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(54) Title: PROCESSES FOR MAKING SYNTHESIS GAS AND SYNGAS-DERIVED PRODUCTS

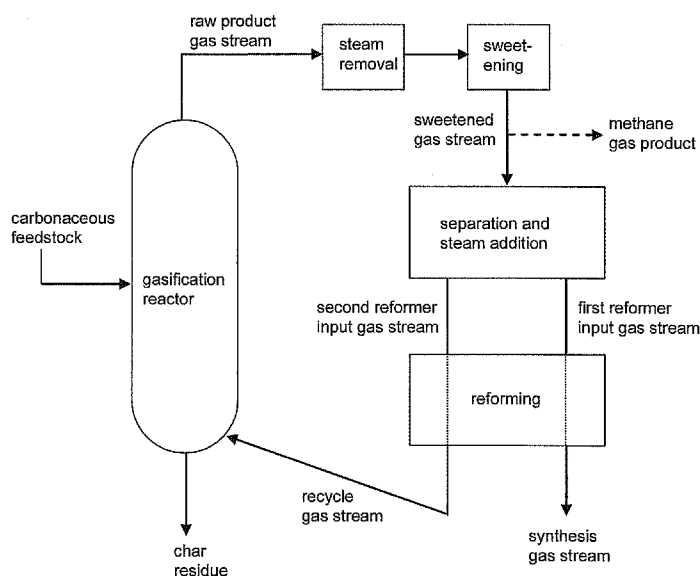


FIG. 1

(57) Abstract: The present invention provides processes for making synthesis gas and processes for making syngas-derived products. For example, one aspect of the present invention provides a process for making a synthesis gas stream comprising hydrogen and carbon monoxide, the process comprising (a) providing a carbonaceous feedstock; (b) reacting the carbonaceous feedstock in a gasification reactor in the presence of steam and a gasification catalyst under suitable temperature and pressure to form a raw product gas stream comprising a plurality of gases comprising methane, hydrogen and carbon monoxide; (c) removing steam from and sweetening the raw product gas stream to form a sweetened gas stream; (d) separating and adding steam to the sweetened gas stream to form a first reformer input gas stream having a first steam/methane ratio; and a second reformer input stream having a second steam/methane ratio, in which the first steam/methane ratio is smaller than the second steam/methane ratio; (e) reforming the second reformer input stream to form a recycle gas stream comprising steam, carbon monoxide and hydrogen; (f) introducing the recycle gas stream to the gasification reactor; and (g) reforming the first reformer input stream to form the synthesis gas stream.



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PROCESSES FOR MAKING SYNTHESIS GAS AND SYNGAS-DERIVED PRODUCTS

Field of the Invention

[0001] The present invention relates to processes for making synthesis gas (syngas). Moreover, the invention also relates to processes for making syngas-derived products.

Background of the Invention

[0002] In view of numerous factors such as higher energy prices and environmental concerns, the production of value-added gaseous products from lower-fuel-value carbonaceous feedstocks, such as petroleum coke and coal, is receiving renewed attention. The catalytic gasification of such materials to produce methane and other value-added gases is disclosed, for example, in US3828474, US3998607, US4057512, US4092125, US4094650, US4204843, US4468231, US4500323, US4541841, US4551155, US4558027, US4606105, US4617027, US4609456, US5017282, US5055181, US6187465, US6790430, US6894183, US6955695, US2003/0167961A1, US2006/0265953A1, US2007/000177A1, US2007/083072A1, US2007/0277437A1 and GB1599932.

[0003] Reforming furnaces are often used to make synthesis gas (i.e., a gas mixture having predominant quantities of CO and H₂) from clean feedstocks such as natural gas or relatively low-boiling hydrocarbons. In typical reforming processes, the feedstock and excess steam are fed through tubes bearing a supported metal catalyst (e.g., nickel) at temperatures ranging up to 1550°F and pressures ranging up to 500 psig. Lower-fuel-value carbonaceous feedstocks such as coal and petroleum coke cannot be used directly in such processes, as they would foul the metal catalyst. Gasification-based processes have been proposed for the conversion of such carbonaceous feedstocks into synthesis gas.

[0004] For example, in one such process a carbonaceous feedstock is gasified non-catalytically by partial oxidation by a mixture of oxygen and steam; about a third of the feedstock is burned in the process to provide heat and pressure, making this process relatively energy inefficient. Carbon dioxide from the combustion is co-mingled with the product gas and requires additional acid gas removal capacity as compared with carbon dioxide from combustion of furnace fuel. Oxygen for the combustion must be separated from air in an energy intensive cryogenic distillation. In other such processes, catalytic gasification is followed by one or more cryogenic separations to separate the catalytic gasification product

gas into methane and CO/H₂ fractions. Cryogenic processes are equipment-intensive and energy-inefficient, making such processes disadvantaged. Accordingly, processes are needed which can efficiently form synthesis gas and products derived therefrom from lower-fuel-value carbonaceous feedstocks.

Summary of the Invention

[0005] In one aspect, the present invention provides a process for making a synthesis gas stream comprising hydrogen and carbon monoxide, the process comprising the steps of: (a) providing a carbonaceous feedstock; (b) reacting the carbonaceous feedstock in a gasification reactor in the presence of steam and a gasification catalyst under suitable temperature and pressure to form a raw product gas stream comprising a plurality of gases comprising methane, hydrogen and carbon monoxide; (c) removing steam from and sweetening the raw product gas stream to form a sweetened gas stream; (d) separating and adding steam to at least a first portion of the sweetened gas stream to form a first reformer input gas stream having a first steam/methane ratio; and a second reformer input stream having a second steam/methane ratio, in which the first steam/methane ratio is smaller than the second steam/methane ratio; (e) reforming the second reformer input stream to form a recycle gas stream comprising steam, carbon monoxide and hydrogen; (f) introducing the recycle gas stream to the gasification reactor; and (g) reforming the first reformer input stream to form the synthesis gas stream.

[0006] In a second aspect, the present invention provides a process for making a synthesis gas stream comprising hydrogen and carbon monoxide, the process comprising the steps of: (a) providing a carbonaceous feedstock; (b) reacting the carbonaceous feedstock in a gasification reactor in the presence of steam and a gasification catalyst under suitable temperature and pressure to form a raw product gas stream comprising a plurality of gases comprising methane, hydrogen and carbon monoxide; (c) removing steam from and sweetening the raw product gas stream to form a sweetened gas stream; (d) separating and adding steam to at least a first portion of the sweetened gas stream to form a first reformer input gas stream having a first steam/methane ratio; and a second reformer input stream having a second steam/methane ratio, in which the first steam/methane ratio is smaller than the second steam/methane ratio; (e) reforming the second reformer input stream to form a recycle gas stream comprising steam, carbon monoxide and hydrogen; (f) introducing the recycle gas stream to the gasification reactor; (g) reforming the first reformer input stream to

form the synthesis gas stream; and (h) reacting the synthesis gas stream to form a syngas-derived product and heat energy.

[0007] In a third aspect, the present invention provides a process for making a synthesis gas stream comprising hydrogen and carbon monoxide, the process comprising the steps of: (a) providing a carbonaceous feedstock; (b) reacting the carbonaceous feedstock in a gasification reactor in the presence of steam and a gasification catalyst under suitable temperature and pressure to form a raw product gas stream comprising a plurality of gases comprising methane, hydrogen and carbon monoxide; (c) removing steam from and sweetening the raw product gas stream to form a sweetened gas stream; (d) separating and adding steam to at least a first portion of the sweetened gas stream to form a first reformer input gas stream having a first steam/methane ratio; and a second reformer input stream having a second steam/methane ratio, in which the first steam/methane ratio is smaller than the second steam/methane ratio; (e) reforming the second reformer input stream to form a recycle gas stream comprising steam, carbon monoxide and hydrogen; (f) introducing the recycle gas stream to the gasification reactor; (g) reforming the first reformer input stream to form the synthesis gas stream; and (h) reacting the synthesis gas stream to form a syngas-derived product and a combustible tail gas mixture.

Brief Description of the Figures

[0008] FIG. 1 is a schematic diagram of a process for making a synthesis gas stream according to one embodiment of the invention.

[0009] FIG. 2 is a schematic diagram of a process for making a synthesis gas stream according to another embodiment of the invention.

[0010] FIG. 3 is a schematic diagram of a process for making a synthesis gas stream according to another embodiment of the invention.

[0011] FIG. 4 is a schematic diagram of a process for making a synthesis gas stream according to another embodiment of the invention.

Detailed Description

[0012] The present invention relates generally to processes for making synthesis gas and processes for making syngas-derived products. An example of a process according to one aspect of the invention is illustrated in flowchart form in FIG. 1. Generally, in one process

for making synthesis gas according to the present invention, reaction of a carbonaceous feedstock in a gasification reactor forms a raw product gas stream comprising a plurality of gases comprising methane, hydrogen and carbon monoxide. This raw product gas stream is sweetened (e.g., by removing acid gases such as hydrogen sulfide), and has steam removed therefrom to form a sweetened gas stream. At least a first portion of the sweetened gas stream is separated and combined with steam to form a first reformer input gas stream having a first steam/methane ratio; and a second reformer input stream having a second steam/methane ratio, in which the first steam/methane ratio is smaller than the second steam/methane ratio. The first reformer input stream is reformed to form a synthesis gas stream. The second reformer input stream is reformed to form a recycle gas stream comprising steam, carbon monoxide and hydrogen, which is introduced to the gasification reactor. The process according to this aspect of the invention can efficiently provide synthesis gas without the use of equipment-intensive and energy-inefficient cryogenic techniques. In certain embodiments, the invention provides processes for gasifying heavy carbonaceous feedstocks to form synthesis gas without the need for cryogenic separation of gases, supplying all necessary heat by furnace firing at atmospheric pressure. Moreover, since the gasification reaction is catalyzed, the process according to this aspect of the invention can use relatively lower temperatures in the gasification reactor, thereby increasing the overall energy efficiency of the process. Additionally, since the recycle gas stream can emerge from the reforming step at high temperature, a separate recycle preheat furnace may not be required.

[0013] Generally, in one process for making a syngas-derived product according to the present invention, a synthesis gas stream is made as described above, then reacted to form a syngas-derived product and heat energy, a combustible tail gas mixture, or both. The heat energy and/or the combustible tail gas mixture can be used to generate process steam and electrical power, e.g., through heating or generating steam and driving it through a turbine. The heat energy and/or combustible tail gas mixture can also be used to provide energy to the process for making the synthesis gas stream. In another embodiment of invention, the combustible tail gas is used as a supplementary fuel to fire reforming furnaces; this integration is particularly useful because the amount of combustible tail gas is proportional to the firing duty of the reforming furnaces. Accordingly, in this aspect of the invention, synthesis gas can be converted to a useful synthesis gas-derived product, while the energy

stored in the CO triple bond can be liberated, recovered and used, thereby increasing the overall energy efficiency of the process.

[0014] The present invention can be practiced, for example, using any of the developments to catalytic gasification technology disclosed in commonly owned US2007/0000177A1, US2007/0083072A1 and US2007/0277437A1; and U.S. Patent Application Serial Nos. 12/178,380 (filed 23 July 2008), 12/234,012 (filed 19 September 2008) and 12/234,018 (filed 19 September 2008). Moreover, the processes of the present invention can be practiced in conjunction with the subject matter of the following U.S. Patent Applications, each of which was filed on even date herewith: Serial No. _____, entitled "PETROLEUM COKE COMPOSITIONS FOR CATALYTIC GASIFICATION" (attorney docket no. FN-0008 US NP1); Serial No. _____, entitled "CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR" (attorney docket no. FN-0007 US NP1); Serial No. _____, entitled "PETROLEUM COKE COMPOSITIONS FOR CATALYTIC GASIFICATION" (attorney docket no. FN-0011 US NP1); Serial No. _____, entitled "CARBONACEOUS FUELS AND PROCESSES FOR MAKING AND USING THEM" (attorney docket no. FN-0013 US NP1); Serial No. _____, entitled "CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR" (attorney docket no. FN-0014 US NP1); Serial No. _____, entitled "COAL COMPOSITIONS FOR CATALYTIC GASIFICATION" (attorney docket no. FN-0009 US NP1); Serial No. _____, entitled "PROCESSES FOR MAKING SYNGAS-DERIVED PRODUCTS" (attorney docket no. FN-0012 US NP1); Serial No. _____, entitled "CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR" (attorney docket no. FN-0015 US NP1); Serial No. _____, entitled "CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR" (attorney docket no. FN-0016 US NP1); Serial No. _____, entitled "CONTINUOUS PROCESSES FOR CONVERTING CARBONACEOUS FEEDSTOCK INTO GASEOUS PRODUCTS" (attorney docket no. FN-0018 US NP1); and Serial No. _____, entitled "STEAM GENERATING SLURRY GASIFIER FOR THE CATALYTIC GASIFICATION OF A CARBONACEOUS FEEDSTOCK" (attorney docket no. FN-0017 US NP1). All of the above are incorporated herein by reference for all purposes as if fully set forth.

[0015] All publications, patent applications, patents and other references mentioned herein, if not otherwise indicated, are explicitly incorporated by reference herein in their entirety for all purposes as if fully set forth.

[0016] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. In case of conflict, the present specification, including definitions, will control.

[0017] Except where expressly noted, trademarks are shown in upper case.

[0018] Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described herein.

[0019] Unless stated otherwise, all percentages, parts, ratios, *etc.*, are by weight.

[0020] When an amount, concentration, or other value or parameter is given as a range, or a list of upper and lower values, this is to be understood as specifically disclosing all ranges formed from any pair of any upper and lower range limits, regardless of whether ranges are separately disclosed. Where a range of numerical values is recited herein, unless otherwise stated, the range is intended to include the endpoints thereof, and all integers and fractions within the range. It is not intended that the scope of the present invention be limited to the specific values recited when defining a range.

[0021] When the term "about" is used in describing a value or an end-point of a range, the invention should be understood to include the specific value or end-point referred to.

[0022] As used herein, the terms "comprises," "comprising," "includes," "including," "has," "having" or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but can include other elements not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, "or" refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

[0023] The use of "a" or "an" to describe the various elements and components herein is merely for convenience and to give a general sense of the invention. This description should be read to include one or at least one and the singular also includes the plural unless it is obvious that it is meant otherwise.

[0024] The materials, methods, and examples herein are illustrative only and, except as specifically stated, are not intended to be limiting.

Carbonaceous Feedstock

[0025] The term "carbonaceous feedstock" as used herein refers to a carbonaceous material that is used as a feedstock in a catalytic gasification reaction. The carbonaceous feedstock can be formed, for example, from coal, petroleum coke, liquid petroleum residues, asphaltenes or mixtures thereof. The carbonaceous feedstock can come from a single source, or from two or more sources. For example, the carbonaceous feedstock can be formed from one or more tar sands petcoke materials, one or more coal materials, or a mixture of the two. In one embodiment of the invention, the carbonaceous feedstock is coal, petroleum coke, or a mixture thereof.

Petroleum coke

[0026] The term "petroleum coke" as used herein includes both (i) the solid thermal decomposition product of high-boiling hydrocarbon fractions obtained in petroleum processing (heavy residues – "resid petcoke") and (ii) the solid thermal decomposition product of processing tar sands (bituminous sands or oil sands – "tar sands petcoke"). Such carbonization products include, for example, green, calcined, needle petroleum coke and fluidized bed petroleum coke.

[0027] Resid petcoke can be derived from a crude oil, for example, by coking processes used for upgrading heavy-gravity crude oil distillation residue, which petroleum coke contains ash as a minor component, typically about 1.0 wt% or less, and more typically about 0.5 wt% or less, based on the weight of the coke. Typically, the ash in such lower-ash cokes predominantly comprises metals such as nickel and vanadium.

[0028] Tar sands petcoke can be derived from an oil sand, for example, by coking processes used for upgrading oil sand. Tar sands petcoke contains ash as a minor component, typically in the range of about 2 wt% to about 12 wt%, and more typically in the range of about 4 wt% to about 12 wt%, based on the overall weight of the tar sands petcoke.

Typically, the ash in such higher-ash cokes predominantly comprises materials such as compounds of silicon and/or aluminum.

[0029] The petroleum coke (either resid petcoke or tar sands petcoke) can comprise at least about 70 wt% carbon, at least about 80 wt% carbon, or at least about 90 wt% carbon, based on the total weight of the petroleum coke. Typically, the petroleum coke comprises less than about 20 wt% percent inorganic compounds, based on the weight of the petroleum coke.

[0030] Petroleum coke in general has an inherently low moisture content typically in the range of from about 0.2 to about 2 wt%. (based on total petroleum coke weight); it also typically has a very low water soaking capacity to allow for conventional catalyst impregnation methods.

Liquid Petroleum Residue

[0031] The term “liquid petroleum residue” as used herein includes both (i) the liquid thermal decomposition product of high-boiling hydrocarbon fractions obtained in petroleum processing (heavy residues – “resid liquid petroleum residue”) and (ii) the liquid thermal decomposition product of processing tar sands (bituminous sands or oil sands – “tar sands liquid petroleum residue”). The liquid petroleum residue is substantially non-solid; for example, it can take the form of a thick fluid or a sludge.

[0032] Resid liquid petroleum residue can be derived from a crude oil, for example, by processes used for upgrading heavy-gravity crude oil distillation residue. Such liquid petroleum residue contains ash as a minor component, typically about 1.0 wt% or less, and more typically about 0.5 wt% or less, based on the weight of the residue. Typically, the ash in such lower-ash residues predominantly comprises metals such as nickel and vanadium.

[0033] Tar sands liquid petroleum residue can be derived from an oil sand, for example, by processes used for upgrading oil sand. Tar sands liquid petroleum residue contains ash as a minor component, typically in the range of about 2 wt% to about 12 wt%, and more typically in the range of about 4 wt% to about 12 wt%, based on the overall weight of the residue. Typically, the ash in such higher-ash residues predominantly comprises materials such as compounds of silicon and/or aluminum.

Asphaltenes

[0034] Asphaltenes typically comprise aromatic carbonaceous solids at room temperature, and can be derived, from example, from the processing of crude oil and crude oil tar sands.

Coal

[0035] The term “coal” as used herein means peat, lignite, sub-bituminous coal, bituminous coal, anthracite, or mixtures thereof. In certain embodiments, the coal has a carbon content of less than about 85%, or less than about 80%, or less than about 75%, or less than about 70%, or less than about 65%, or less than about 60%, or less than about 55%, or less than about 50% by weight, based on the total coal weight. In other embodiments, the coal has a carbon content ranging up to about 85%, or up to about 80%, or up to about 75% by weight, based on the total coal weight. Examples of useful coals include, but are not limited to, Illinois #6, Pittsburgh #8, Beulah (ND), Utah Blind Canyon, and Powder River Basin (PRB) coals. Anthracite, bituminous coal, sub-bituminous coal, and lignite coal may contain about 10 wt%, about 5 to about 7 wt%, about 4 to about 8 wt %, and about 9 to about 11 wt%, ash by total weight of the coal on a dry basis, respectively. However, the ash content of any particular coal source will depend on the rank and source of the coal, as is familiar to those skilled in the art. See, for example, “Coal Data: A Reference”, Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels, U.S. Department of Energy, DOE/EIA-0064(93), February 1995.

Catalytic Gasification Methods

[0036] The gasification processes referred to in the context of the present invention include reacting a particulate carbonaceous feedstock in a gasifying reactor in the presence of steam and a gasification catalyst under suitable temperature and pressure to form a plurality of gaseous products comprising methane and at least one or more of hydrogen, carbon monoxide, and other higher hydrocarbons, and a solid char residue. Examples of such gasification processes are, disclosed, for example, in previously incorporated US3828474, US3998607, US4057512, US4092125, US4094650, US4204843, US4468231, US4500323, US4541841, US4551155, US4558027, US4606105, US4617027, US4609456, US5017282, US5055181, US6187465, US6790430, US6894183, US6955695, US2003/0167961A1, US2006/0265953A1, US2007/000177A1, US2007/083072A1, US2007/0277437A1 and GB1599932; commonly owned U.S. Patent Application Serial Nos. 12/178,380 (filed 23 July 2008), 12/234,012 (filed 19 September 2008) and 12/234,018 (filed 19 September 2008); as well as in previously incorporated U.S. Patent Applications Serial No. _____, entitled

“CONTINUOUS PROCESSES FOR CONVERTING CARBONACEOUS FEEDSTOCK INTO GASEOUS PRODUCTS” (attorney docket no. FN-0018 US NP1); Serial No. _____, entitled “CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR” (attorney docket no. FN-0014 US NP1); Serial No. _____, entitled “CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR” (attorney docket no. FN-0015 US NP1); Serial No. _____, entitled “CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR” (attorney docket no. FN-0016 US NP1); Serial No. _____, entitled “STEAM GENERATING SLURRY GASIFIER FOR THE CATALYTIC GASIFICATION OF A CARBONACEOUS FEEDSTOCK” (attorney docket no. FN-0017 US NP1); and Serial No. _____, entitled “CARBONACEOUS FUELS AND PROCESSES FOR MAKING AND USING THEM” (attorney docket no. FN-0013 US NP1).

[0037] The gasification reactors for such processes are typically operated at moderately high pressures and temperatures, requiring introduction of the particulate carbonaceous feedstock to the reaction zone of the gasification reactor while maintaining the required temperature, pressure, and flow rate of the particulate carbonaceous feedstock. Those skilled in the art are familiar with feed systems for providing feedstocks to high pressure and/or temperature environments, including, star feeders, screw feeders, rotary pistons, and lock-hoppers for feeding solids, and centrifugal pumps and steam atomized spray nozzles for feeding liquids. It should be understood that the feed system can include two or more pressure-balanced elements, such as lock hoppers, which would be used alternately.

[0038] In some instances, the particulate carbonaceous feedstock can be prepared at pressure conditions above the operating pressure of the gasification reactor. Hence, the particulate carbonaceous feedstock can be directly passed into the gasification reactor without further pressurization.

[0039] Typically, the carbonaceous feedstock is supplied to the gasifying reactor as particulates having an average particle size of from about 250 microns, or from about 25 microns, up to about 500, or up to about 2500 microns. One skilled in the art can readily determine the appropriate particle size for the particulates. For example, when a fluid bed gasification reactor is used, the particulate carbonaceous feedstock can have an average particle size which enables incipient fluidization of the particulate petroleum coke feed

material at the gas velocity used in the fluid bed gasification reactor. Processes for preparing particulates are described in more detail below.

[0040] Suitable gasification reactors include counter-current fixed bed, co-current fixed bed, fluidized bed, entrained flow, and moving bed reactors. The pressure in the gasification reactor typically will be about from about 10 to about 100 atm (from about 150 to about 1500 psig). The gasification reactor typically will be operated at moderate temperatures of at least about 450°C, or of at least about 600°C or above, to about 900°C, or to about 750°C, or to about 700°C; and at pressures of at least about 50 psig, or at least about 200 psig, or at least about 400 psig, to about 1000 psig, or to about 700 psig, or to about 600 psig.

[0041] The gas utilized in the gasification reactor for pressurization and reactions of the particulate carbonaceous feedstock typically comprises steam, and optionally oxygen, air, CO and/or H₂, and is supplied to the reactor according to methods known to those skilled in the art. Typically, the carbon monoxide and hydrogen produced in the gasification is recovered and recycled. In certain embodiments of the present invention, hydrogen and CO in the recycle gas stream (i.e., generated by reforming the second reformer input gas stream) is substituted for the hydrogen and CO that would otherwise be cryogenically separated and recycled. For adequate heat balance, the total amount of hydrogen plus CO in the recycle gas stream can be approximately equal to the amount of hydrogen and CO in the raw product gas, as described in more detail below. In some embodiments the gasification environment remains substantially free of air, particularly oxygen. In one embodiment of the invention, the reaction of the carbonaceous feedstock is carried out in an atmosphere having less than 1% oxygen by volume.

[0042] Any of the steam boilers known to those skilled in the art can supply steam to the gasification reactor. Such boilers can be fueled, for example, through the use of any carbonaceous material such as powdered coal, biomass *etc.*, and including but not limited to rejected carbonaceous materials from the particulate carbonaceous feedstock preparation operation (*e.g.*, fines, *supra*). Steam can also be supplied from a second gasification reactor coupled to a combustion turbine where the exhaust from the reactor is thermally exchanged to a water source to produce steam. Steam may also be generated from heat recovered from the hot raw gasifier product gas.

[0043] The recycle gas stream, described in more detail below, will include steam, H₂ and CO at a high temperature (*e.g.*, in the range of 1200°F to 1800°F). According to this aspect

of the invention, the recycle gas stream is introduced to the gasification reactor, as shown schematically in FIG. 1. In one embodiment of the invention, the amount of CO and H₂ in the recycle gas stream is sufficient to ensure that reaction is run under thermally neutral (adiabatic) conditions. In certain embodiments of the invention, the recycle gas stream can provide the steam and the small amount of heat input required for the gasification reaction. In other embodiments of the invention, the recycle gas stream can be further heated, for example by superheating in a recycle gas furnace. Recycled steam from other process operations can also be used for supplying steam to the reactor. For example, when the slurried particulate carbonaceous feedstock is dried with a fluid bed slurry drier, the steam generated through vaporization can be fed to the gasification reactor.

[0044] Reaction of the particulate carbonaceous feedstock under the described conditions typically provides a raw product gas comprising a plurality of gaseous products comprising methane and at least one or more of hydrogen, carbon monoxide and other higher hydrocarbons, and a solid char residue. The char residue produced in the gasification reactor during the present processes is typically removed from the gasification reactor for sampling, purging, and/or catalyst recovery. Methods for removing char residue are well known to those skilled in the art. One such method taught by EP-A-0102828, for example, can be employed. The char residue can be periodically withdrawn from the gasification reactor through a lock hopper system, although other methods are known to those skilled in the art.

[0045] The raw product gas stream leaving the gasification reactor can pass through a portion of the gasification reactor which serves as a disengagement zone where particles too heavy to be entrained by the gas leaving the gasification reactor are returned to the fluidized bed. The disengagement zone can include one or more internal cyclone separators or similar devices for removing particulates from the gas. The gas effluent passing through the disengagement zone and leaving the gasification reactor generally contains CH₄, CO₂, H₂, CO, H₂S, NH₃, unreacted steam, entrained particles, and other trace contaminants such as COS and HCN.

[0046] Residual entrained particles are typically removed by suitable means such as external cyclone separators followed by Venturi scrubbers. The recovered particles can be processed to recover alkali metal catalyst.

[0047] The raw product gas stream from which the fines have been removed can then be passed through a heat exchanger to cool the gas and to remove steam therefrom. The

recovered heat can be used, for example, to preheat recycle gas and generate high pressure steam. In certain embodiments of the invention, the recovered heat can be used to heat the portion of the sweetened gas stream that is subsequently separated and reformed; the first reformer input gas stream and/or the second reformer input gas stream. For example, as shown in schematic view in FIG. 2, the portion of the sweetened gas stream can be heated by heat-exchange with the with the raw product gas stream before it is reformed. Residual entrained particles can also be removed by any suitable means such as external cyclone separators followed by Venturi scrubbers. The recovered particles can be processed to recover alkali metal catalyst.

[0048] The raw product gas stream can then be sweetened, for example by removing acid gas and sulfur (i.e., sulfur-containing compounds such as COS and H₂S) therefrom. For example, the exiting the Venturi scrubbers can be fed to COS hydrolysis reactors for COS removal (sour process) and further cooled in a heat exchanger to recover residual heat prior to entering water scrubbers for ammonia recovery, yielding a scrubbed gas comprising at least H₂S, CO₂, CO, H₂, and CH₄. Methods for COS hydrolysis are known to those skilled in the art, for example, see US4100256.

[0049] The residual heat from the scrubbed gas can be used to generate low pressure steam. Scrubber water and sour process condensate can be processed to strip and recover H₂S, CO₂ and NH₃; such processes are well known to those skilled in the art. NH₃ can typically be recovered as an aqueous solution (e.g., 20 wt%).

[0050] A subsequent acid gas removal process can be used to remove H₂S and CO₂ from the scrubbed gas stream by a physical or chemical absorption method involving solvent treatment of the gas to give a cleaned gas stream. Such processes involve contacting the scrubbed gas with a solvent such as monoethanolamine, diethanolamine, methyldiethanolamine, diisopropylamine, diglycolamine, a solution of sodium salts of amino acids, methanol, hot potassium carbonate or the like. One method can involve the use of Selexol® (UOP LLC, Des Plaines, IL USA) or Rectisol® (Lurgi AG, Frankfurt am Main, Germany) solvent having two trains; each train consisting of an H₂S absorber and a CO₂ absorber. The spent solvent containing H₂S, CO₂ and other contaminants can be regenerated by any method known to those skilled in the art, including contacting the spent solvent with steam or other stripping gas to remove the contaminants or by passing the spent solvent through stripper columns. Recovered acid gases can be sent for sulfur recovery processing.

The resulting sweetened gas stream typically contains mostly CH₄, H₂, and CO and, typically, small amounts of CO₂ and H₂O. Any recovered H₂S from the acid gas removal and sour water stripping can be converted to elemental sulfur by any method known to those skilled in the art, including the Claus process. Elemental sulfur can be recovered as a molten liquid.

[0051] In one embodiment of the invention, all of the sweetened gas stream is separated into first and second reformer input gas streams and reformed, as described in more detail below. In other embodiments of the invention, only a portion of the sweetened gas stream is separated into first and second reformer input gas streams and reformed. Another portion of the sweetened gas stream can, for example, be used as a fuel to provide heat to the reforming steps (e.g., by being burned in a reformer furnace), described below. In other embodiments of the invention, a portion of the sweetened gas stream is processed to provide a methane gas product. For example, this portion of the sweetened gas stream can be further processed to separate and recover CH₄ by any suitable gas separation method known to those skilled in the art including, but not limited to, cryogenic distillation and the use of molecular sieves or ceramic membranes. One method for recovering CH₄ from this portion of the sweetened gas stream involves the combined use of molecular sieve absorbers to remove residual H₂O and CO₂ and cryogenic distillation to fractionate and recover CH₄. Typically, two gas streams can be produced by the gas separation process, a methane product stream and a syngas stream (H₂ and CO). The syngas stream can be recycled to the gasification reactor, as described herein. If necessary, a portion of the methane product can be used as plant fuel.

[0052] Further process details can be had by reference to the previously incorporated publications and applications.

Gasification Catalyst

[0053] Gasification processes according to the present invention use a carbonaceous feed material (e.g., a coal and/or a petroleum coke) and further use an amount of a gasification catalyst, for example, an alkali metal component, as alkali metal and/or a compound containing alkali metal, as well as optional co-catalysts, as disclosed in the previously incorporated references. Typically, the quantity of the alkali metal component in the composition is sufficient to provide a ratio of alkali metal atoms to carbon atoms in a molar ratio ranging from about 0.01, or from about 0.02, or from about 0.03, or from about 0.04, to about 0.06, or to about 0.07, or to about 0.08. Further, the alkali metal is typically loaded onto a carbon source to achieve an alkali metal content of from about 3 to about 10 times

more than the combined ash content of the carbonaceous material (e.g., coal and/or petroleum coke), on a mass basis.

[0054] Suitable alkali metals are lithium, sodium, potassium, rubidium, cesium, and mixtures thereof. Particularly useful are potassium sources. Suitable alkali metal compounds include alkali metal carbonates, bicarbonates, formates, oxalates, amides, hydroxides, acetates, or similar compounds. For example, the catalyst can comprise one or more of Na_2CO_3 , K_2CO_3 , Rb_2CO_3 , Li_2CO_3 , Cs_2CO_3 , NaOH , KOH , RbOH or CsOH , and particularly, potassium carbonate and/or potassium hydroxide.

[0055] Typically, carbonaceous feedstocks include a quantity of inorganic matter (e.g. including calcium, alumina and/or silica) which form inorganic oxides (“ash”) in the gasification reactor. At temperatures above about 500 to 600°C, potassium and other alkali metals can react with the alumina and silica in ash to form insoluble alkali aluminosilicates. In this form, the alkali metal is substantially water-insoluble and inactive as a catalyst. To prevent buildup of the residue in a coal gasification reactor, a solid purge of char residue, *i.e.*, solids composed of ash, unreacted or partially-reacted carbonaceous feedstock, and various alkali metal compounds (both water soluble and water insoluble) are routinely withdrawn. Preferably, the alkali metal is recovered from the char residue for recycle; any unrecovered catalyst is generally compensated by a catalyst make-up stream. The more alumina and silica in the feedstock, the more costly it is to obtain a higher alkali metal recovery.

[0056] The ash content of the carbonaceous feedstock can be selected to be, for example, to be about 20 wt% or less, or about 15 wt% or less, or about 10 wt% or less.

[0057] In certain embodiments of the present invention, the gasification catalyst is substantially extracted (e.g., greater than 80%, greater than 90%, or even greater than 95% extraction) from the char residue. Processes have been developed to recover gasification catalysts (such as alkali metals) from the solid purge in order to reduce raw material costs and to minimize environmental impact of a catalytic gasification process. The char residue can be quenched with recycle gas and water and directed to a catalyst recycling operation for extraction and reuse of the alkali metal catalyst. Particularly useful recovery and recycling processes are described in US4459138, as well as previously incorporated US4057512, US2007/0277437A1, U.S. Patent Application Serial No. _____, entitled “CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR” (attorney docket no. FN-0007 US NP1), U.S. Patent Application Serial No. _____,

entitled "CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR" (attorney docket no. FN-0014 US NP1), U.S. Patent Application Serial No. _____, entitled "CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR" (attorney docket no. FN-0015 US NP1), and U.S. Patent Application Serial No. _____, entitled "CATALYTIC GASIFICATION PROCESS WITH RECOVERY OF ALKALI METAL FROM CHAR" (attorney docket no. FN-0016 US NP1). Reference can be had to those documents for further process details.

[0058] In certain embodiments of the invention, at least 70%, at least 80%, or even at least 90% of the water-soluble gasification catalyst is extracted from the char residue.

Methods for Preparing the Carbonaceous Feedstock for Gasification

[0059] The carbonaceous feedstock for use in the gasification process can require initial processing.

[0060] The carbonaceous feedstock can be crushed and/or ground according to any methods known in the art, such as impact crushing and wet or dry grinding to yield particulates. Depending on the method utilized for crushing and/or grinding of the petroleum coke, the resulting particulates can need to be sized (e.g., separated according to size) to provide an appropriate particles of carbonaceous feedstock for the gasifying reactor. The sizing operation can be used to separate out the fines of the carbonaceous feedstock from the particles of carbonaceous feedstock suitable for use in the gasification process.

[0061] Any method known to those skilled in the art can be used to size the particulates. For example, sizing can be preformed by screening or passing the particulates through a screen or number of screens. Screening equipment can include grizzlies, bar screens, and wire mesh screens. Screens can be static or incorporate mechanisms to shake or vibrate the screen. Alternatively, classification can be used to separate the particulate carbonaceous feedstock. Classification equipment can include ore sorters, gas cyclones, hydrocyclones, rake classifiers, rotating trommels, or fluidized classifiers. The carbonaceous feedstock can be also sized or classified prior to grinding and/or crushing.

[0062] In one embodiment of the invention, the carbonaceous feedstock is crushed or ground, then sized to separate out fines of the carbonaceous feedstock having an average particle size less than about 45 microns from particles of carbonaceous feedstock suitable for use in the gasification process. As described in more detail below, the fines of the

carbonaceous feedstock can remain unconverted (*i.e.*, unreacted in a gasification or combustion process), then combined with char residue to provide a carbonaceous fuel of the present invention.

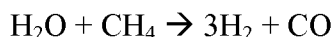
[0063] That portion of the carbonaceous feedstock of a particle size suitable for use in the gasifying reactor can then be further processed, for example, to impregnate one or more catalysts and/or cocatalysts by methods known in the art, for example, as disclosed in US4069304 and US5435940; previously incorporated US4092125, US4468231 and US4551155; previously incorporated U.S. Patent Application Serial Nos. 12/234,012 and 12/234,018; and previously incorporated U.S. Patent Applications Serial No. _____, entitled "PETROLEUM COKE COMPOSITIONS FOR CATALYTIC GASIFICATION" (attorney docket no. FN-0008 US NP1), Serial No. _____, entitled "PETROLEUM COKE COMPOSITIONS FOR CATALYTIC GASIFICATION" (attorney docket no. FN-0011 US NP1), and Serial No. _____, entitled "COAL COMPOSITIONS FOR CATALYTIC GASIFICATION" (attorney docket no. FN-0009 US NP1).

Separation and Steam Addition

[0064] As described above, the portion of the sweetened gas stream that is to be reformed into CO and H₂ has steam added to it and is separated to form a first reformer input gas stream having a first steam/methane ratio; and a second reformer input stream having a second steam/methane ratio. The first steam/methane ratio is smaller than the second steam/methane ratio. For example, the first steam/methane ratio can be in the range of from about 3:1 to about 7:1 (e.g., about 5:1). The second steam/methane ratio can be, for example, in the range of from about 7:1 to about 12:1 (e.g., about 9.4:1). In this aspect of the invention, the recycle gas stream is enriched in steam, and can provide most, or even all of the steam necessary for the catalytic gasification. The person of skill in the art can use any method to generate the reformer input streams from the sweetened gas stream. For example, as shown in the schematic of FIG. 3, in one embodiment of the invention the separating and adding steam to at least the first portion of the sweetened gas stream comprises adding steam to the sweetened gas stream to form a first intermediate gas stream having the first steam/methane ratio; splitting the first intermediate gas stream to form the product reformer input stream and a second intermediate gas stream; and adding steam to the second intermediate gas stream to form the recycle reformer input stream.

Reforming

[0065] The first reformer input gas stream and the second reformer input gas stream are reformed. In the reforming reaction, methane reacts with steam to form hydrogen and carbon monoxide according to the following equation:



In certain embodiments of the invention, the reforming reaction converts substantially all (e.g., greater than about 80%, greater than about 90% or even greater than about 95%) of the methane in the reformer input gas streams to carbon monoxide. The reforming reaction can be performed, for example, at a temperature in the range of from about 1300°F to about 1800°F (e.g., about 1550°F), and at pressures in the range of from about 200 psig to about 500 psig (e.g., about 350 psig). The reforming reaction can be performed, for example, on the catalyst-lined interior of a tube within a steam reforming furnace. The catalyst can be, for example, a metallic constituent supported on an inert carrier. The metallic constituent can be, for example, a metal selected from Group VI-B and the iron group of the periodic table, such as chromium, molybdenum, tungsten, nickel, iron or cobalt. The catalyst can include a small amount of potassium carbonate or a similar compound as a promoter. Suitable inert carriers include silica, alumina, silica-alumina, and zeolites. Each reformer input gas stream can be reformed by passing it through a separate tube (e.g., shaped in a coil) within a single reformer furnace, as shown in FIGS. 1-3. Of course, separate reforming furnaces can also be used. In certain embodiments of the invention, a second portion of the sweetened gas is used to fuel the reformer furnace(s), as shown in schematic view in FIG. 3. For example, a fraction of the sweetened gas stream ranging from about 15 to about 30% (e.g., about 22%) can be used to fuel the reformer furnace. In another embodiment of the invention, the furnace fuel may be supplemented by natural gas or by combustible tail gas from any of the synthesis reactions disclosed herein.

[0066] The second reformer input gas stream is reformed to form the recycle gas stream, which is reintroduced to the reactor, as described above. In one embodiment of the invention, the amount of hydrogen plus the amount of carbon monoxide in the recycle gas stream is within about 50% of the amount of hydrogen plus the amount of carbon monoxide in the raw product gas stream. For example, the amount of hydrogen plus the amount of carbon monoxide in the recycle gas stream can be within about 10% of the amount of hydrogen plus the amount of carbon monoxide in the raw product gas stream. In such embodiments of the invention, the recycle gas stream can provide heat balance to the gasification reaction.

Synthesis gas

[0067] The first reformer input gas stream is reformed, as described above, to form a synthesis gas stream comprising hydrogen and carbon monoxide. In some embodiments of the invention, the synthesis gas stream undergoes further processing steps. For example, the synthesis gas stream can be cooled through heat exchange; the recovered heat can be used to heat or generate steam, or to heat another gas stream within the process. The synthesis gas stream can also have its carbon monoxide/hydrogen ratio adjusted. In one embodiment of the invention, the carbon monoxide/hydrogen ratio of the synthesis gas stream is adjusted by raising the carbon monoxide/hydrogen ratio by reacting carbon dioxide with hydrogen to form carbon monoxide and water. This so-called back shift reaction can be performed, for example, at a temperature in the range of from about 300 to about 550°F (e.g., 412°F) in an atmosphere including carbon dioxide. The person of skill in the art can determine the appropriate reaction conditions for the back shift reaction. A process according to this embodiment of the invention is shown in schematic view in FIG. 4.

[0068] As described above, in certain embodiments of the invention, the process does not include the cryogenic separation of carbon monoxide, hydrogen or both from methane. In processes of the present invention, the reforming furnace can replace the cryogenic separation and its inefficient use of energy.

Syngas-derived products

[0069] Another aspect of the invention is a process for making a syngas-derived product. A syngas-derived product is a product formed from the reaction of syngas, in which carbon from the synthesis gas carbon monoxide is incorporated. The syngas-derived product can itself be a final, marketable product; it can also be an intermediate in the synthesis of other products. First, a synthesis gas stream is made according to any process described above. Then, the synthesis gas stream is reacted to form a syngas-derived product. As the person of skill in the art will appreciate, synthesis gas can be used as a feedstock in a wide variety of reactions to form a wide variety of syngas-derived products. For example, the syngas-derived product can be used to make compounds having two or more carbons, such as, for example, one or more hydrocarbons, one or more oxyhydrocarbons, and mixtures thereof. The syngas-derived product can be, for example, methanol, ethanol, dimethyl ether, diethyl ether, methyl *t*-butyl ether, acetic acid, acetic anhydride, Fischer-Tropsch diesel fuel or synthetic crude oil (syncrude). The reaction of the synthesis gas can produce heat energy, a combustible tail gas mixture, or both.

[0070] In embodiments of the invention in which the reaction of the synthesis gas forms heat energy, the heat energy can be recovered and used, for example, in a preceding process step or in other applications. For example, the heat energy can be used to generate or heat steam. In embodiments of the invention in which the reaction of the synthesis gas forms a combustible tail gas mixture, it can be burned to generate or further heat the steam. The steam can be used in a preceding process step; for example, it can be provided to the gasification reactor for reaction with the carbonaceous feedstock, as described above; added to the sweetened gas stream in the formation of one or both of the reformer input gas streams, as described above; and/or used to dry the carbonaceous feedstock (e.g., after catalyst loading), as described above. The steam can also be driven through a turbine for the generation of electrical power, which can be used within the plant or sold. As the skilled artisan will appreciate, the recovered heat energy from the reaction of the synthesis gas stream, or steam generated therefrom or heated thereby, can be used in other applications not specifically detailed herein.

[0071] In certain embodiments of the invention, the reaction of the synthesis gas stream forms a combustible tail gas mixture (e.g., as a by-product). The combustible tail gas mixture can comprise, for example, hydrogen, hydrocarbons, oxyhydrocarbons, or a mixture thereof. The combustible tail gas mixture can be burned to provide heat energy, which can be recovered and used, for example, in a preceding process step, or for some other application. For example, in one embodiment of the invention, the combustible tail gas mixture is burned to provide heat for one or both of the reforming steps (e.g., by firing a reformer furnace). The combustible tail gas mixture can also be burned to generate or heat steam. The steam can be used in a preceding process step; for example, it can be provided to the gasification reactor for reaction with the carbonaceous feedstock, as described above; added to the sweetened gas stream in the formation of one or both of the reformer input gas streams, as described above; and/or used to dry the carbonaceous feedstock (e.g., after catalyst loading), as described above. The steam can also be driven through a turbine for the generation of electrical power, which can be used within the plant or sold. As the skilled artisan will appreciate, the heat energy generated by burning the combustible tail gas mixture, or steam generated therefrom or heated thereby, can be used in other applications not specifically detailed herein.

We claim:

1. A process for making a synthesis gas stream comprising hydrogen and carbon monoxide, characterized in that the process comprising the steps of:
 - (a) providing a carbonaceous feedstock;
 - (b) reacting the carbonaceous feedstock in a gasification reactor in the presence of steam and a gasification catalyst under suitable temperature and pressure to form a raw product gas stream comprising a plurality of gases comprising methane, hydrogen and carbon monoxide;
 - (c) removing steam from and sweetening the raw product gas stream to form a sweetened gas stream;
 - (d) separating and adding steam to at least a first portion of the sweetened gas stream to form a first reformer input gas stream having a first steam/methane ratio; and a second reformer input stream having a second steam/methane ratio, in which the first steam/methane ratio is smaller than the second steam/methane ratio;
 - (e) reforming the second reformer input stream to form a recycle gas stream comprising steam, carbon monoxide and hydrogen;
 - (f) introducing the recycle gas stream to the gasification reactor; and
 - (g) reforming the first reformer input stream to form the synthesis gas stream.
2. The process of claim 1, characterized in that the process further comprises the step of reacting the synthesis gas stream to for a syngas-derived product and heat energy.
3. The process of claim 2, characterized in that the process further comprises the steps of recovering the heat energy formed from the reaction of the synthesis gas stream, and using the heat energy to generate or heat steam.
4. The process of claim 3, characterized in that the steam is provided to the gasification reactor for reaction with the carbonaceous feedstock.
5. The process of any claims 1-4, characterized in that the process further comprises the step of reacting the synthesis gas stream to for a syngas-derived product and a combustible tail gas mixture.

6. The process of claim 5, characterized in that the tail gas mixture is burned to generate or heat steam.
7. The process of claim 6, characterized in that the steam is driven through a turbine for the generation of electrical power.
8. The process of any of claims 1-7, characterized in that the process does not include the cryogenic separation of carbon monoxide, hydrogen or both from methane.
9. The process of any of claims 1-8, characterized in that only a portion of the sweetened gas stream is separated into first and second reformer input gas streams and reformed.
10. The process of claim 9, characterized in that another portion of the sweetened gas is used as a fuel to provide heat to the reforming steps.
11. The process of claim 9, characterized in that another portion of the sweetened gas stream is processed to provide a methane gas product.

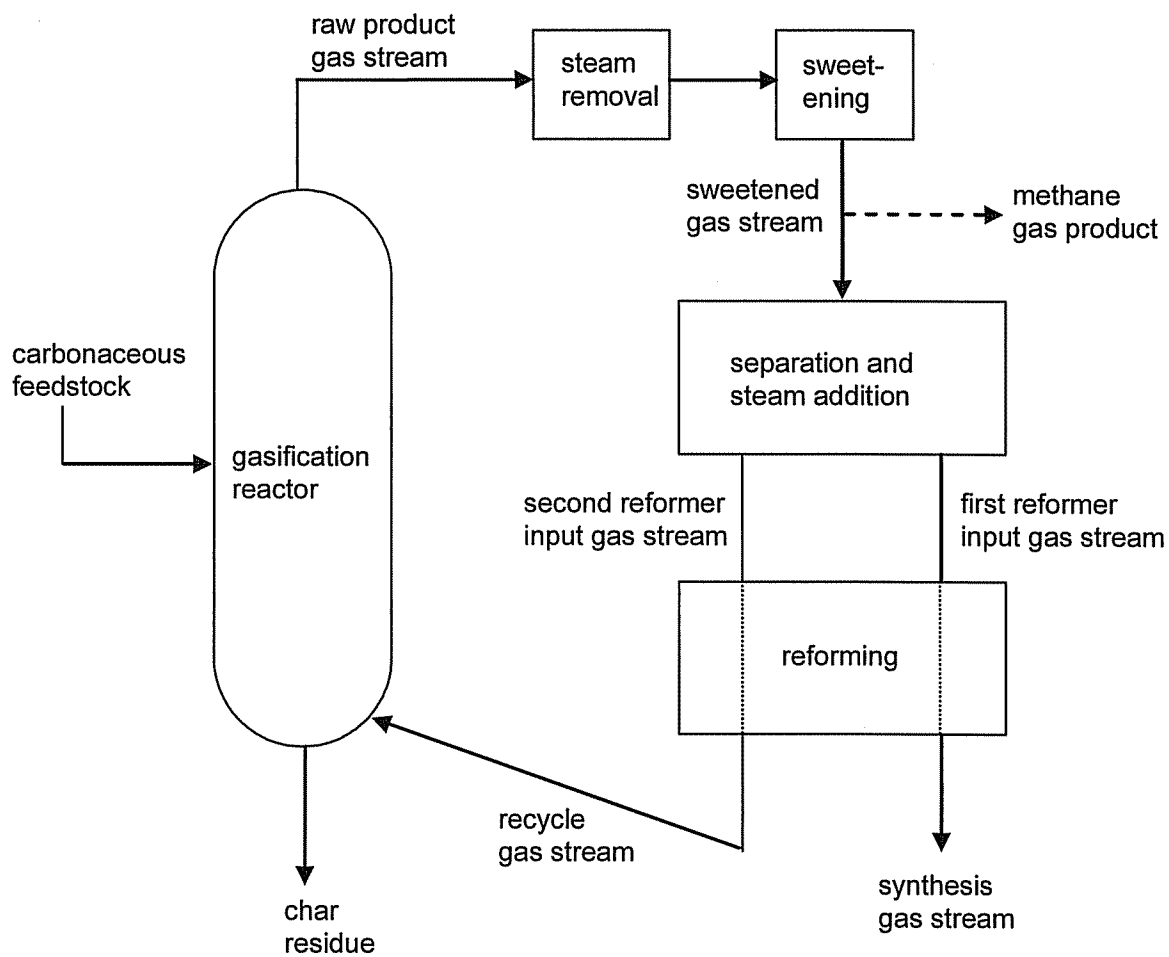


FIG. 1

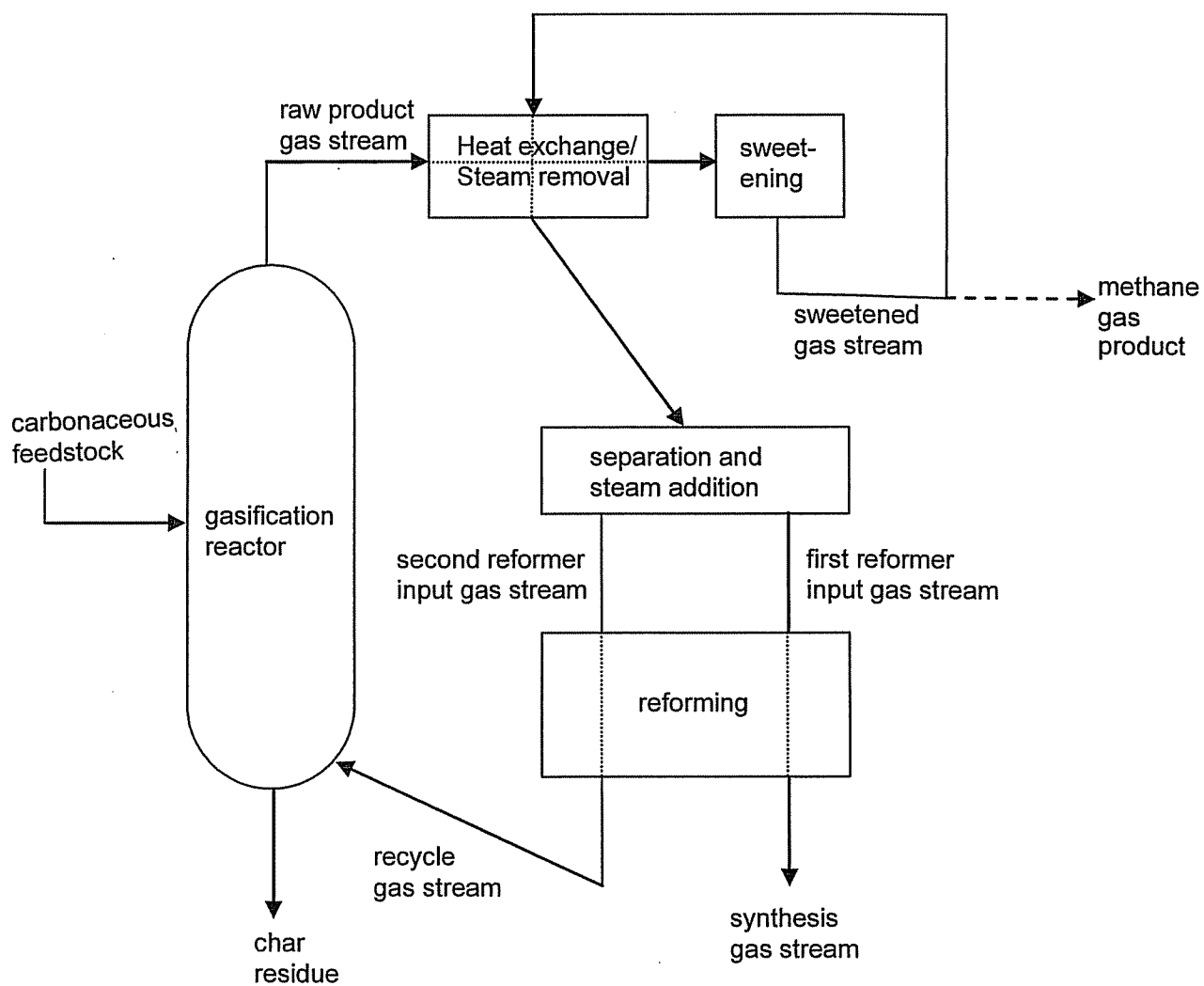


FIG. 2

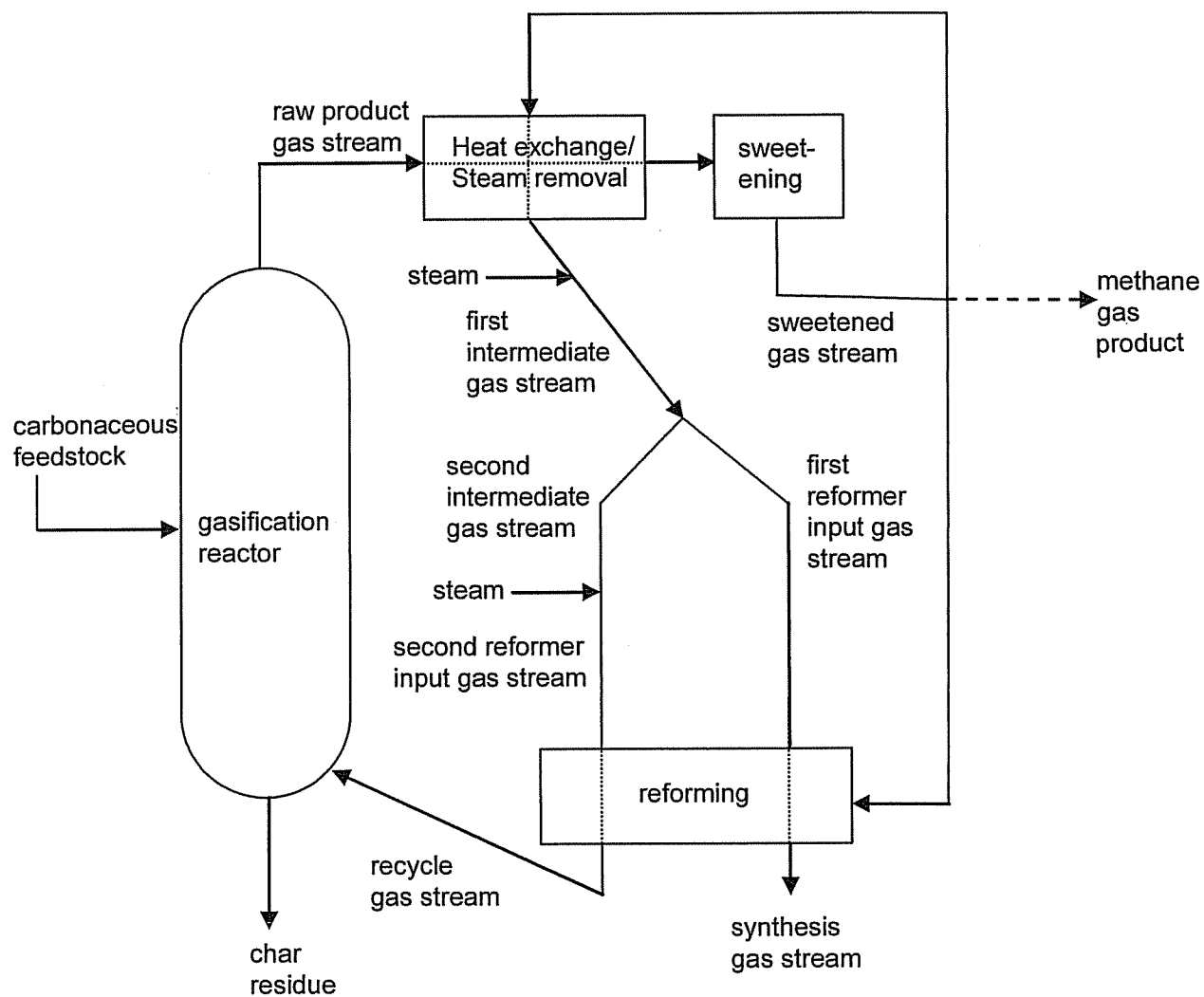


FIG. 3

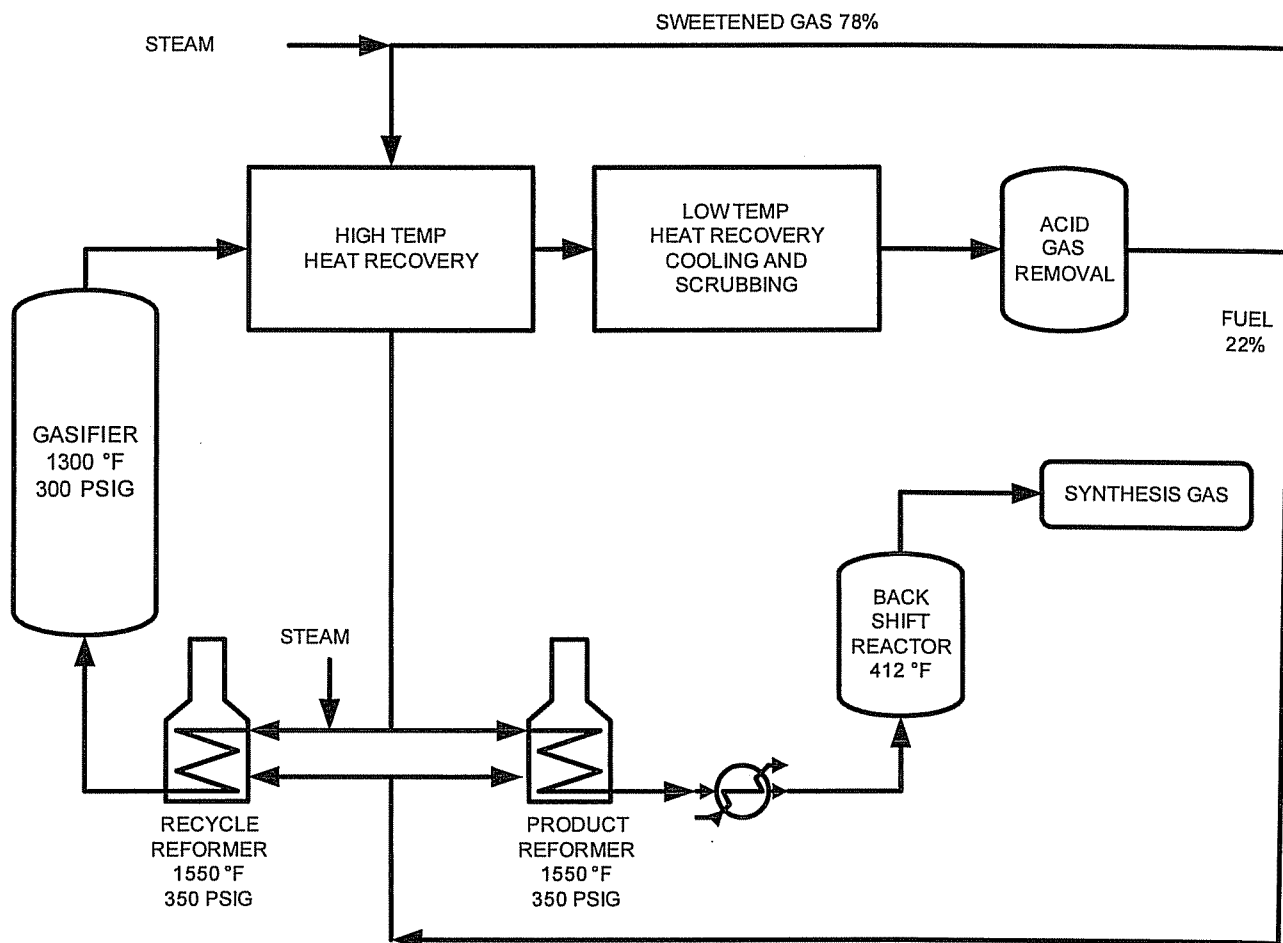


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2008/088148

A. CLASSIFICATION OF SUBJECT MATTER

INV. C10J3/00 C10J3/46 C10L3/08 C10K3/02

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C10J C10K C10L C07C

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

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 118 204 A (EAKMAN JAMES M ET AL) 3 October 1978 (1978-10-03) figure 1 column 4, line 15 - column 9, line 65 column 9, line 66 - column 10, line 13 claims 1-13	1-8
A	US 4 348 487 A (GOLDSTEIN STUART S ET AL) 7 September 1982 (1982-09-07) column 9, line 15 - column 10, line 63 figure 1	1-8



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *&* document member of the same patent family

Date of the actual completion of the international search

2 April 2009

Date of mailing of the international search report

06/05/2009

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Authorized officer

Zuurdeeg, Boudewijn

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2008/088148

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