HEAT RECYCLING SYSTEM FOR USE WITH A GASIFIER

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ABSTRACT

The present invention provides a system that recycles heat recovered from hot products of a carbonaceous feedstock gasification process back into the gasification process. The hot gaseous products are used to heat working fluids such as air and water to produce hot air, hot water or steam. The heated fluids are used to return heat back to the gasification process. The system also comprises a control system to optimize the efficiency of a gasification process by minimizing energy consumption of the process, while also maximizing energy production.
HEAT RECYCLING SYSTEM FOR USE WITH A GASIFIER

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit of priority under 35 U.S.C. §119(e) from U.S. Provisional Application Ser. No. 60/746,612, filed May 5, 2006. This application also claims benefit of priority to International Patent Application No. PCT/CA2006/000881, filed Jun. 5, 2006. This application also claims benefit of priority under 35 U.S.C. §119(e) from U.S. Provisional Application Ser. No. 60/864,116, filed Nov. 2, 2006. This application also claims benefit of priority under 35 U.S.C. §119(e) from U.S. Provisional Application Ser. No. 60/911,179, filed Apr. 11, 2007. This application also claims benefit of priority under 35 U.S.C. §119(e) from U.S. Provisional Application Ser. No. 60/797,973, filed May 5, 2006. The contents of all of the aforementioned applications are hereby expressly incorporated by reference in their entirety and for all purposes.

FIELD OF THE INVENTION

[0002] This invention relates to the gasification of carbonaceous feedstock, and in particular to a system that recovers heat generated by the gasification process and recycles it for use within the system and optionally for external applications.

BACKGROUND OF THE INVENTION

[0003] Gasification is a process that enables the conversion of carbonaceous feedstock, such as municipal solid waste (MSW) or coal, into a combustible gas. The gas can be used to generate electricity, steam or as a basic raw material to produce chemicals and liquid fuels. Possible uses for the gas include: the combustion in a boiler for the production of steam for internal processing and/or other external purposes, or for the generation of electricity through a steam turbine; the combustion directly in a gas turbine or a gas engine for the production of electricity; fuel cells; the production of methanol and other liquid fuels; as a further feedstock for the production of chemicals such as plastics and fertilizers; the extraction of both hydrogen and carbon monoxide as discrete industrial fuel gases; and other industrial applications.

[0004] Generally, the gasification process consists of feeding carbonaceous feedstock into a heated chamber (the gasifier) along with a controlled and/or limited amount of oxygen and optionally steam. In contrast to incineration or combustion, which operate with excess oxygen to produce CO₂, H₂O, SO₂, and NOₓ, gasification processes produce a raw gas composition comprising CO, H₂, H₂S, and NH₃. After clean-up, the primary gasification products of interest are H₂ and CO.

[0005] Useful feedstock can include any municipal waste, waste produced by industrial activity and biomedical waste, sewage, sludge, coal, heavy oils, petroleum coke, heavy refinery residuals, refinery wastes, hydrocarbon contaminated soils, biomass, and agricultural wastes, tires, and other hazardous waste. Depending on the origin of the feedstock, the volatiles may include H₂O, H₂, N₂, O₂, CO₂, CO, CH₄, H₂S, NH₃, C₃H₈, unsaturated hydrocarbons such as acetylenes, olefins, aromatics, tars, hydrocarbon liquids (oils) and char (carbon black and ash). As the feedstock is heated, water is the first constituent to evolve. As the temperature of the dry feedstock increases, pyrolysis takes place. During pyrolysis the feedstock is thermally decomposed to release tars, phenols, and light volatile hydrocarbon gases while the feedstock is converted to char.

[0006] Char comprises the residual solids consisting of organic and inorganic materials. After pyrolysis, the char has a higher concentration of carbon than the dry feedstock and may serve as a source of activated carbon. In gasifiers operating at a high temperature (>1200°C) or in systems with a high temperature zone, inorganic mineral matter is fused or vitrified to form a molten glass-like substance called slag.

[0007] Since the slag is in a fused, vitrified state, it is usually found to be non-hazardous and may be disposed of in a landfill as a non-hazardous material, or sold as an ore, road-bed, or other construction material. It is becoming less desirable to dispose of waste material by incineration because of the extreme waste of fuel in the heating process and the further waste of disposing, as a residual waste, material that can be converted into a useful syngas and solid material.

[0008] The means of accomplishing a gasification process vary in many ways, but rely on four key engineering factors: the atmosphere (level of oxygen or air or steam content) in the gasifier; the design of the gasifier; the internal and external heating means; and the operating temperature for the process. Factors that affect the quality of the product gas include: feedstock composition, preparation and particle size; gasifier heating rate; residence time; the plant configuration including whether it employs a dry or slurry feed system, the feedstock-reactant flow geometry; the design of the dry ash or slag removal system; whether it uses a direct or indirect heat generation and transfer method; and the syngas cleanup system. Gasification is usually carried out at a temperature in the range of about 650°C to 1200°C, either under vacuum, at atmospheric pressure or at pressures up to about 100 atmospheres.

[0009] There are a number of systems that have been proposed for capturing heat produced by the gasification process and utilizing such heat to generate electricity, generally known as combined cycle systems.

[0010] The energy in the product gas coupled with substantial amounts of recoverable sensible heat produced by the process and throughout the gasification system can generally produce sufficient electricity to drive the process, thereby alleviating the expense of local electricity consumption. The amount of electrical power that is required to gasify a ton of a carbonaceous feedstock depends directly upon the chemical composition of the feedstock.

[0011] If the gas generated in the gasification process comprises a wide variety of volatiles, such as the kind of gas that tends to be generated in a low temperature gasifier with a “low quality” carbonaceous feedstock, it is generally referred to as off-gas. If the characteristics of the feedstock and the conditions in the gasifier generate a gas in which CO and H₂ are the predominant chemical species, the gas is referred to as syngas. Some gasification facilities employ technologies to convert the raw off-gas or the raw syngas to a more refined gas composition prior to cooling and cleaning through a gas quality conditioning system.
Utilizing plasma heating technology to gasify a material is a technology that has been used commercially for many years. Plasma is a high temperature luminous gas that is at least partially ionized, and is made up of gas atoms, gas ions, and electrons. Plasma can be produced with any gas in this manner. This gives excellent control over chemical reactions in the plasma as the gas might be neutral (for example, argon, helium, neon), reductive (for example, hydrogen, methane, ammonia, carbon monoxide), or oxidative (for example, oxygen, carbon dioxide). In the bulk phase, a plasma is electrically neutral.

Some gasification systems employ plasma heat to drive the gasification process at a high temperature and/or to reform the offgas/syngas by converting, reconstituting, or reforming longer chain volatiles and tars into smaller molecules with or without the addition of other inputs or reactants when gaseous molecules come into contact with the plasma heat, they will dissociate into their constituent atoms. Many of these atoms will react with other input molecules to form new molecules, while others may recombine with themselves. As the temperature of the molecules in contact with the plasma heat decreases all atoms fully recombine. As input gases can be controlled stoichiometrically, output gases can be controlled to, for example, produce substantial levels of carbon monoxide and insubstantial levels of carbon dioxide.

The very high temperatures (3000 to 7000° C.) achievable with plasma heating enable a high temperature gasification process where virtually any input feedstock including waste in as-received condition, including liquids, gases, and solids in any form or combination can be accommodated. The plasma technology can be positioned within a primary gasification chamber to make all the reactions happen simultaneously (high temperature gasification), can be positioned within the system to make them happen sequentially (low temperature gasification with high temperature refinement), or some combination thereof.

The gas produced during the gasification of carbonaceous feedstock is usually very hot but may contain small amounts of unwanted compounds and requires further treatment to convert it into a useable product. Once a carbonaceous material is converted to a gaseous state, undesirable substances such as metals, sulfur compounds and ash may be removed from the gas. For example, dry filtration systems and wet scrubbers are often used to remove particular matter and acid gases from the gas produced during gasification. A number of gasification systems have been developed which include systems to treat the gas produced during the gasification process.

These factors have been taken into account in the design of various different systems which are described, for example, in U.S. Pat. Nos. 6,686,556, 6,630,113, 6,380,507, 6,215,678, 5,666,891, 5,798,497, 5,756,957, and U.S. Patent Application Nos. 2004/0251241, 2002/0144981. There are also a number of patents relating to different technologies for the gasification of coal for the production of synthesis gases for use in various applications, including U.S. Pat. Nos. 4,141,694; 4,181,504; 4,208,191; 4,410,336; 4,472,172; 4,606,799; 5,331,906; 5,486,269, and 6,200,430.

Prior systems and processes have not adequately addressed the problems that must be dealt with on a continuously changing basis. Some of these types of gasification systems describe means for adjusting the process of generating a useful gas from the gasification reaction. Accordingly, it would be a significant advancement in the art to provide a system that can efficiently gasify carbonaceous feedstock in a manner that maximizes the overall efficiency of the process, and/or the steps comprising the overall process.

This background information is provided for the purpose of making known information believed by the applicant to be of possible relevance to the present invention. No admission is necessarily intended, nor should be construed, that any of the preceding information constitutes prior art against the present invention.

SUMMARY OF THE INVENTION

This invention provides a system for optimizing the efficiency of gasifying carbonaceous feedstock by recovering sensible heat from the gasification process and recycling it for use within the system and optionally for external applications.

This invention provides a system that recycles heat recovered from a hot gas, and transfers the recovered heat back to a gasifier. In particular the system comprises means to transfer the hot gas to a gas-to-liquid heat exchanger, where the heat from the hot gas is transferred to a fluid to produce a heated fluid and a cooled gas, and means to transfer the heated fluid to the gasifier. The heated fluid is passed into the gasifier to provide heat required to drive the gasification reaction. The heated fluid may also optionally be used to preheat or pretreat, directly or indirectly, the feedstock to be gasified.

In accordance with one embodiment of the invention, the system also comprises a control system comprising sensing elements for monitoring operating parameters of the system, and response elements for adjusting operating conditions within the system to optimize the gasification process, wherein the response elements adjust the operating conditions within the system according to the data obtained from the sensing elements, thereby optimizing the efficiency of a gasification process by minimizing energy consumption of the process, while also maximizing energy production.

In accordance with one aspect of the invention, there is provided a process for improving the efficiency of a carbonaceous feedstock gasification process by recycling sensible heat from a hot gas produced by the gasification process back into the gasification process using a gas-to-liquid heat exchanger, the process comprising the steps of passing the hot product gas through the gas-to-liquid heat exchanger, passing the cooled fluid through the gas-to-liquid heat exchanger, transferring heat from the hot product gas to the cooled fluid via the gas-to-liquid heat exchanger to produce a cooled product gas which exits the heat exchanger via a cooled product gas outlet, and a heated fluid which exits the heat exchanger via a heated fluid outlet, and using the heated fluid to provide heat for the carbonaceous feedstock gasification process.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features of the invention will become more apparent in the following detailed description in which reference is made to the appended drawings.
FIG. 1 is a block flow diagram of a system for recycling heat recovered from a hot gas product of a gasification process back to a gasifier, according to one embodiment of the present invention.

FIG. 2 is a block flow diagram of the recovery of heat from the gas product of the gasification process using a heat exchanger and a heat recovery steam generator, according to one embodiment of the present invention.

FIG. 3 is a block flow diagram of a system for cooling hot gas products, including a heat exchanger for recovery of heat from the gas product of the gasification process, and a quench step for further product gas cooling, according to one embodiment of the present invention.

FIG. 4A is a schematic diagram showing the functional requirements for a gas-to-air heat exchanger, according to one embodiment of the present invention.

FIG. 4B is a schematic diagram depicting a gas-to-air heat exchanger, according to one embodiment of the present invention.

FIG. 5 is a schematic diagram depicting a gas-to-air heat exchanger, according to one embodiment of the present invention.

FIG. 6 is a schematic diagram of a converter and its various inputs, according to one embodiment of the present invention.

FIG. 7 is a schematic diagram depicting possible end uses of exchange-steam produced by the recovery of heat from a product gas in a heat recovery steam generator, according to various embodiments of the present invention.

FIG. 8 is a schematic diagram showing a piping system to transfer the exchange-air to the converter, according to one embodiment of the present invention.

FIG. 9 is a schematic diagram depicting a high level concept of various temperature controls within the system, according to one embodiment of the present invention.

FIG. 10 is a schematic diagram showing a high level view of a gas flow/pressure control subsystem, according to one embodiment of the present invention.

FIGS. 11A to 11I are block flow diagrams depicting overviews of various embodiments of the present invention.

FIG. 12 is a cross-sectional view through one embodiment of a gasifier, detailing the feedstock input, gas outlet, solid residue outlet, and the location of exchange-air inlets, according to one embodiment of the present invention.

FIG. 13 is a central longitudinal cross-sectional view through one embodiment of a gasifier, detailing the feedstock input, gas outlet, and the location of air boxes.

FIG. 14 details the air box assembly of the gasifier illustrated in FIG. 13.

DETAILED DESCRIPTION OF THE INVENTION

Unless defined otherwise, 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.

As used herein, the term “about” refers to a ±10% variation from the nominal value. It is to be understood that such a variation is always included in any given value provided herein, whether or not it is specifically referred to.

For the purposes of the present invention, the term syngas (or synthesis gas) refers to the product of a gasification process, and may include carbon monoxide, hydrogen, and carbon dioxide, in addition to other gaseous components such as methane, nitrogen and water vapour.

As used herein, the term “exchange-air” refers to air after it has been heated using sensible heat from the product gas using a gas-to-air heat exchanger according to the present invention. It is within the scope of the present invention to heat gases other than air, including, but not limited to, oxygen or enriched air, using the system as described herein.

As used herein, the term “converter” refers to an apparatus for converting carbonaceous feedstocks into a raw syngas product, also referred to as product gas. The converter includes the gasifier and the plasma gas reformulator.

As used herein, the term “carbonaceous feedstock” can be any carbonaceous material appropriate for gasifying in the present gasification process, and can include, but is not limited to, any waste materials, coal (including low grade, high sulfur coal not suitable for use in coal-fired power generators), petroleum coke, heavy oils, biomass, sewage sludge, sludge from pulp and paper mills and agricultural wastes. Waste materials suitable for gasification include both hazardous and non-hazardous wastes, such as municipal waste, wastes produced by industrial activity (paint sludges, off-spec paint products, spent sorbents), automobile fluff, used tires and biomedical wastes, and can be any carbonaceous material inappropriate for recycling, including non-recyclable plastics, sewage sludge, coal, heavy oils, petroleum coke, heavy refinery residuals, refinery wastes, hydrocarbon contaminated solid waste and biomass, agricultural wastes, tires, hazardous waste, industrial waste and biomass. Examples of biomass useful for gasification include, but are not limited to, waste or fresh wood, remains from fruit, vegetable and grain processing, paper mill residues, straw, grass, and manure.

As used herein, the term “product gas” means generally, the gas generated by the gasification facility, prior to cooling and cleaning by processes designated to remove contaminants. Depending on the design of the gasification facility it can be used to refer to, for example, raw offgas, raw syngas, reformed offgas or reformed syngas.

As used herein, the terms “gas-to-air heat exchanger” and “gas heat exchanger” are interchangeable, and refer to the heat exchanger used to transfer sensible heat from the hot gas product to air.

A “sensing element” is defined to describe any element of the system configured to sense a characteristic of a process, a process input or process output, wherein such characteristic may be represented by a characteristic value useable in monitoring, regulating and/or controlling one or more local, regional and/or global process of the system. Sensing elements may include, but are not limited to, sensors, detectors, monitors, analyzers or any combination thereof for the sensing of process, fluid and/or material temperature, pressure, flow, composition and/or other such
characteristics, as well as material position and/or disposition at any given point within the system and any operating characteristic of any process device used within the system.

[0048] A “response element” is defined to describe any element of the system configured to respond to a sensed characteristic in order to operate a process device operatively associated therewith in accordance with one or more pre-determined or computed control parameters, wherein the one or more control parameters are defined to provide a desired process result. Response elements may include, but are not limited to, drivers, static and/or dynamically variable power sources, inducers, and any other element configurable to impart a physical action to a device based on one or more control parameters. Response elements may be operatively coupled to various process devices, which may include, but are not limited to, material input mechanisms, plasma heat sources, additive input means, gas blowers, additive input blowers, gas flow regulators, additive input flow regulators, solid residue conditioner additive input regulators and plasma heat source regulators, and other such process devices operable to affect any local, regional and/or global process.

[0049] The present invention provides a system for optimizing the efficiency of the process of gasifying a carbonaceous feedstock into a gaseous product by minimizing energy consumption of the process while also maximizing energy production. In particular, the present invention provides a heat recycling system for use with a gasifier, wherein sensible heat from the gasification process is efficiently recovered, and wherein the recovered heat is transferred to one or more processes within the system, and optionally to processes outside the system.

[0050] The system comprises a heat exchanging system for recovery of heat from the hot product gas, wherein the heat exchanger transfers sensible heat from the product gas to a suitable fluid. Fluids suitable for the present heat exchanging process include, but are not limited to, air, water, oil, or another gas such as nitrogen or carbon dioxide. In particular, the system comprises a conduit system for transferring a hot product gas of a gasification process to a gas-to-fluid heat exchanger, where the heat from the hot product gas is transferred to a fluid to produce a heated fluid and a cooled product gas. The system further comprises another conduit system for transferring the heated fluid to the gasification process.

[0051] In one embodiment, the gas-to-fluid heat exchanger is a gas-to-air heat exchanger, wherein the heat is transferred from the product gas to air to produce a heated air exchange. In one embodiment, the gas-to-fluid heat exchanger is a heat recovery steam generator, wherein the heat is transferred to water to produce heated water or steam.

[0052] According to one embodiment of the present invention, as schematically depicted in FIG. 1, there is provided a heat recycling system 5000 for transferring heat produced during a gasification process back to a converter 1000 to drive the gasification reaction.

[0053] In this embodiment, this is accomplished by heating air 5010 with the heat from a hot product gas 5020 produced in a converter 1000 in a gas-to-air heat exchanger 5100 to produce a heated air product (hereinafter referred to as exchange-air 5015) and a cooled product gas 5025, and passing the heated exchange-air 5015 back into the converter 1000.

[0054] Energy efficiencies are therefore optimized by this system, since the recycling of recovered sensible heat back to the gasification process reduces the amount of energy inputs required from external sources for the steps of drying, volatilizing and gasifying the feedstock. The recovered sensible heat may also serve to minimize the amount of plasma heat required to achieve a defined product gas quality. Thus, the present invention allows for the efficient gasification of a carbonaceous feedstock, wherein the heat required for gasification is provided by hot exchange-air, where the exchange-air has been heated using sensible heat recovered from the hot product gas.

[0055] The sensible heat transferred from the product gas to the heated exchange-air can also be used for external heating applications, as well as heating applications elsewhere in the gasification process.

[0056] For example, the heated exchange-air can be used directly or indirectly to preheat or pretreat the feedstock to be gasified. In the case of a direct heating/pretreating step, the exchange-air is directly passed through the feedstock to heat and/or remove moisture. In the case of an indirect heating/pretreating step, the heat is transferred from the heated exchange-air to oil (or to water to produce steam), wherein the heated oil (or steam product) is used to heat the wall of a feedstock dryer/preheater. In all cases, the recycling of sensible heat minimizes the amount of energy inputs required for these heating applications.

[0057] It is therefore within the scope of the present invention to transfer the heat from the heated exchange-air to any working fluid of interest. Such working fluids of interest include, but are not limited to, oil, water, or another gas such as nitrogen or carbon dioxide. Where heat is transferred to a working fluid other than air, an appropriate heat exchanging system is used.

[0058] After heat is recovered in the gas-to-air heat exchanger, the product gas, although cooled, may still contain too much heat to undergo filtering and conditioning steps as are known in the art. The present invention therefore also optionally provides for the further cooling of the product gas prior to such subsequent filtering and conditioning steps.

[0059] In the embodiment depicted in FIG. 2, the heat recycling system 5001 heats air 5010 with the heat from a hot product gas 5020 in a gas-to-air heat exchanger 5102 to produce a heated air product (hereinafter referred to as exchange-air 5015) and a partially cooled product gas 5023, and passing the heated exchange-air back into the converter 1000. Heat recycling system 5001 also includes a subsystem for recovering additional heat from the partially cooled product gas 5023 after it has passed through the gas-to-air heat exchanger 5102. Accordingly, the system 5001 further comprises a heat recovery steam generator 5302, whereby additional heat recovered from the product gas is used to convert water 5030 to steam (referred to as exchange-steam 5035), thereby also producing a fully cooled product gas 5025.

[0060] The exchange-steam produced in the heat recovery steam generator can be used to drive downstream energy generators such as steam turbines and/or be used in direct-drive turbines and/or can be added to the gasification process. The exchange-steam can also be used in other systems,
for example, for the extraction of oil from tar sands or in local heating applications, or it can be supplied to local industrial clients for their purposes. In one embodiment, the steam produced using heat from the product gas is saturated steam. In another embodiment, the steam produced using heat from the product gas is superheated steam, which can be produced either directly through heat exchange between water and product gas or between saturated steam and product gas.

[0061] The system of the present invention is for use with a converter in which the feedstocks are converted (via offgas intermediates) to a hot, raw gaseous product. A typical converter for use with this invention comprises a feedstock inlet for inputting the feedstock to be gasified, one or more exchange-air inlets for providing heated exchange-air to drive the gasification process, a hot product gas outlet, and optionally one or more process additive inlets. The converter also comprises one or more plasma heat sources to convert the offgas intermediates of the gasification process to the raw product gas.

[0062] Where the system does not include a system for recovering additional heat from the partially cooled product gas after it has passed through the gas-to-air heat exchanger, another system for further cooling the product gas prior to conditioning may be provided. In one embodiment, as depicted in FIG. 3, the system 5003 in addition to cooling the hot product gas 5020 in the gas-to-air heat exchanger 5103 to produce a partially cooled product gas 5023 and heated exchange-air 5015, also comprises a dry quench step 6103 for further cooling the product gas prior to conditioning. The dry quench step is provided to remove excess heat from the product gas by the addition of a controlled amount of atomized water 6030 to provide a cooled product gas 5025 as may be required for the subsequent filtering and conditioning steps. Selection of an appropriate system for further cooling of the product gas prior to conditioning is within the knowledge of a worker skilled in the art.

[0063] According to one embodiment of the present invention, the present system also comprises a control subsystem comprising sensing elements for monitoring operating parameters of the system, and response elements for adjusting operating conditions within the system to optimize the gasification process, wherein the response elements adjust the operating conditions within the system according to the data obtained from the sensing elements, thereby optimizing the efficiency of a gasification process by minimizing energy consumption of the process, while also maximizing energy production.

[0064] The control subsystem may also be used to optimize the composition (i.e., heating value) of the product gas produced, and optionally to ensure that the system is maintained within safe operational parameters.

[0065] Heat Exchangers

[0066] The present invention provides a system for transferring heat produced during the gasification process back to a gasifier to drive the gasification reaction. This can be achieved by recovering sensible heat from hot product gas using a heat exchanging system (e.g., a gas-to-fluid heat exchanger) to transfer the heat from the product gas to a suitable working fluid, thereby producing a heated fluid and cooled product gas. In one embodiment, the heated fluid produced in the gas-to-fluid heat exchanger is passed back into the gasifier.

[0067] In one embodiment, the gas-to-fluid heat exchanger comprises one or more gas-to-air heat exchangers.

[0068] The functional requirements for a gas-to-air heat exchanger are shown in FIG. 4A, where the hot product gas 5020 and the air 5010 are each passed through the gas-to-air heat exchanger 5104, whereby sensible heat is transferred from the hot product gas 5020 to the air 5010 (blown by process air blower 5012) to provide a heated exchange-air 5015 and a cooled product gas 5025.

[0069] Different classes of heat exchangers may be used in the present system, including shell and tube heat exchangers, both of straight, single-pass design and of U-tube, multiple pass design, as well as plate-type heat exchangers. The selection of appropriate heat exchangers is within the knowledge of a worker of ordinary skill in the art.

[0070] Some particulate matter will be present in the product gas, thus the gas-to-air heat exchanger is designed specifically for a high level of particulate loading. The particle size is typically between 0.5 to 100 micron. In one embodiment depicted in FIG. 4B, the heat exchanger is a single pass vertical flow heat exchanger 5104B, wherein the product gas 5020 flows in the tube side and the air 5010 flows on the shell side. In the single pass vertical flow embodiment, the product gas 5020 flows vertically in a “once through” design, which minimizes areas where build up or erosion from particulate matter could occur.

[0071] The product gas velocities should be maintained to be high enough for self-cleaning, while still minimizing erosion. In one embodiment, gas velocities are between 3000 to 5000 m/min. Under normal flow conditions, gas velocities are from about 3800 m/min to about 4700 m/min.

[0072] Due to the significant difference in the air input temperature and hot product gas, each tube in the gas-to-air heat exchanger preferably has an individual expansion bellows to avoid tube rupture. Tube rupture may occur where a single tube becomes plugged and is therefore no longer expanding/contracting with the rest of the tube bundle. In those embodiments where the process air pressure is greater than the product gas pressure, tube rupture presents a high hazard due to problems resulting from air entering gas mixture.

[0073] In an embodiment of the present invention, the system is run intermittently, i.e., subject to numerous start-up and shut down cycles as desired. Therefore, it is important that the equipment must be designed to withstand repeated thermal expansion and contraction.

[0074] In order to minimize the hazard potential from a tube leak, the system of the present invention further comprises one or more individual temperature transmitters, as depicted in FIG. 5, located, for example, temperature transmitters 5581 at the product gas inlet 5521 and temperature transmitters 5582 at the product gas outlet 5526 of the gas-to-air heat exchanger, as well as for temperature transmitters 5583 at the exchange-air outlet 5517. Where a temperature transmitter is associated with the product gas outlet 5526 of the gas-to-air heat exchanger 5105, the temperature transmitter is positioned to detect a temperature rise resulting from combustion in the event of having exchange-air leak into the product gas conduit. Detection of such a temperature rise will result in the automatic shut down of the process air blower 5012 so as to eliminate the source of oxygen.
[0075] Where a temperature transmitter is associated with the exchange-air outlet 5517 of the gas-to-air heat exchanger 5105, this temperature transmitter is used to ensure the temperature of the exchange-air remains within a set range of temperatures as required for the gasification process. In order to avoid providing too much heated exchange-air (or exchange-air that is too hot) to the gasification process, which could result in overheating the feedstock, a control valve 5590 is opened to vent excess exchange-air to the atmosphere.

[0076] In addition, the heat exchangers are provided, as required, with ports for instrumentation, inspection and maintenance, as well as repair and/or cleaning of the conduits.

[0077] In one embodiment, the gas-to-fluid heat exchanger is a heat recovery steam generator, which uses the recovered heat to generate exchange-steam. In one embodiment, the water is provided into the heat exchanger in the form of low temperature steam. In another embodiment, the exchange-steam produced is saturated or superheated steam.

[0078] The exchange-steam so produced can be used as a process steam additive for the gasification process, or used to drive a turbine to produce electricity or drive rotating process equipment, for example, a gas blower.

[0079] Steam that is not used within the conversion process, to produce electricity or to drive rotating process equipment, may be used for other commercial purposes, such as in local heating applications, or for improving the extraction of oil from the tar sands. The exchange-steam can also be used to indirectly heat feedstock in a feedstock conditioner, thereby drying the feedstock prior to gasification in the converter.

[0080] The heat recovery steam generator employed in one embodiment of the present system is a shell and tube heat exchanger, wherein the process gas flows vertically through the tubes and water is boiled on the shell side.

[0081] The heat exchanging system for the heat recovery steam generator is designed with the understanding that some particular matter will be present in the product gas. Again, product gas velocities here are also maintained at a level high enough for self-cleaning of the tubes, while minimizing erosion.

[0082] Converters for Use with This System

[0083] The present system includes a converter for converting the feedstock to a gaseous product. This conversion takes place via gasification of the feedstock and reformulation of the intermediate gaseous products. The stages of the feedstock gasification include: i) drying of the feedstock to remove residual moisture, ii) volatilization of volatile constituents of the dried feedstock to produce a char intermediate, and iii) conversion of the char to offgas and ash. The gaseous products of the gasification process therefore include the volatile constituents and offgas, which are optionally subjected to a reformulating step to provide the gaseous product. In one embodiment, the reformulating step is a plasma-assisted reformulating step.

[0084] The converter therefore comprises a refractory-lined chamber having at least one feedstock inlets, one or more exchange-air inlets, a gas outlet, and a solid residue outlet. The converter also optionally comprises one or more process additive inlets, and one or more plasma heat sources.

[0085] In one embodiment, the converter is a horizontally oriented gasifier, wherein feedstock enters the gasifier through a feedstock inlet located at one end of the gasifier. The feedstock undergoes gasification as it is transferred toward a solid residue outlet located at the opposite end of the gasifier.

[0086] The gasification process may also be carried out in one of a number of standard gasifiers as are known in the art. Examples of gasifiers known in the art include, but are not limited to entrained flow reactor vessels, fluidized bed reactors, and rotary kiln reactors, each of which is adapted to accept feedstock in the form of solids, particulates, slurry, liquids, gases, or a combination thereof. The gasifier can have a wide range of length-to-diameter ratios and can be oriented either vertically or horizontally.

[0087] In each of these embodiments, the gasification process is facilitated by the introduction of a heated fluid through appropriately adapted heated fluid inlets, in accordance with the present invention. In one embodiment, the gasification process is facilitated by the introduction of heated exchange-air through exchange-air inlets.

[0088] In accordance with the present invention, the heated fluid may be provided as required to different regions of the gasifier through independent heated fluid feed and distribution systems.

[0089] In one embodiment, the heated fluid feed and distribution systems comprise exchange-air inlets that allow for the introduction of heated exchange-air to the gasification region. These inlets are positioned within the converter to distribute the heated exchange-air throughout the converter to initiate and drive the gasification of the feedstock. In one embodiment, the exchange-air inlets comprise perforations located in the floor of the gasifier. In one embodiment, the exchange-air inlets comprise perforations located in the walls of the gasifier.

[0090] In one embodiment, the exchange-air inlets comprise separate air boxes for each region from which hot exchange-air can pass through perforations in the floor of the converter to that region. In one embodiment, the exchange-air inlets are independently controlled spargers for each region.

[0091] Optionally, to avoid blockage of the exchange-air inlets during processing, the inlet hole size is selected such that it creates a restriction and thus a pressure drop across each hole. This pressure drop is sufficient to prevent waste particles from entering the inlet holes. The inlet holes can optionally be tapered outwards towards the upper face to preclude particles becoming stuck in a hole.

[0092] The converter may be designed such that the process for converting the feedstock to a product gas (i.e., the gasification and reformulating steps) both take place generally in a single region, or chamber, within the system.

[0093] The converter may also be designed such that the feedstock to product gas conversion process takes place in more than one region, i.e., wherein the gasification and reformulation steps are separated to some extent from each other and take place in discrete regions within the system. In these kinds of converters, the process occurs either in more
than one region within one chamber, in separate chambers or some combination thereof, wherein the regions are in fluid communication with one another.

[0094] In a multi-region converter, a first, or primary, region or chamber (also referred to as a gasifier) is used to heat the feedstock to dry the feedstock (if residual moisture is present), extract the volatile constituents of the feedstock, and convert the resulting char to a gaseous product and ash, thereby producing an offgas product, while a second region or chamber (also referred to as a reformulator) is used to apply plasma heat and other process additives (e.g., air and/or steam) to assure the complete conversion of the offgases and volatiles into a product gas. Where two or more distinct regions or chambers are used for the gasification of the feedstock and the conversion of offgases to product gas, the gas exiting the final region of the converter is the product gas.

[0095] In one embodiment, the different stages of the gasification process may take place in different regions of a gasifier. One skilled in the art would appreciate that conceptually, the conditions in the gasifier at any location could be optimized in response to the character of the feedstock material at that particular location by segregating the gasifier into an infinite number of regions. The practical embodiment of this concept, however, is to segregate the gasifier into a finite number of regions optimized in response to the general or average feedstock material characteristics of a larger area. It would be apparent to a worker skilled in the art that the gasifier could therefore be segregated into two, three, four or more regions depending on the characteristics of the feedstock.

[0096] In accordance with one embodiment of the present invention, each stage of the gasification process is facilitated by the introduction of an appropriate amount of heated exchange-air through suitably adapted exchange-air inlets.

[0097] The feedstock is introduced through the one or more feedstock inlets, which are disposed to provide optimum exposure of the feedstock to the heated exchange-air, or other heated fluids, for complete and efficient conversion of the feedstock to a gaseous product.

[0098] In one embodiment, the present system allows for the provision of a high carbon feedstock (HCF), such as shredded plastic, either in combination with the feedstock prior to introduction to the converter, or through a dedicated HCF inlet, thereby enabling quick response to process demands for higher or lower carbon input to meet the required gas quality.

[0099] The optional process additive inlets provide for the addition of gases such as oxygen, air, oxygen-enriched air, steam or other gases useful for the gasification process, into the converter. The process additive inlets can include air input ports, steam input ports, exchange-air input ports and exchange steam input ports. These ports are positioned within the converter for the optimal distribution of process additives throughout. The steam additives may be provided by a heat recovery steam generator.

[0100] The oxygen in the exchange-air is also used to balance the chemistry to produce the required product gas and remove the maximum amount of carbon. The oxygen also initiates or increases the rate of the exothermic reactions that produce carbon monoxide, carbon dioxide, hydrogen and other large hydrocarbon particles. The heat from the exothermic reactions, along with the heat provided by the heated exchange-air and/or other heated fluids, together increase the processing temperature in the converter.

[0101] FIG. 6 is a schematic diagram summarizing the various inputs and outputs associated with one embodiment of a converter for use with the system of the present invention. This embodiment is a converter 1006 comprising a horizontally oriented gasifier 2006 having a feedstock inlet 2604, wherein the feedstock comprises a combination of municipal solid waste MSW and a high carbon feedstock HCF (such as plastic). The converter 1006 has multiple exchange-air inlets 2619A, 2619B and 2619C located to provide the exchange-air 5015 as required for the gasification reaction. The converter also has exchange-air inlets 3616 and steam inlets 3630 proximal to plasma torches 3008 to provide air and steam additives as required for the plasma reformulating reaction. The converter 1006 has a solid residue outlet 2608 in communication with a solid residue conditioning chamber 4620.

[0102] Material is moved laterally through the gasifier in order to facilitate specific stages of the gasification process (drying, volatilization, char-to-ash conversion). This lateral movement of material through gasifier is achieved via the use of one or more lateral transfer units, which can include, but are not limited to a movable shelf, movable platform, pusher ram, plow, screw element or belt.

[0103] The one or more lateral transfer units can act in coordinated manner or individual lateral transfer units can act independently. In order to optimize control of the material flow rate and pile height, the individual lateral transfer units can be moved individually, at varying speeds, at varying movement distances, at varying frequency of movement. The lateral transfer units must be able to effectively operate in the harsh conditions of the gasifier and in particular must be able to operate at high temperatures.

[0104] The converter is lined with a refractory material that can be one or a combination of conventional refractory materials known in the art which are suitable for use in a vessel for a high temperature (e.g., a temperature of about 1100° C. to 1400° C.) non-pressurized reaction. Examples of such refractory materials include, but are not limited to, high temperature fired ceramics (such as aluminum oxide, aluminum nitride, aluminum nitrate, boron nitride, zirconium phosphate, chromium oxide), glass ceramics and high alumina brick containing principally, silica, alumina and titania.

[0105] The solid residue outlet is located to allow for the removal of the solid by-products of the gasification reaction from the converter. Solid by-products of the gasification process, also referred to as solid residue, may take the form of char, ash, slag, or some combination thereof, which are removed, continuously or intermittently, from the converter through appropriately adapted outlets. Char can either be removed prior to complete conversion to gaseous products, or it can remain in the gasifier for further conversion to ash. The ash product is then removed through the solid residue outlet, to, for example, an ash collection chamber, or optionally to a solid residue conditioning chamber for further processing. Appropriate solid residue removal outlet design and location in the converter is selected using the knowledge of a worker skilled in the relevant art, according to the requirements of the system and the type of by-product to be removed.
0106. The solid residue outlet is generally disposed at or near the bottom of the chamber to enable the residue to be removed passively, using gravity flow. Some systems optionally employ a solid residue removal system to actively convey the residue from the bottom of the converter. Such active solid residue removal can be provided by one of a variety of devices known in the art. Examples include, but are not limited to, screws, pusher rams, horizontal rotating paddles, horizontal rotating arms, and horizontal rotating wheels.

0107. In those embodiments where the solid residue (e.g., ash by-product) of the gasification process is further converted to slag, the ash-to-slag conversion takes place in a solid residue conditioning chamber. A plasma heat source may be employed in the solid residue conditioning chamber to melt the ash into slag. The molten slag, at a temperature of, for example, about 1100°C to about 1600°C, may be periodically or continuously exhausted from the solid residue conditioning chamber and is thereafter cooled to form a solid slag material. Such slag material may be utilized for landfill disposal. The solid product may further be broken into aggregates for conventional uses. Alternatively, the molten slag can be poured into containers to form ingots, bricks, tiles or similar construction material.

0108. Where the solid residue of the gasification process contains some unconverted carbon, the plasma heat of the slag conditioning step ensures complete conversion of the unconverted carbon to hot gaseous products having fuel value. This gaseous product is referred to as the residue gas. In one embodiment, the heat is recovered from the hot residue gas using a dedicated residue gas-to-air heat exchanger, producing a heated air product and a cooled residue gas. The cooled residue gas is optionally further conditioned in a dedicated gas conditioning subsystem to produce a gas product that can be combined with the gaseous product of the main gasification process.

0109. System for Further Cooling Product Gas Prior to Conditioning Step

0110. The present invention, in addition to a gas-to-fluid heat exchanger, optionally includes a system for further cooling the product gas prior to a conditioning step. In one embodiment, the system for further cooling the product gas prior to cleaning and conditioning also provides for the recovery of additional heat. Where recovery of further sensible heat from the product gas is an objective, the heat is transferred from the gas to another working fluid, for example water, oil, or air. The products of such embodiments can include, respectively, heated water (or steam), heated oil, or additional hot air.

0111. In one embodiment, the system of the present invention recovers further sensible heat from the product gas using a heat exchanger to transfer the heat from the partially cooled product gas to water, thereby producing either heated water or steam, and a gas that has been further cooled. In one embodiment, the heat exchanger employed in this step is a heat recovery steam generator, which uses the recovered heat to generate exchange-steam. In one embodiment, the water is provided into the heat exchanger in the form of low temperature steam. In another embodiment, the exchange-steam produced is saturated or superheated steam.

0112. FIG. 7 depicts the relationship between a gas-to-air heat exchanger 5107 and a heat recovery steam generator 5307, according to one embodiment of the invention. The exchange-steam 5035 produced in the heat recovery steam generator 5307 can be used in various downstream applications. FIG. 7 depicts different possible end uses (labeled A through G) for the exchange-steam produced using a heat recovery steam generator, according to various embodiments of the present invention.

0113. For example, as depicted in option D, the exchange-steam 5035 produced can be passed into the converter 1007 as a process steam additive, in one embodiment of the invention. The exchange-steam 5035 can be used as a process steam additive during the gasification process to ensure sufficient free oxygen and hydrogen to maximize the conversion of the feedstock into the product gas. The use of steam as an oxygen containing process additive is preferred because of its low cost and ease of handling. Steam also includes hydrogen, which may be a desired product of the gasification process.

0114. The exchange-steam produced may also be passed through a turbine 5715, thereby driving rotating process equipment, for example, an exchange-air blower 5712 (option B), or a product gas blower 5722 (option C).

0115. Steam that is not used within the conversion process or to drive rotating process equipment, may be used for other commercial purposes, such as the production of electricity through the use of a steam turbine 5705 (option A), or in local heating applications 5710 (option E) or it can be supplied to local industrial clients for their purposes, or it can be used for improving the extraction of oil from the tar sands 5780 (option F). The exchange-steam can also be used to indirectly heat feedstock in a feedstock conditioner 5767, thereby drying the feedstock prior to gasification in the converter (option G).

0116. In one embodiment where the system for further cooling the product gas prior to conditioning does not include the recovery of additional heat, the cooling step comprises a dry quench step, wherein the product gas temperature is reduced by direct controlled (adiabatic saturation) injection of atomized water.

0117. In one embodiment, where cooling of different systems or processes is required, the excess heat can be removed (and recovered) by a water cooling step. The resulting heated water can be, in turn, used to heat working fluids for use elsewhere in the gasification process. Heated water streams come from various sources including, but not limited to, gas cooling processes in the gas conditioning system or plasma heat source cooling systems. Heated water can also be used to preheat oil for various applications.

0118. Conduit Systems

0119. Conduit systems are employed to transfer gases from one component of the system to another. Accordingly, the system comprises a gas conduit system to transfer the hot product gas product to a heat exchanger for recovery of sensible heat. The system also comprises an exchange-air conduit system to transfer the heated exchange-air to the converter, where it is introduced to the converter via exchange-air inlets. The conduit systems typically employ one or more pipes, or lines, through which the gases are transported.

0120. Where the system comprises a heat recovery steam generator, the system will also comprise an exchange-steam
conduit system to transfer the heated exchange-steam for use in one or more of the applications previously listed. The exchange-steam conduit system may comprise multiple pipes running in parallel, or a system of branching conduits, where a given branch is designated for a specific application.

[0121] Materials and size specifications for the conduit system gas lines are selected as required to provide safe and efficient conveyance of the gas. Where the gas being conveyed is the high temperature product gas, design thickness and type of refractory used are selected to ensure that the shell wall temperature is about 200°C in order to remain above the acid gas dew point to prevent corrosion. In one embodiment, the hot product gas lines are carbon steel and refractory lined. In one embodiment, the heated exchange-air lines comprise stainless steel piping.

[0122] In order to maximize the amount of sensible heat that can be recovered from the hot product gas, or to minimize cooling of the heated exchange-air or exchange steam, the conduit system is optionally provided with a means for minimizing heat loss to the surrounding environment. Heat loss may be minimized, for example, through the use of an insulating barrier around the conduits comprising insulating materials as are known in the art and by designing the plant to minimize lengths of conduits. This is particularly important for high temperature conduits.

[0123] In one embodiment, the heated exchange-air exits the gas-to-air heat exchanger in a single pipe, which is then split into several smaller diameter pipes in order to provide the heated exchange-air to different regions of the converter as required. Each branch of the piping system includes an air flow control valve to control the flow of heated air to the different regions of the converter as required.

[0124] The product gas conduit system optionally employs one or more flow regulating devices and/or blowers, located throughout the system to provide a means for managing the flow rate of the gaseous product.

[0125] The exchange-air conduit system will optionally employ one or more flow regulating devices, flow meters and/or blower, located throughout the system as required to control the flow rate of the exchange-air. In one embodiment, as depicted in FIG. 8, exchange-air flow control valves 5890A, 5890B, and 5890C, are provided to control the flow of exchange-air to different regions of the converter. Each branch of the piping system includes an air flow control valve to control the flow of heated air to the different regions of the converter as required.

[0126] In one embodiment, there is one exchange-air flow control valve 5892 to control the flow of exchange-air to the reformulator 3008. In this embodiment, the exchange-air is provided as a process additive.

[0127] The exchange-air conduits also optionally comprise means for diverting exchange-air, for example, to venting outlets or to optional additional heat exchange systems.

[0128] The flow regulating devices, and/or blowers, and/or diversion means are optionally controlled by a control subsystem, as is discussed in detail below.

[0129] The conduit system will also optionally comprise service ports to provide access to the system for the purpose of carrying out routine maintenance, as well as repair and/or cleaning of the conduits.

[0130] Plasma Heating Sources

[0131] The system of the present invention employs one or more plasma heat sources to convert the offgas produced by the gasification process to the product gas. Plasma heat sources are also provided in the solid residue conditioner to melt and condition the solid residue.

[0132] A variety of commercially available plasma heat sources which can develop suitably high flame temperatures for sustained periods at the point of application can be utilized in the system. In general, such plasma heat sources are available in sizes from about 100 kW to over 6 MW in output power. The plasma heat sources can employ one, or a combination, of suitable working gases. Examples of suitable working gases include, but are not limited to air, argon, helium, neon, hydrogen, methane, ammonia, carbon monoxide, oxygen, nitrogen, and carbon dioxide. In one embodiment of the present invention, the plasma heat source is continuously operating using air as the plasma medium so as to produce a temperature in the gasifier in excess of about 900°C to about 1300°C as required for converting the offgas to the product gas.

[0133] In this respect, a number of alternative plasma technologies are suitable for use in the present system. For example, it is understood that transferred arc and non-transferred arc torches (both AC and DC), using appropriately selected electrode materials, may be employed. It is also understood that inductively coupled plasma torches (ICP) may also be employed. Selection of an appropriate plasma heat source is within the ordinary skills of a worker in the art.

[0134] In one embodiment of the present invention, the one or more plasma heat sources will be positioned to optimize the offgas conversion to product gas. The position of the one or more plasma heat sources is selected according to the design of the gasification system, for example, according to whether the system employs a one stage or two stage gasification process. For instance, in an embodiment employing a two stage gasification process, the plasma heat source may be disposed in a position relative to, and pointed in the direction of, the inlet through which the offgas enters the reformulating chamber, or reformulating zone. In those embodiments that employ a one stage gasification process, the one or more plasma heat sources may extend towards the core of the gasifier. In all cases, the position of the plasma heat sources is selected according to the requirements of the system, and for optimal conversion of the offgas to product gas.

[0135] In one embodiment, the plasma heat used in the plasma reformulator is provided by a DC non-transferred arc.

[0136] In one embodiment, the plasma heat sources are located adjacent to one or more air and/or steam input ports such that the air and/or steam additives are injected into the path of the plasma discharge of the plasma heat source.

[0137] In a further embodiment, the plasma heat sources may be movable, fixed or a combination thereof.
In one embodiment, the plasma heat used in the solid residue conditioner is provided by a DC non-transferred arc torch. In another embodiment, the plasma heat used in the solid residue conditioner is provided by a DC transferred arc torch.

Control System

In order to optimize the efficiency of the present invention, there is also optionally provided a system for controlling the conditions under which the present process is carried out, as well as the operating conditions of the system according to the present invention. Where the end use of the gas product is to generate electricity, the control subsystem also provides for optimal energy production by ensuring that the gas composition and pressure are maintained within the tolerances of the gas engines/generators used to produce the electricity.

In one embodiment of the present invention, a control system may be provided to control one or more processes implemented in, and/or by, the various systems and/or subsystems disclosed herein, and/or provide control of one or more process devices contemplated herein for affecting such processes. In general, the control system may operatively control various local and/or regional processes related to a given system, subsystem or component thereof, and/or related to one or more global processes implemented within a system, such as a gasification system, within or in cooperation with which the various embodiments of the present invention may be operated, and thereby adjusts various control parameters thereof adapted to affect these processes for a defined result. Various sensing elements and response elements may therefore be distributed throughout the controlled system(s), or in relation to one or more components thereof, and used to acquire various process, reactant and/or product characteristics, compare these characteristics to suitable ranges of such characteristics conducive to achieving the desired result, and respond by implementing changes in one or more of the ongoing processes via one or more controllable process devices.

The control system generally comprises, for example, one or more sensing elements for sensing one or more characteristics related to the system(s), process(es) implemented therein, input(s) provided therefore, and/or output(s) generated thereby. One or more computing platforms are communicatively linked to these sensing elements for accessing a characteristic value representative of the sensed characteristic(s), and configured to compare the characteristic value(s) with a predetermined range of such values defined to characterize these characteristics as suitable for selected operational and/or downstream results, and compute one or more process control parameters conducive to maintaining the characteristic value with this predetermined range. A plurality of response elements may thus be operatively linked to one or more process devices operable to affect the system, process, input and/or output thereof, and thereby adjust the sensed characteristic, and communicatively linked to the computing platform(s) for accessing the computed process control parameter(s) and operating the process device(s) in accordance therewith.

In one embodiment, the control system provides a feedback, feedforward and/or predictive control of various systems, processes, inputs and/or outputs related to the conversion of carbonaceous feedstock into a gas, so to promote an efficiency of one or more processes implemented in relation thereto. For instance, various process characteristics may be evaluated and controllably adjusted to influence these processes, which may include, but are not limited to, the heating value and/or composition of the feedstock, the characteristics of the product gas (e.g., heating value, temperature, pressure, flow, composition, carbon content, etc.), the degree of variation allowed for such characteristics, and the cost of the inputs versus the value of the outputs. Continuous and/or real-time adjustments to various control parameters, which may include, but are not limited to, heat source power, additive feed rate(s) (e.g., oxygen, oxidants, steam, etc.), feedstock feed rate(s) (e.g., one or more distinct and/or mixed feeds), gas and/or system pressure/flow regulators (e.g., blowers, relief and/or control valves, flares, etc.), and the like, can be executed in a manner whereby one or more process-related characteristics are assessed and optimized according to design and/or downstream specifications.

Alternatively, or in addition thereto, the control system may be configured to monitor operation of the various components of a given system for assuring proper operation, and optionally, for ensuring that the process(es) implemented thereby are within regulatory standards, when such standards apply.

In accordance with one embodiment, the control system may further be used in monitoring and controlling the total energetic impact of a given system. For instance, a given system may be operated such that an energetic impact thereof is reduced, or again minimized, for example, by optimizing one or more of the processes implemented thereby, or again by increasing the recuperation of energy (e.g., waste heat) generated by these processes. Alternatively, or in addition thereto, the control system may be configured to adjust a composition and/or other characteristics (e.g., temperature, pressure, flow, etc.) of a product gas generated via the controlled process(es) such that such characteristics are not only suitable for downstream use, but also substantially optimized for efficient and/or optimal use. For example, in an embodiment where the product gas is used for driving a gas engine of a given type for the production of electricity, the characteristics of the product gas may be adjusted such that these characteristics are best matched to optimal input characteristics for such engines.

In one embodiment, the control system may be configured to adjust a given process such that limitations or performance guidelines with regards to reactant and/or product residence times in various components, or with respect to various processes of the overall process are met and/or optimized for. For example, an upstream process rate may be controlled so to substantially match one or more subsequent downstream processes.

In addition, the control system may, in various embodiments, be adapted for the sequential and/or simultaneous control of various aspects of a given process in a continuous and/or real time manner.

In general, the control system may comprise any type of control system architecture suitable for the application at hand. For example, the control system may comprise a substantially centralized control system, a distributed control system, or a combination thereof. A centralized control system will generally comprise a central controller...
configured to communicate with various local and/or remote sensing devices and response elements configured to respectively sense various characteristics relevant to the controlled process, and respond thereto via one or more controllable process devices adapted to directly or indirectly affect the controlled process. Using a centralized architecture, most computations are implemented centrally via a centralized processor or processors, such that most of the necessary hardware and/or software for implementing control of the process is located in a same location.

A distributed control system will generally comprise two or more distributed controllers which may each communicate with respective sensing and response elements for monitoring local and/or regional characteristics, and respond thereto via local and/or regional process devices configured to affect a local process or sub-process. Communication may also take place between distributed controllers via various network configurations, wherein a characteristics sensed via a first controller may be communicated to a second controller for response thereon, wherein such distal response may have an impact on the characteristic sensed at the first location. For example, a characteristic of a downstream product gas may be sensed by a downstream monitoring device, and adjusted by adjusting a control parameter associated with the converter that is controlled by an upstream controller. In a distributed architecture, control hardware and/or software is also distributed between controllers, wherein a same but modularly configured control scheme may be implemented on each controller, or various cooperative modular control schemes may be implemented on respective controllers.

Alternatively, the control system may be subdivided into separate yet communicatively linked local, regional and/or global control subsystems. Such an architecture could allow a given process, or series of interrelated processes to take place and be controlled locally with minimal interaction with other local control subsystems. A global master control system could then communicate with each respective local control subsystem to direct necessary adjustments to local processes for a global result.

The control system of the present invention may use any of the above architectures, or any other architecture commonly known in the art, which are considered to be within the general scope and nature of the present disclosure. For instance, processes controlled and implemented within the context of the present invention may be controlled in a dedicated local environment, with optional external communication to any central and/or remote control system used for related upstream or downstream processes, when applicable. Alternatively, the control system may comprise a sub-component of a regional and/or global control system designed to cooperatively control a regional and/or global process. For instance, a modular control system may be designed such that control modules interactively control various sub-components of a system, while providing for inter-modal communications as needed for regional and/or global control.

The control system generally comprises one or more central, networked and/or distributed processors, one or more inputs for receiving current sensed characteristics from the various sensing elements, and one or more outputs for communicating new or updated control parameters to the various response elements. The one or more computing platforms of the control system may also comprise one or more local and/or remote computer readable media (e.g. ROM, RAM, removable media, local and/or network access media, etc.) for storing therein various predetermined and/or readjusted control parameters, set or preferred system and process characteristic operating ranges, system monitoring and control software, operational data, and the like. Optionally, the computing platforms may also have access, either directly or via various data storage devices, to process simulation data and/or system parameter optimization and modeling means. Also, the computing platforms may be equipped with one or more optional graphical user interfaces and input peripherals for providing managerial access to the control system (system upgrades, maintenance, modification, adaptation to new system modules and/or equipment, etc.), as well as various optional output peripherals for communicating data and information with external sources (e.g. modem, network connection, printer, etc.).

The processing system and any one of the sub-processing systems can comprise exclusively hardware or any combination of hardware and software. Any of the sub-processing systems can comprise any combination of none or more proportional (P), integral (I) or differential (D) controllers, for example, a P-controller, an I-controller, a PI-controller, a PD controller, a PID controller etc. It will be apparent to a person skilled in the art that the ideal choice of combinations of P, I, and D controllers depends on the dynamics and delay time of the part of the reaction process of the gasification system and the range of operating conditions that the combination is intended to control, and the dynamics and delay time of the combination controller. It will be apparent to a person skilled in the art that these combinations can be implemented in an analog hardwire form which can continuously monitor, via sensing elements, the value of a characteristic and compare it with a specified value to influence a respective control element to make an adequate adjustment, via response elements, to reduce the difference between the observed and the specified value. It will further be apparent to a person skilled in the art that the combinations can be implemented in a mixed digital hardware-software environment. Relevant effects of the additionally discretionary sampling, data acquisition, and digital processing are well known to a person skilled in the art. P, I, D combination control can be implemented in feedforward and feedback control schemes.

In corrective, or feedback, control the value of a control parameter or control variable, monitored via an appropriate sensing element, is compared to a specified value or range. A control signal is determined based on the deviation between the two values and provided to a control element in order to reduce the deviation. It will be appreciated that a conventional feedback or responsive control system may further be adapted to comprise an adaptive and/or predictive component, wherein response to a given condition may be tailored in accordance with modeled and/or previously monitored reactions to provide a reactive response to a sensed characteristic while limiting potential overshoots in compensatory action. For instance, acquired and/or historical data provided for a given system configuration may be used cooperatively to adjust a response to a system and/or process characteristic being sensed to be within a given range from an optimal value for which previous responses have been monitored and adjusted to
provide a desired result. Such adaptive and/or predictive control schemes are well known in the art, and as such, are not considered to depart from the general scope and nature of the present disclosure.

[0155] Control Elements

[0156] Sensing elements contemplated within the present context, as defined and described above, are provided to monitor one or more parameters, including, but not limited to, temperature and gas flow rates, gas pressure, height of the feedstock pile in the gasifier, gas composition and heating value, at specified locations throughout the system.

[0157] Response elements contemplated within the present context, as defined and described above, can include, but are not limited to, various control elements operatively coupled to process-related devices configured to affect a given process by adjustment of a given control parameter related thereto. For instance, process devices operable within the present context via one or more response elements, may include, but are not limited to air and product gas blowers, feedstock inputs, pressure and temperature regulators, lateral transfer units and plasma heat sources.

Accordingly, examples of operating conditions which may be adjusted by the response elements of the control sub-system include one or more of the exchange-air flow rate (i.e., the process air blower speed), the rate of feedstock input, the ratio of feedstock input (e.g., MSW to high carbon feedstock), the pressure of the system, the movement of the lateral transfer units, the rate of input of process additives such as steam, and the power to the plasma heat sources.

[0158] In one embodiment of the invention, the control subsystem comprises temperature sensing elements to monitor the temperature at sites located throughout the system. The temperature sensing elements for monitoring the temperature may be temperature transmitters such as thermocouples or optical thermometers installed at locations in the system as required.

[0159] FIG. 9 depicts an overview of various means for monitoring and controlling the temperature within the system, indicating the location at which temperature transmitters and flow regulators are installed throughout the system. For example, temperature transmitters 5982 are located to monitor the temperature of the product gas at the gas-to-air heat exchanger product gas outlet 5926. Temperature transmitters 5981 are also located to monitor the temperature of the heated exchange-air 5015 at the exchange-air outlet 5917 of the gas-to-air heat exchanger 5109.

[0160] Temperature transmitters and may also be located throughout the converter in order to monitor the processing temperatures during the gasification and reformulating processes. Monitoring the temperature, for example, in the region of the converter in which the gasification process takes place, ensures the optimum conversion efficiency by maintaining the feedstock pile at as high a temperature as possible for as long as possible, without reaching temperatures that will melt or agglomerate the feedstock. Temperature control within the pile is achieved by adjusting the flow of heated exchange-air into a given region of the gasifier 2009 through adjustments to control valves 5994A, 5994B and 5994C, in order to stabilize the temperatures as required for the different stages of the gasification process. Temperatures at the different stages are measured by temperature transmitters 5984A, 5984B and 5984C, respectively. Controlling the temperature at the different stages of the gasification process may also be achieved by controlled movement of the feedstock through the gasifier by the lateral transfer units.

[0161] Temperatures in the reformulation region 3009 of the converter are monitored by temperature transmitter 5983. Power to the plasma torches 2980 may be adjusted as required in order to stabilize the temperatures in the reformulation region 3009 in order to maintain an optimum temperature for fully reformulating the offgas, volatiles, tars and soot into a defined gas product.

[0162] The temperature transmitter 5981 installed on the exchange-air outlet 5917 to measure the temperature of the heated exchange-air ensures that the heat recycling process is carried out under conditions that ensure the air is heated to a temperature appropriate for use in the gasification process. For example, if the optimum temperature of the exchange-air for use in a gasifier is about 600°C, a temperature transmitter installed on the air outlet stream will be used to ensure the temperature of the exchange-air does not exceed, for example, 625°C. In order to avoid providing too much heated exchange-air (or exchange-air that is too hot) to the gasification process, which could result in overheating the feedstock, a control valve 5990 is opened to vent the excess exchange-air to the atmosphere.

[0163] Accordingly, means for controlling the control valve 5990 for venting exchange-air to the atmosphere is also optionally provided. For example, in some instances it is necessary to heat more air than required for the process due to equipment considerations (e.g., when starting a shutdown procedure). In such instances, the exchange-air can be vented as required.

[0164] According to one embodiment of the invention, the control strategy sets a fixed set point for the optimum heated exchange-air output temperature, for example, about 600°C. In such an embodiment, even when the exchange-air flow through the gas-to-air heat exchanger is reduced, the exit gas temperature of the gas-to-air heat exchanger will remain the same. The reduced air flow through the gas-to-air heat exchanger will therefore result in an increased temperature of the product gas exiting the gas-to-air heat exchanger, and entering the next stage of the process, for example, a heat recovery steam generator. When airflow through the system is reduced, however, product gas flow will consequently also reduce, so the increased product gas inlet temperature to the heat recovery steam generator will only be momentarily high. For example, if airflow is reduced to 50%, the maximum product gas inlet temperature that the steam generator would momentarily see is approximately 800°C, which is within the temperature limits of the design.

[0165] Monitoring the temperature of the product gas at the gas-to-air heat exchanger inlet can also ensure that the temperature of the product gas as it enters a respective heat exchanger does not exceed the ideal operating temperature of that device. For example, if the design temperature for the gas-to-air heat exchanger is 1050°C, temperature data obtained from a temperature transmitter on the inlet gas stream to the heat exchanger can be used to control both exchange-air flow rates through the system and plasma heat power in order to maintain the optimum product gas temperature. In addition, measurement of the product gas tem-
perature at the product gas outlet of the gas-to-air heat exchanger may be useful to ensure that the optimum amount of sensible heat has been recovered from the product gas at the heat recovery stage.

[0166] If the temperature of the gas exiting the converter exceeds a predetermined limit, this may be an indication that the tubes are starting to plug, at which time the system should be shut down for maintenance. The heat exchangers are therefore provided, as required, with ports for convenient inspection and maintenance.

[0167] In one embodiment of the invention, the control subsystem comprises sensing elements to monitor pressure and gas flow rates throughout the gasification system. These pressure sensing elements may include pressure sensors such as pressure transducers, pressure transmitters or pressure taps located in the system, for example, on a vertical wall of the gasifier, or in association with downstream elements of the gasification system such as a gas storage tank.

[0168] Data relating to the pressure and gas flow in the system is used by the control subsystem to determine whether adjustments to parameters such as torch power or the rate of addition of solid residue material are required.

[0169] In one embodiment of the invention, the control subsystem comprises response elements for adjusting the pressure within the system, thereby maintaining a desired pressure in the system within certain defined tolerances. Any pressure variations caused, for example, when the product gas blower speed or exchange-air input rate is adjusted, are corrected by making adjustments to certain operational parameters as determined by the control subsystem.

[0170] FIG. 10 depicts an overview of various means for monitoring and controlling product gas pressure and flow throughout the system. Pressure transmitters 7095 on a downstream gas storage tank 7010 send a signal to exchange-air flow control valves at the converter 1010, whereby, for example, a decrease in the gas storage tank pressure sends a signal to increase the exchange-air flow into the gasifier 2010, and vice versa. The flow of exchange-air to the gasifier 2010 is controlled using control valves 5994A, 5994B and 5994C. An increased amount of exchange-air 5015 delivered to the gasifier 2010 results in an increased rate at which feedstock is gasified, thereby producing in an increased product gas 5020 flow (and an increase in the system pressure).

[0171] Any change in the demand for exchange-air 5015 in the gasifier 2010 affects the process air blower discharge pressure as measured by pressure transmitter 5095, which then adjusts the speed on the variable frequency drive (VFD) on the process air blower 5012. The speed of the process air blower 5012 is increased when low pressure is detected in the storage tank 7010, and the speed is decreased when high pressure is detected in the storage tank. When an increased amount of gas is being produced, the control subsystem may also automatically adjust the speed on a gas blower VFD to alleviate this pressure increase, delivering more gas to the storage tank which results in an increase in the storage tank pressure.

[0172] In response to data acquired by pressure sensors located throughout the system, the speed of the downstream induction blower is adjusted according to whether the pressure in the system is increasing (whereby the fan will decrease in speed) or decreasing (whereby the fan will decrease in speed). In one embodiment, data relating to the pressure at points throughout the system are obtained on a continuous basis, thereby allowing the control subsystem to make frequent adjustments to the fan speed to maintain the system pressure within a predetermined set point.

[0173] In one embodiment, the system is maintained under slight negative pressure relative to atmospheric pressure to prevent gases being expelled into the environment.

[0174] In one embodiment, the internal pressure is adjusted using an induction blower located downstream of the gasifier that operates by pulling the product gas out of the gasifier. The induction blower thus employed maintains the system at atmospheric or negative pressure. In one embodiment, a control valve is provided in a gas outlet line to increase or restrict the flow of gas that is being removed by the downstream gas blower.

[0175] In systems in which positive pressure is maintained, the blower is operated such that the rate of removal of the product gas is decreased, or even shut off, so that the gases are forced to “push” their way through the system resulting in a higher (positive) pressure.

[0176] Fluctuations in the gas flow may occur as the result of non-homogeneous conditions in the gasification process (e.g. malfunctions in the torch, blockages in gas lines, or interruptions in the feedstock input). If fluctuations in gas flow persist, the system may be shut down until the problem is solved.

[0177] Since addition of high carbon feedstock, air and/or steam process additives during the gasification process affects the conversion chemistry, it is desirable to monitor the product gas composition. In one embodiment of the invention, the control subsystem comprises sensing elements to monitor the composition of the gas product. Monitoring the composition of the product gas can be achieved, for example, by means of a gas analyzer. A gas analyzer can determine, for example, the hydrogen, carbon monoxide and/or carbon dioxide content of the product gas. One method that can be used to determine the chemical composition of the product gas is through gas chromatography (GC) analysis. Sample points for these analyses can be located throughout the system. In one embodiment, the gas composition is measured using a Fourier Transform Infrared (FTIR) Analyzer, which measures the infrared spectrum of the gas.

[0178] Although high temperature gas analysis devices exist, composition is generally measured after the product gas has been cooled and after it has undergone a conditioning step to remove particulate matter and other contaminants.

[0179] The product gas composition can be controlled by controlling the composition of the feedstock (e.g., the ratio of MSW to HCF) being gasified, as well as the amount of air and/or steam process additives being added to the gasification and reformulating reactions. Accordingly, the control subsystem provides a means to control the ratio of the MSW to HCF, rate of the addition of the feedstock stream, as well as the amount of air and/or steam process additives being added to the converter.
In one embodiment of the invention, the control subsystem comprises means to adjust the rate and/or amounts of air inputs into the gasifier and/or the reformulator. In one embodiment of the invention, the control subsystem comprises means to adjust the rate and/or amounts of steam inputs into the reformulator.

In one embodiment of the invention, the control subsystem comprises means to adjust the rate of addition of the high carbon feedstock (HCF) inputs to the gasifier, in response to process demands for higher or lower carbon input to provide the desired gas composition. In one embodiment of the invention, the control subsystem comprises means to adjust the rate of addition of MSW to the gasifier. The MSW and optionally the HCF inputs are added to the gasifier using a number of possible input means that are selected and adapted as required for the form of the material added. The materials may be added in a continuous manner, for example, by using a rotating screw or auger mechanism. Alternatively, the materials can be added in a discontinuous fashion, for example, by using a pusher ram to add material in portions as required.

In one embodiment, the feedstock input rate is controlled by adjusting a feed screw conveyor speed via a drive motor variable frequency drive (VDFs). The input rate will be adjusted as required according to the heating capability of the heated exchange-air inputs.

The system may further comprise means for monitoring and controlling pile height (or level) in order to maintain stable processing conditions within the converter. This provides the ability to maintain stable pile height inside the converter. Controlling the pile height prevents fluidization of the material from exchange-air injection which could occur at low level, while also preventing poor temperature distribution through the pile resulting from restricted airflow that would occur at high level. Maintaining a stable pile height also ensures consistent converter residence time.

A series of level switches in the gasifier measure pile depth. In one embodiment, the level switches are microwave devices with an emitter on one side of the gasifier and a receiver on the other side, which detects either presence or absence of solid material at that point inside the converter.

In one embodiment of the invention, there are provided lateral transfer units to move the material being gasified through the different regions of the gasifier. The amount and location of feedstock in the gasifier is a function of feed rate and motion of the lateral transfer units, as well as the amounts of heated exchange-air inputs. Accordingly, in such an embodiment, the control subsystem comprises means to control the movement of the material through the different regions of the gasifier as required.

In one embodiment, the lateral transfer units are rams, wherein the feedstock is conveyed through the different regions of the gasifier at a rate determined by the stroke length and frequency. For example, the control subsystem may employ limit switches or other means of travel control such as computer controlled variable speed motor drives to control the length, speed and/or frequency of the ram stroke so that the amount of material moved with each stroke can be controlled.

In one embodiment, the lateral transfer units comprise one or more screw conveyors, wherein the rate of transfer of material through the gasifier is controlled by adjusting the conveyor speed via drive motor variable frequency drives.

In one embodiment of the invention, the control subsystem comprises means to adjust the power, and optionally the position, of the plasma heat source. For example, when the temperature of the product gas at the gas outlet of the converter is too high, the control subsystem may command a drop in the power rating of the plasma heat source.

Use of the Gasification System/The Process

The system according to the present invention gasifies a feedstock, using a process for gasification of the feedstock which generally comprises the steps of passing the feedstock into a converter where it is subjected to the heating effect of heated exchange-air. Upon heating by the exchange-air, the feedstock is dried and volatile components in the dried feedstock are volatilized. In an embodiment of the invention, the heated exchange-air further drives the complete conversion of the resulting char to its gaseous constituents, leaving an ash by-product. The combined products of the drying, volatilization and combustion steps provide an offgas, which is further subjected to the heat from a plasma heat source to convert the offgas to a hot gas product comprising carbon monoxide, carbon dioxide, hydrogen, water vapour (and nitrogen due to the use of air in the gasification process). Steam and/or air process additives may be optionally added at the gasification stage and/or the offgas conversion stage.

In an embodiment of the invention, the process further comprises the step of subjecting by-product ash to heating by means of a secondary plasma heat source to form a slag product.

The process of the present invention further comprises the steps of passing the hot gas product through a heat exchanger, transferring heat from the hot product gas to air to produce a heated exchange-air and a cooled product gas, and using the heated exchange-air in the gasification of the carbonaceous feedstock.

The process of the present invention further comprises the steps of passing the cooled gas product into a second heat exchanger, transferring heat from the first cooled gas to the water to produce a further cooled gas and steam.

The process of the present invention maximizes net conversion efficiency by offsetting the amount of electricity that has to be consumed to create the heat which drives the gasification process, to drive rotating machinery, and to power the plasma heat sources. For applications having the objective of generating electricity, the efficiency is measured by comparing the energy consumed by the overall gasification process with the amount of energy generated using the product gas (for example, to power gas turbines or in fuel cell technologies), and through the recovery of sensible heat to generate steam to power steam turbines.

The gasification process can further comprise a feedback control step of adjusting one or more of the feedstock input rate, the exchange-air flow rate, the product gas flow rate, the steam process additive input rate and the amount of power supplied to the plasma heat sources based on changes in the flow rate/pressure, temperature and/or
composition of the product gas. The feedback control step thus allows the flow rate, temperature and/or composition of the synthesis gas to be maintained within acceptable ranges.

[0196] In one embodiment of the present invention, the process further comprises the step of pre-heating the carbonaceous feedstock prior to adding to the converter.

[0197] In one embodiment, the gasification process according to the present invention employs the use of exchange-air to heat the gasifier to a temperature appropriate for gasifying feedstocks. In another embodiment, which is typically used at the start-up phase of the system, air is fed into the system, whereby it can be heated using plasma heat, or heat recovered from other stages in the gasification processes, to provide a hot start-up gas which then enters the gas-to-air heat exchanger to generate heated exchange-air. The exchange-air is transferred to the exchange-inlets to heat up the gasifier, such that the entire process can run without the use of fossil fuels.

[0198] FIGS. 11A to 11I depict various options for the recycling of heat in accordance with the present invention.

[0199] FIG. 11A is a block flow diagram describing one embodiment of the invention, wherein hot product gas 5020A is produced by gasifying carbonaceous feedstock in a converter 1000A. The hot product gas 5020A is passed through a heat exchanger 5100A, where the heat is transferred from the hot product gas 5020A to air 5010A blown through the heat exchanger by an air blower 5012A to produce heated exchange-air 5015A and a cooled product gas 5025A. The heated exchange-air 5015A is then passed back into converter 1000A to drive the gasification process. The cooled product gas 5025A is then further cooled by a dry quench step 6111A prior to being passed through a gas conditioning system 6000A. The product gas, after cooling and cleaning, is then combusted in a gas engine 5060A, and the hot combustion gases 5061A are exhausted to the atmosphere.

[0200] FIG. 11B is a block flow diagram describing one embodiment of the invention, wherein hot product gas 5020B is produced by gasifying carbonaceous feedstock in a converter 1000B. The hot product gas is passed through a heat exchanger 5100B, where the heat is transferred from the hot product gas 5020B to air 5010B blown through the heat exchanger by an air blower 5012B to produce heated exchange-air 5015B and a cooled product gas 5023B. The heated exchange-air 5015B is then passed back into converter 1000B to drive the gasification process. Additional heat is recovered from the cooled product gas 5023B by passing the gas through the heat recovery steam generator 5300B prior to being passed through a gas conditioning system 6000B. The additional heat is transferred to water 5030B to produce steam 5035B. The product gas, after cooling and cleaning, is then combusted in a gas engine 5060B, and the hot combustion gases 5061B are exhausted to the atmosphere.

[0201] FIG. 11C is a block flow diagram describing the embodiment of FIG. 11B, wherein the hot combustion gases 5061B from the gas engines are passed through a second heat recovery steam generator 5300C, where heat from the hot combustion gases is transferred to water 5030C to generate steam 5030C.

[0202] FIG. 11D is a block flow diagram describing the embodiment of FIG. 11B, wherein the steam 5035B generated in the heat recovery steam generator 5300B is used to power a steam turbine 5065B to generate electricity.

[0203] FIG. 11E is a block flow diagram describing the embodiment of FIG. 11C, wherein the steam (5035B and 5035C) generated in a heat recovery steam generator (5300B and 5300C) is combined and used to power a steam turbine 5065E to generate electricity.

[0204] FIG. 11F is a block flow diagram describing the embodiment of FIG. 11B, wherein the heated exchange-air 5015B is also passed into a feedstock conditioner 5067F to pre-dry the feedstock 5088F prior to being fed into converter 1000F for gasification.

[0205] FIG. 11G is a block flow diagram describing the embodiment of FIG. 11B, wherein the steam 5035FS generated in the heat recovery steam generator 5300B is used to indirectly heat a feedstock conditioner 5067G, thereby pre-drying the feedstock 5088G prior to being fed into the converter 1000G for gasification.

[0206] FIG. 11H is a block flow diagram describing one embodiment of the invention, wherein hot product gas 5020H is produced by gasifying carbonaceous feedstock in a converter 1000H. The hot product gas 5020H is passed through a heat exchanger 5100H, where the heat is transferred from the hot product gas 5020H to air blown through the heat exchanger by an air blower 5012H to produce heated exchange-air 5015H and a cooled product gas 5025H. The heated exchange-air 5015H is then passed back into the converter 1000H to drive the gasification process. The cooled product gas is then passed through a gas conditioning system. The product gas, after cooling and cleaning, is then combusted in a gas engine 5060H, and the hot combustion gases 5061H are exhausted to the atmosphere. This embodiment includes a solid residue conditioning step, wherein the hot gases produced in the solid residue conditioner 4020H are also passed through a heat exchanger 5105H, wherein heat from the hot gases is transferred to air 5111H that is blown through the heat exchanger 5105H to produce a second heated air product 5115H. The second heated air product 5115H is then used to indirectly heat a feedstock conditioner 5067H, thereby pre-drying the feedstock 5088H prior to being fed into the converter 1000H for gasification.

[0207] FIG. 11I is a block flow diagram describing one embodiment of the invention, wherein hot product gas 5020I is produced by gasifying carbonaceous feedstock in a converter 1000I. The hot product gas 5020I is passed through a heat exchanger 5100I, where the heat is transferred from the hot product gas 5020I to air blown through the heat exchanger by an air blower 5012I to produce heated exchange-air 5015I and a cooled product gas 5025I. The heated exchange-air 5015I is then passed back into converter 1000I to drive the gasification process. The cooled product gas 5025I is then passed through a gas conditioning system 6000I, and into a system for storing and homogenizing the gas product 7000I. A portion of the product gas 5225I is then combusted in a gas engine 5060I, and the hot combustion gases 5061I are exhausted to the atmosphere, while another portion of the product gas 5225I is combusted in a gas burner 5067I to provide heat for pre-heating the converter 1005I of another gasification system.

[0208] The invention will now be described with reference to a specific example. It will be understood that the follow-
In general, the system of the present invention is used by feeding exchange-air into a converter where feedstock is subjected to sufficient heat to allow the gasification reaction to take place.

In the exemplary embodiments depicted in FIG. 12 and 13, the gasifiers 2100 and 2200 each have stepped floors having three floor levels, or steps. Optionally, each floor level is sloped between about 5 and about 10 degrees. In a step-floor gasifier, the individual steps (floor levels) provide conditions appropriate for the respective drying, volatilization and char-to-ash conversion stages of the gasification process, to thereby allowing for the optimization of the gasification process.

In each of these exemplary gasifiers, the feedstock is fed onto the first step, where the conditions are provided such that the major process here is that of drying, with some volatilization and char-to-ash conversion. The normal temperature range for this step (as measured at the bottom of the material pile) lies between 300 and 900 °C.

The dried feedstock is then transferred to the second step, where the conditions are provided such that the major process here is that of volatilization of the dried feedstock to form char, with a small degree (the remainder) of the drying operation as well as some char-to-ash conversion. The normal temperature range for this step is between 400 and 950 °C.

The char is then transferred to the third step, where the conditions are provided such that the major process is that of char-to-ash conversion with a lesser amount (the remainder) of volatilization. The normal temperature range lies between 600 and 1000 °C.

Movement over the steps is facilitated by the lateral transfer units with each step optionally being serviced by an independently controlled lateral transfer unit.

In the embodiment of the gasifier depicted in FIG. 12, the gasifier 2100 comprises a refractory-lined horizontally oriented gasification chamber 2102 having a feedstock input 2104, gas outlet 2106 and a solid residue outlet 2108. The gasification chamber 2102 has a stepped floor with a plurality of floor levels 2112, 2114 and 2116. Each floor level has a series of exchange-air inlets 2126 located in the side walls proximal to the floor level to allow for the addition of exchange-air. Input of exchange-air is regulated to promote gasification of the reactant material.

In the embodiment of the gasifier depicted in FIG. 13, the gasifier 2200 comprises a refractory-lined horizontally oriented gasification chamber 2202 having a feedstock input 2204, gas outlet 2206 and a solid residue outlet 2208. The gasification chamber 2202 has a stepped floor with a plurality of floor levels 2212, 2214 and 2216.

Each level or step has a perforated floor through which heated air can be introduced. The air feed for each level or step is independently controllable. Independent air feed and distribution through the perforated floor 2270 is achieved by a separate air box 2272, 2274, and 2276 which forms the floor at each step.

A representative air box is illustrated in FIG. 14, which clearly shows the perforated top plate 2302 of the air box, as well as a connection flange 2280 for connection to the exchange-air conduit system.

The offgas formed in the gasifier are then further treated in a reformulating chamber with a plasma heat source and optionally with steam and additional heated exchange-air. These additives are optionally added in the reformulation step to ensure formation of a product gas having a defined composition. The temperature during the reformulation step is maintained in a range that is high enough to keep the reactions at an appropriate level to ensure complete conversion to the defined gas product, while minimizing pollution production. In the exemplary embodiment, the temperature range of the reformulation step is from about 900 °C to about 1300 °C.

If, after the reformulating stage, the temperature of the product gas is too high, steam is optionally added to reduce the exit temperature of the product gas. The product gas exits the plasma reformulating zone at a temperature of about 900 °C to about 1100 °C. In the exemplary embodiment, the product gas exit temperature is about 1000 °C ±100 °C. The flow rate of the hot product gas is about 6000 Nm³/hr to about 9500 Nm³/hr, typically about 7950 Nm³/hr. The hot product gas then passes into a gas-to-air heat exchanger.

In the present example, air enters the gas-to-air heat exchanger at ambient temperature, i.e., from about −30 to about 40 °C. The air is circulated through the system using air blowers, entering the gas-to-air heat exchanger at a rate of about 1000 Nm³/hr to 5150 Nm³/hr, typically at a rate of about 4300 Nm³/hr.

In the present example, the air is heated in the heat exchanger to produce exchange-air having a temperature of about 500 °C to about 625 °C. In the exemplary embodiment, the exchange-air temperature is about 600 °C. The hot product gas, in turn, is cooled to a temperature of about 500 °C to about 800 °C. In the exemplary embodiment, the product gas temperature is about 740 °C. The heated exchange-air is passed into the gasifier through the exchange-air inlets to gasify the feedstock, as discussed above.

The gas-to-air heat exchanger of the exemplary embodiment is a shell-tube type heat exchanger designed specifically for the high level of particulate loading in the product gas, wherein the product gas flows on the tube side, and the air flows counter currently on the shell side.

In the exemplary embodiment, the cooled product gas is further cooled using a dry quench step to remove excess heat from the product gas, thereby providing a cooled product gas as required for the subsequent filtering and conditioning steps. The cooled product gas is then further passed through a gas conditioning stage to remove acid gases, heavy metals, particulate matter and other contaminants.

The residue by-products of the gasification process are further conditioned in a residue conditioning chamber by melting with a dedicated plasma heat source. The products of the residue conditioning step are an inert slag material and a hot gas.
Although the invention has been described with reference to certain specific embodiments, various modifications thereof will be apparent to those skilled in the art without departing from the spirit and scope of the invention as outlined in the claims appended hereto.

The disclosure of all patents, publications, including published patent applications, and database entries referenced in this specification are specifically incorporated by reference in their entirety to the same extent as if each such individual patent, publication, and database entry were specifically and individually indicated to be incorporated by reference.

1. A system that recycles heat recovered from a hot gas to a carbonaceous feedstock gasifier, the system comprising:
   - means to transfer the hot gas to a gas-to-fluid heat exchanger, where the heat from the hot gas is transferred to a fluid to produce a heated fluid and cooled gas;
   - means to transfer the heated fluid to the gasifier; and
   - a control system comprising sensing elements for monitoring operating parameters of the system, and response elements for adjusting operating conditions within the system to optimize the gasification process;
   - wherein the response elements adjust the operating conditions within the system according to the data obtained from the sensing elements, thereby optimizing the efficiency of a gasification process by minimizing energy consumption of the process, while also maximizing energy production.

2. The system according to claim 1, wherein the hot gas is a gas produced during a carbonaceous feedstock gasification process.

3. The system according to claim 2, wherein the fluid is air, water, oil, nitrogen or carbon dioxide.

4. The system according to claim 3, wherein the fluid is air, and the gas-to-fluid heat exchanger is a gas-to-air heat exchanger.

5. The system according to claim 3, wherein the fluid is water, and the gas-to-fluid heat exchanger is a heat recovery steam generator.

6. A system that recycles heat recovered from a hot gas to a carbonaceous feedstock gasifier, the system comprising:
   - means to transfer the hot gas to a gas-to-air heat exchanger, where the heat from the hot gas is transferred to air to produce a heated air and a cooled gas; and
   - means to transfer the heated air to the gasifier.

7. The system according to claim 6, wherein the hot gas is a gas produced in a gasifier during a carbonaceous feedstock gasification process.

8. The system according to claim 6, wherein the means to transfer the hot gas to the gas-to-air heat exchanger comprises a hot gas conduit system providing fluid communication between a hot gas outlet on the gasifier and a hot gas inlet on the gas-to-air heat exchanger, and the means to transfer the heated air to the gasifier comprises an air conduit system providing fluid communication between an air outlet on the gas-to-air heat exchanger and an air inlet on the gasifier, wherein the hot gas is transferred from the gasifier to the gas-to-air heat exchanger through the hot gas conduit, and the heated air is transferred from the gas-to-air heat exchanger through the air conduit system into the air inlet the gasifier.

9. A process for improving the efficiency of a carbonaceous feedstock gasification process by recycling sensible heat from a hot gas produced by the gasification process back into the gasification process using a gas-to-fluid heat exchanger comprising a hot product gas inlet in communication with a cooled product gas outlet, and a cool fluid inlet in communication with a heated fluid outlet, the process comprising the steps of:
   - passing the hot product gas through the hot product gas inlet into the gas-to-fluid heat exchanger;
   - passing the cool fluid through the cool fluid inlet into the gas-to-fluid heat exchanger;
   - transferring heat from the hot product gas to the cool fluid via the gas-to-fluid heat exchanger to produce a cooled product gas which exits the heat exchanger via the cooled product gas outlet, and a heated fluid which exits the heat exchanger via the heated fluid outlet; and
   - using the heated fluid to provide heat for the carbonaceous feedstock gasification process.

10. The process according to claim 9, wherein the fluid is air, and the gas-to-fluid heat exchanger is a gas-to-air heat exchanger.