubber feed and the scrubber feed comprise the un-scrubbed gasifier effluent; and

heating boiler feed water with said heat from the heated scrubber feed, to perform said steam generation and provide generated steam.

17. A process for gasification of a carbonaceous feed, the process comprising:

    in a gasifier, contacting the carbonaceous feed with an oxygen-containing gasifier feed, under gasification conditions, to provide an un-scrubbed gasifier effluent comprising H_2, CO, and water-soluble contaminants;

    optionally following one more intervening operations downstream of the gasifier, feeding at least a portion of the un-scrubbed gasifier effluent, as a heated scrubber feed, to a boiler for steam generation from heat in the heated scrubber feed and for providing a scrubber feed;

    wherein the boiler provides generated steam of varying quantity and/or quality in response to a temperature of the scrubber feed, which is fed to a scrubbing operation to remove at least a portion of the water-soluble contaminants, and provide a scrubbed gasifier effluent.

18. The process of claim 17, wherein:

    in response to a positive deviation of the temperature of the scrubber feed above a setpoint temperature, the generated steam is increased in quantity and/or quality, and

    in response to a negative deviation of the temperature of the scrubber feed below the setpoint temperature, the generated steam is decreased in quantity and/or quality.

19. The process of claim 18, wherein the setpoint temperature of the scrubber feed is from about 100°C (212°F) to about 225°C (437°F).

20. The process of any one of claims 17 to 19, wherein said un-scrubbed gasifier effluent is a filtered gasifier effluent, having been subjected to a filtration operation to remove solid particles.

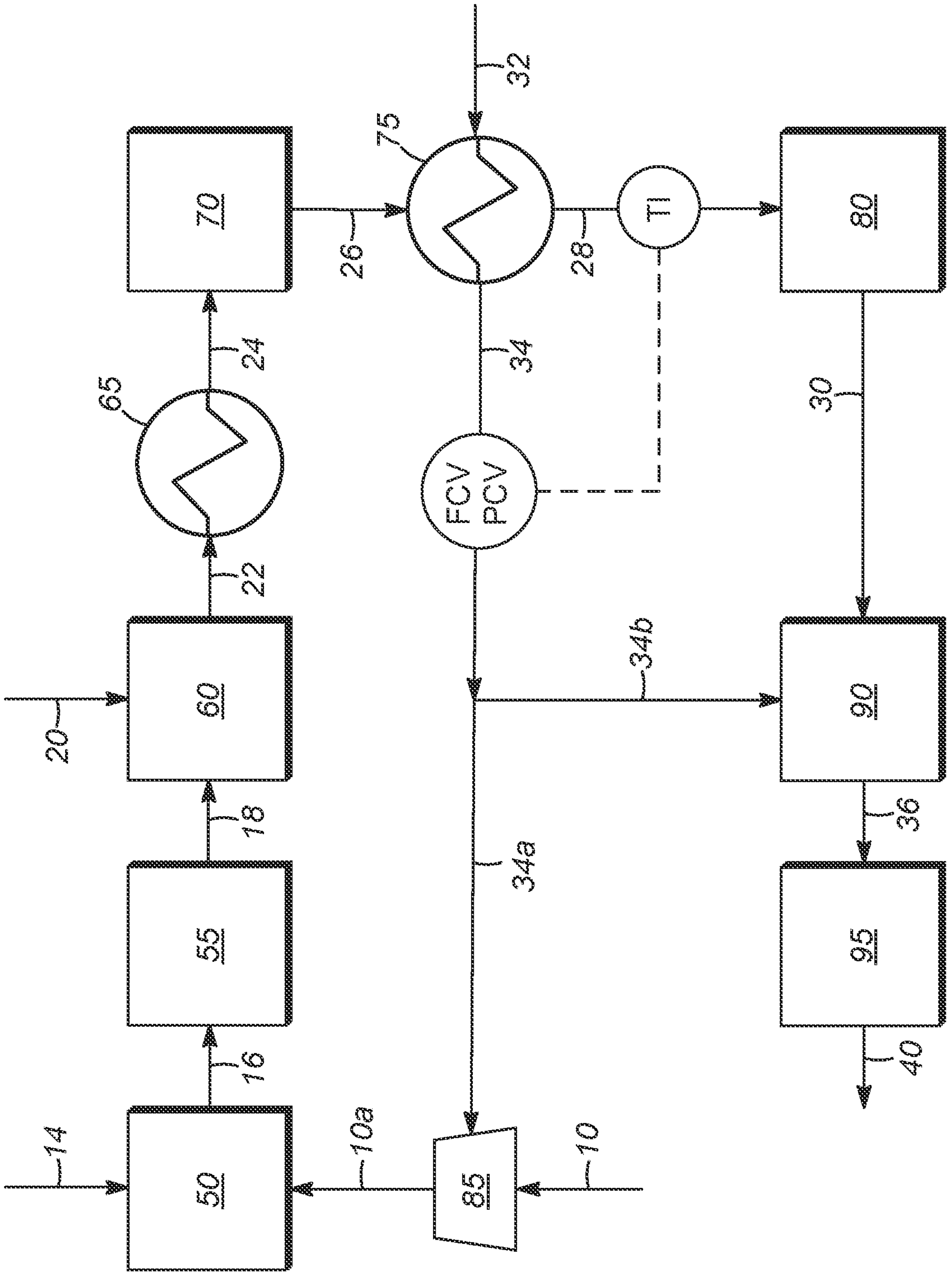
21. The process of claim 20, wherein the filtered gasifier effluent, in addition to having been subjected to said filtration operation, has been further subjected to one or more of (i) a tar removal operation to remove at least a portion of gasifier effluent tar, (ii) a quenching operation comprising direct contact with quench water, and (iii) a convective syngas cooler (CSC) implementing heat-exchanging contact with CSC feed water.

22. The process of any one of claims 17 to 21, further comprising:

feeding at least a portion of the scrubbed gasifier effluent to a water-gas shift (WGS) operation, to provide a WGS product having a H_2:CO molar ratio that is increased, relative to that of the tar-depleted effluent.

23. The process of claim 22, further comprising:

feeding at least a portion of the WGS product to (i) a syngas conversion operation to provide a renewable syngas conversion product, or (ii) a syngas separation operation to provide a renewable syngas separation product.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TI
34
FCV
PCV
80
30
34b
90
34a
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FIGURE 1