US 20140069010A1

(19) **United States**
(12) **Patent Application Publication**
**Hughes et al.**
(10) **Pub. No.: US 2014/0069010 A1**
(43) **Pub. Date: Mar. 13, 2014**

(54) **GENERATING DEOXYGENATED PYROLYSIS VAPORS**

(71) Applicant: **Phillips 66 Company**, Houston, TX (US)

(72) Inventors: **Mark A. Hughes**, Owasso, OK (US); **Tie-Pan Shi**, Bartlesville, OK (US); **Richard D. Sadok**, Bartlesville, OK (US); **Samuel T. Jones**, Dewey, OK (US); **Johnathan T. Gorke**, Owasso, OK (US); **Natalie A. Rebacz**, Bartlesville, OK (US); **Liang Zhang**, Owasso, OK (US); **Martin L. Perkins**, Dewey, OK (US)

(73) Assignee: **Phillips 66 Company**, Houston, TX (US)

(21) Appl. No.: **14/021,540**

(22) Filed: **Sep. 9, 2013**

**Related U.S. Application Data**

(60) Provisional application No. 61/699,098, filed on Sep. 10, 2012.

**Publication Classification**

(51) **Int. Cl.**
*C10K 3/02* (2006.01)

(52) **U.S. Cl.**
CPC .......................................... ***C10K 3/02*** (2013.01)
USPC ................................................ **48/111**; 48/209

(57) **ABSTRACT**

The present disclosure relates generally to novel biomass pyrolysis processes and systems that decrease entrainment of char and other contaminants with the pyrolysis vapors. In certain embodiments, the present disclosure provides methods and systems to prevent entrainment of particles of char and heat carrier with pyrolysis vapors leaving a reactor, while allowing rapid upgrading of the vapors by catalyst(s) that are held in a an upgrading reactor and protected from contact with the char.

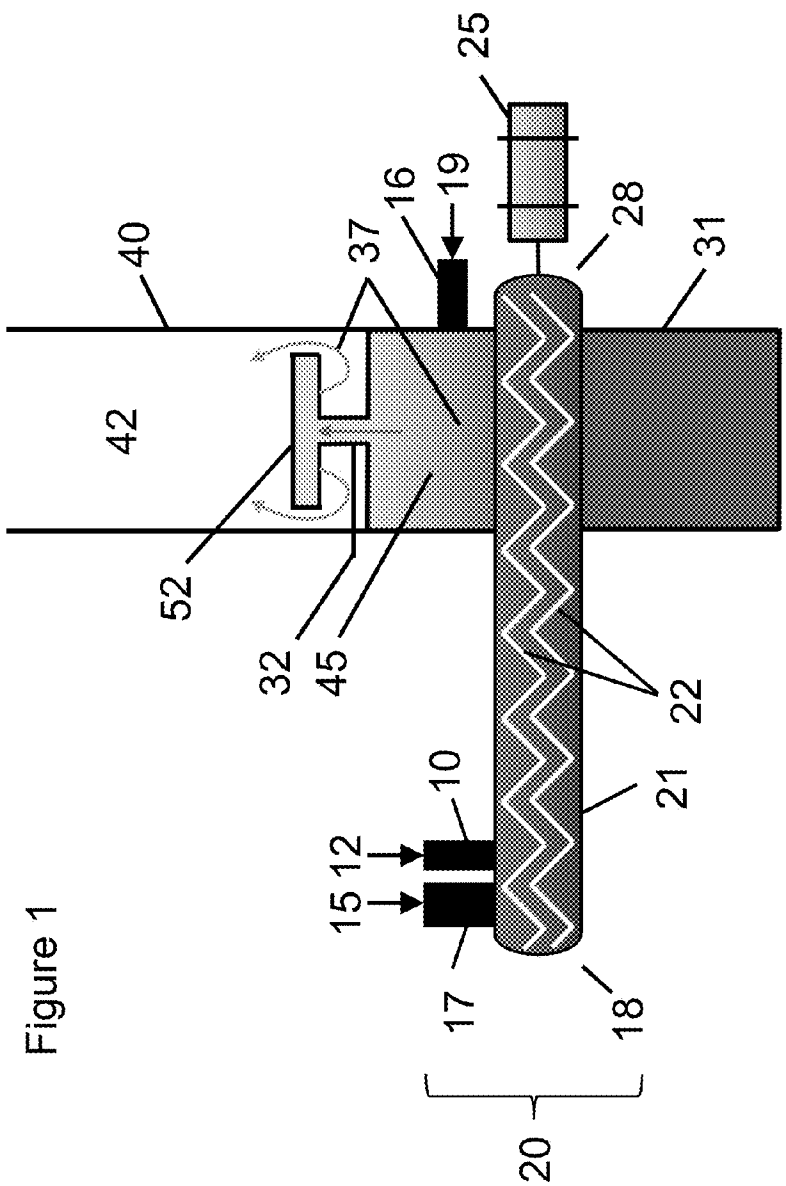



Figure 1

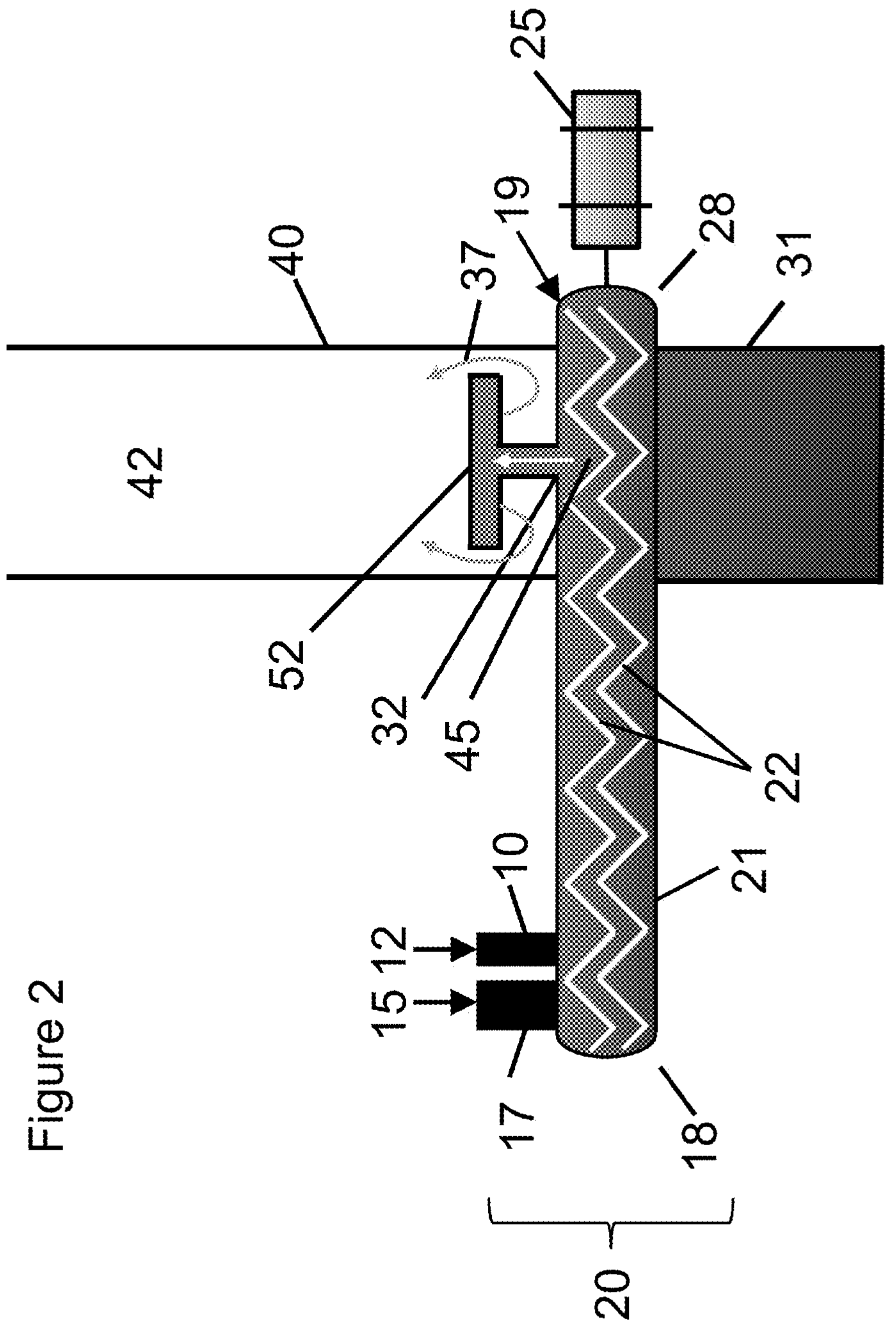


Figure 2

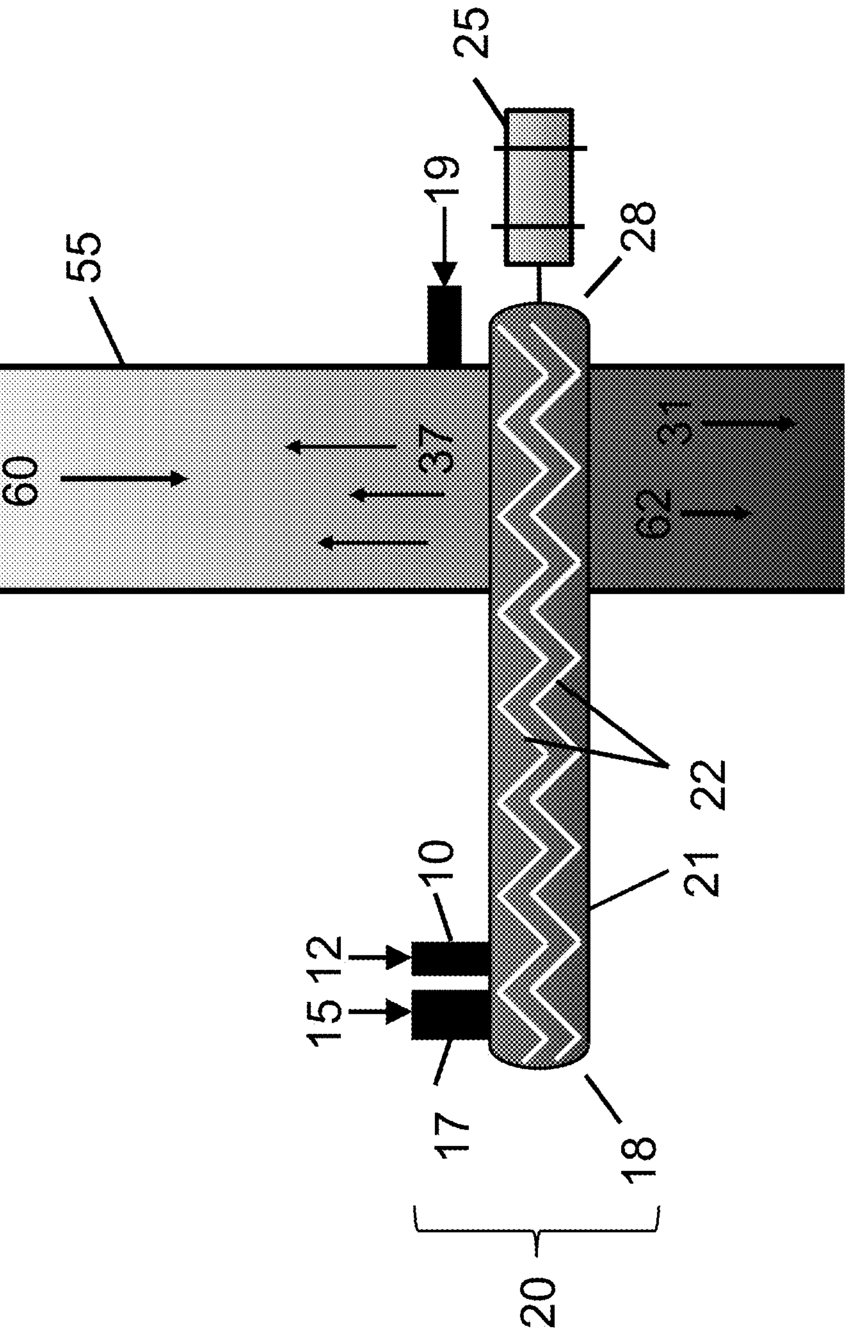



Figure 3

Figure 4

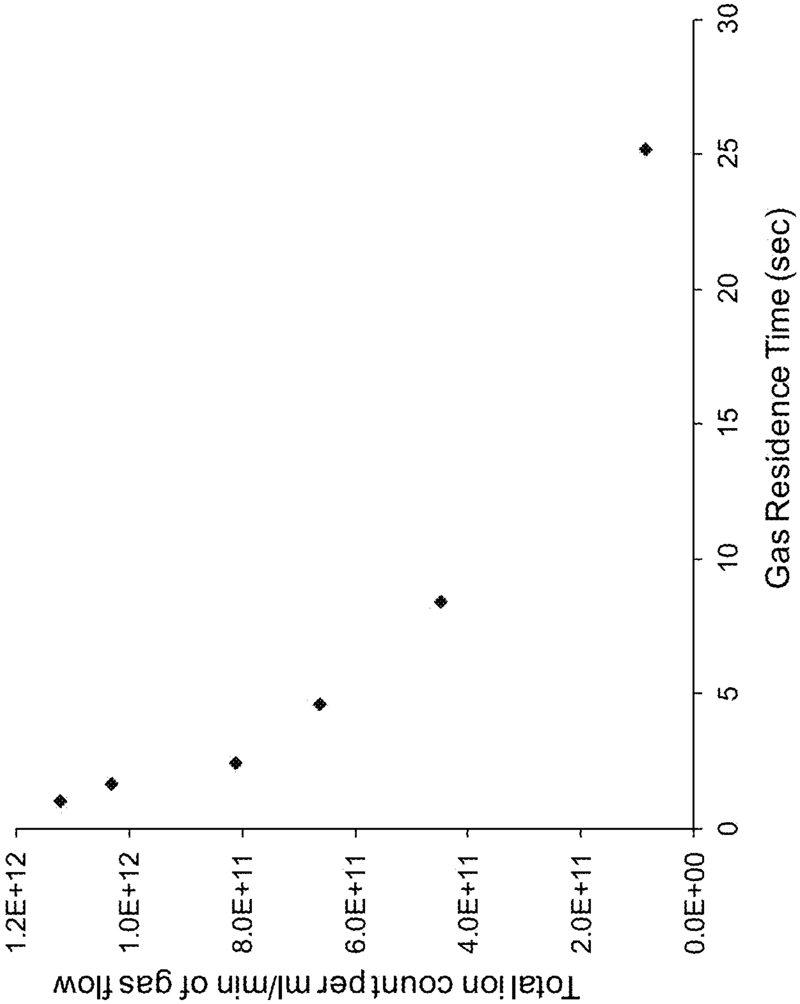
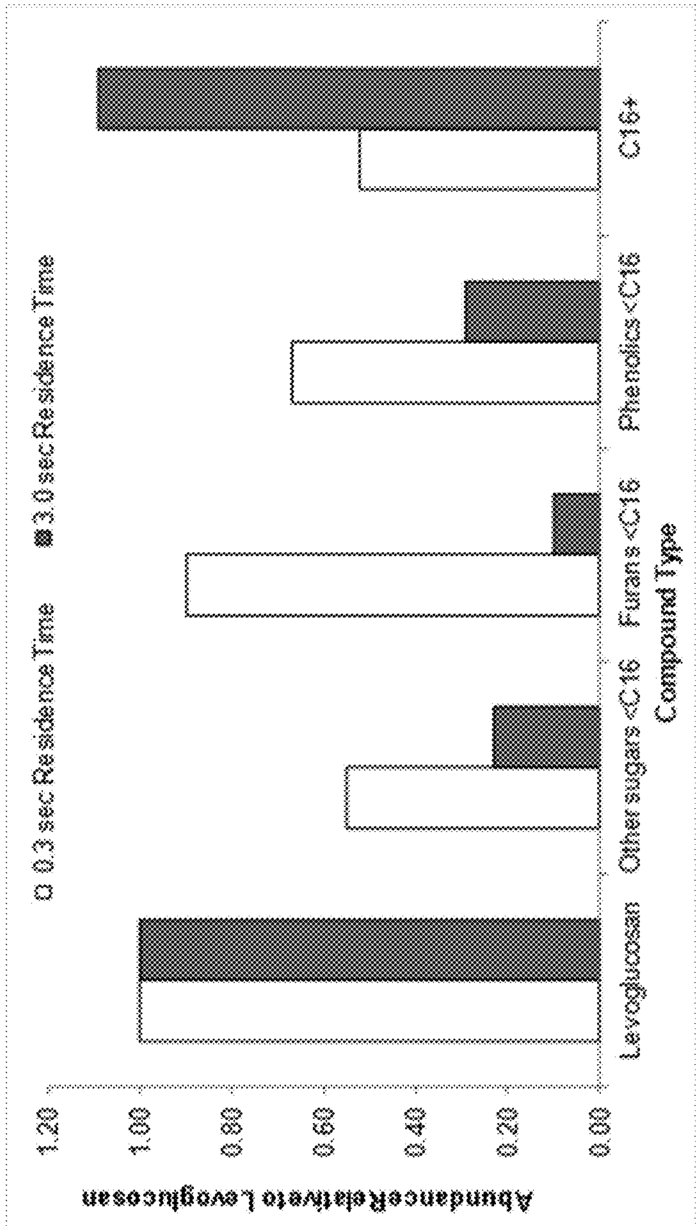

Total ion count per ml/min of gas flow
1.2E+12
1.0E+12
8.0E+11
6.0E+11
4.0E+11
2.0E+11
0.0E+00
0
5
10
15
20
25
30
Gas Residence Time (sec)

Figure 5


0.3 sec Residence Time
3.0 sec Residence Time
Abundance Relative to Levoglucosan
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Levoglucosan
Other sugars <C16
Furans <C16
Phenolics <C16
C16+
Compound Type

# GENERATING DEOXYGENATED PYROLYSIS VAPORS

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application is a non-provisional application which claims benefit under 35 USC §119(e) and priority to U.S. Provisional Application Ser. No. 61/699,098 filed Sep. 10, 2012, entitled "Generating Deoxygenated Pyrolysis Vapors", which is hereby incorporated by reference herein.

## STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

**[0002]** None.

## FIELD OF THE INVENTION

**[0003]** This invention relates to pyrolysis of organic matter into useful chemical or fuel products.

## BACKGROUND

**[0004]** The U.S. Renewable Fuel Standards (RFS) mandate will require higher volumes of advanced biofuels to be produced in the near future. One method being developed to meet this mandate is the fast pyrolysis of biomass. Conventional biomass fast pyrolysis requires rapid heating of biomass in the absence of oxygen. Products include a solid carbonaceous char that contains the vast quantities of metals (e.g. Na, K, and Mg) present in the biomass feedstock. The products also include a highly oxygenated pyrolysis oil (or pyoil) that is not practical for upgrading to a transportation fuel because of thermal stability issues associated with highly reactive oxygenated components. The remainder of the pyrolysis product is classified as non-condensable gas. To generate a viable transportation fuel, catalysts may be employed during the pyrolysis process. Catalysts such as zeolites can deoxygenate the primary products from pyrolysis to create an intermediate liquid that can be upgraded to a fuel using conventional refining methodology. Hydrogen may also be added to perform hydro-catalytic pyrolysis, which improves the quality of the product by significantly lowering the oxygen content, the acid content, etc. The use of hydrogen increases the yield of pyrolysis oil by hydrogenating the primary pyrolysis products, which removes oxygen as water instead of carbon oxides. The relatively low oxygen content intermediate produced is easily upgradable to bio-derived fuels.

**[0005]** Unfortunately, when employing this process, the catalysts tend to rapidly deactivate when contacted by char fines composed of carbon and metals. Additionally, the char fines are often carried out of the pyrolyzer by entrainment with the pyrolysis vapor, resulting in a liquid product containing solids and metals that can negatively impact downstream processes.

**[0006]** There is a need to improve fast pyrolysis technology to allow for rapid catalytic upgrading of primary pyrolysis products into products that are fungible with current petroleum-derived liquid hydrocarbon fuels, while preventing char and associated catalyst poisons from contacting upgrading catalysts that convert these primary products.

## BRIEF SUMMARY OF THE DISCLOSURE

**[0007]** In certain embodiments of the present disclosure, there is provided a process for the production and upgrading of a pyrolysis product, comprising the steps of: (a) pyrolyzing a biomass feedstock in a first reactor comprising at least one auger that conveys the feedstock through the reactor from a first end towards a second end, wherein the pyrolyzing forms primary pyrolysis products comprising a primary gaseous product and char; (b) passing the primary gaseous product through a first outlet at or near the top of the first reactor and to a second reactor, where the upward local velocity of the primary gaseous product prior to passing through the first outlet is sufficient to entrain less than 0.5 wt. % of the char produced by the pyrolyzing of step (a); (c) contacting the primary gaseous product with an upgrading catalyst; (d) removing the char from the first reactor via a second outlet located at or near the bottom of the first reactor.

**[0008]** In certain embodiments of the present disclosure, the primary gaseous product passes upward through a disengagement zone prior to leaving the first reactor via the first outlet, where the terminal falling velocity of entrained char and heat carrier particles becomes greater than the upward local velocity of the primary gaseous product in the disengagement zone, thereby causing at least 99.5 wt. % of the char and heat carrier solid particles produced by the process to be retained in the first reactor.

**[0009]** In certain embodiments, the first outlet is located closer to the second end of the first reactor relative to the second outlet, thereby decreasing entrainment of char in the primary gaseous product. **4**. In certain alternative embodiments, the first outlet is located closer to the first end of the first reactor relative to the second outlet, thereby decreasing entrainment of char in the primary gaseous product.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** A more complete understanding of the present invention and benefits thereof may be acquired by referring to the follow description taken in conjunction with the accompanying drawings in which:

**[0011]** FIG. **1** is a simplified diagram of the inventive process depicting a pyrolysis reactor with a catalyst vessel to receive and upgrade the vapors from the pyrolysis reactor.

**[0012]** FIG. **2** is a simplified diagram of the inventive process depicting a pyrolysis reactor with a catalyst vessel to receive and upgrade the vapors from the pyrolysis reactor.

**[0013]** FIG. **3** is a simplified diagram of the inventive process depicting a pyrolysis reactor with a catalyst vessel to receive and upgrade the vapors from the pyrolysis reactor.

**[0014]** FIG. **4** is a graph depicting total ion count normalized to gas flow rate versus residence time in a micropyrolyzer. Shorter residence times give higher ion counts, which are only generated from low molecular weight species (~200-300 molecular weight) resulting from primary pyrolysis, and not from secondary pyrolysis products.

**[0015]** FIG. **5** is a graph illustrating the relationship between residence time and the pyrolysis products formed.

**[0016]** The invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings. The drawings may not be to scale. It should be understood that the drawings and their accompanying detailed descriptions are not intended to limit the scope of the invention to the particular form disclosed, but rather, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

## DETAILED DESCRIPTION

**[0017]** In the processes and systems of the current invention, a biomass feedstock is fed to a pyrolysis reactor for conversion into a mixture comprising hydrocarbons that are fungible with petroleum-derived fuels that may include, but are not limited to, gasoline, jet-fuel, diesel and gasoil. The methods and systems described herein protect and extend the lifespan of the downstream upgrading catalyst(s) by preventing contact between the catalyst(s) and the char generated during pyrolysis of the biomass feedstock, while simultaneously minimizing the time between production of the pyrolysis vapors and subsequent upgrading, thereby maximizing upgradability of the vapors to a product that is fungible with petroleum-derived transportation fuels, fuel component or mixtures thereof.

**[0018]** The pyrolysis reactor preferably comprises at least one auger that assists in rapidly and evenly distributing heat to the feedstock, as well as helping to convey the feedstock through the pyrolysis reactor. Oxygenated hydrocarbon vapors are produced in the pyrolysis reactor, and these vapors are gravitationally separated from char, heat carrier, and metals in a disengagement zone while avoiding vapor condensation. The vapors are then rapidly contacted with an upgrading catalyst in at least one upgrading reactor comprising at least one upgrading catalyst for conversion of the vapors into a hydrocarbon mixture fungible with current petroleum-derived fuels. Residence time between production of pyrolysis vapors (i.e., the primary gaseous product) and contact with the one or more upgrading catalysts is minimized to prevent secondary pyrolysis reactions that decrease upgradability of the compounds that comprise the primary gaseous product.

**[0019]** The char created by the process described herein is conveyed through the reactor along with heat carrier by the at least one auger, then falls by force of gravity into a sealed char catch and is eliminated from the reactor. The pyrolysis vapors are swept through the pyrolysis reactor, out an outlet near the top of the reactor and immediately into an upgrading vessel containing at least one upgrading catalyst, which may hydrogenate and deoxygenate the pyrolysis products. The vessel may be operated as a fixed bed, fluid bed, or moving bed. Removing the char prior to contacting pyrolysis products with catalyst prevents catalyst fouling/poisoning. The products from the upgrading vessel are condensed or further upgraded, thereby generating a viable transportation fuel or refinable intermediate.

**[0020]** Examples of biomass feedstock used in the present invention include, but are not limited to, oil-containing biomass, such as jatropha plant, macroalgae or microalgae. Carbohydrate-based biomass may also be used as feedstock, where carbohydrate-based refers to biomass where at least a fraction of its composition is made of carbohydrates. Carbohydrate-based biomasses are available from a variety of sources including cellulosic biomass and algal biomass. Specific examples of feedstock useful in the current invention include, but are not limited to: sugars, carbohydrates, fatty acids, proteins, oils, eucalyptus oil, forest residues, dead trees, branches, leaves, tree stumps, yard clippings, wood chips, wood fiber, sugar beets, miscanthus, switchgrass, hemp, corn, corn fiber, poplar, willow, sorghum, sugarcane, palm oil, corn syrup, algal cultures, bacterial cultures, fermentation cultures, paper manufacturing waste, agricultural residues (e.g., corn stover, wheat straw and sugarcane bagasse), dedicated energy crops (e.g., poplar trees, switchgrass, and miscanthus giganteus sugarcane) sawmill and paper mill discards, food manufacturing waste, meat processing waste, animal waste, biological waste and/or municipal sewage.

**[0021]** FIG. **1** depicts an exemplary embodiment for a system for conducting pyrolysis of organic material or biomass to useful chemical products or fuel products. A pyrolysis reactor **20** comprises an external housing **21**, a heat carrier inlet **17** for a heat carrier **15**, an feedstock inlet **10** for a biomass feedstock **12** and one or more helical augers **22** that when driven by a motor **25** to rotate about a longitudinal axis convey the biomass feedstock **12** along the length of the housing **21** from an inlet end **18** towards an outlet end **28**. Near the outlet end **28**, the char falls into a char catch **31** by gravitational force. The biomass feedstock **12** is heated in the pyrolysis reactor **20** by at least one heating method that may include a heating jacket **21**, a heated auger **22**, or via introduction of a heat carrier **15** via a heat carrier inlet **17** proximal the inlet end **18** of the auger reactor **20**. The pyrolysis reactor **20** is operated to exclude most oxygen or air by the introduction of a sweep gas. In the embodiment shown in FIG. **1**, the sweep gas **19** enters through sweep gas inlet **16**, although the sweep gas may alternatively enter the system via other points of entry, such as the biomass feedstock inlet **10** or heat carrier inlet **17**. As the biomass feedstock **12** is rapidly heated, primary gaseous product **37** rise to the upper portion of the pyrolysis reactor **20** and are swept toward the second reactor end **28**, exiting through a first outlet **32**.

**[0022]** Arranged within close proximity of the pyrolysis reactor first outlet **28** is an upgrading reactor **40** containing at least one bed of an active upgrading catalyst **42**. In certain embodiments, the pyrolysis reactor **20** is in direct contact with the upgrading reactor **40** with minimal distance between the pyrolysis reactor **20** and the upgrading catalyst **42**. In the embodiment depicted in FIG. **1**, a distributor plate **52** is placed above the outlet **32** to assist in retaining within the reactor **20** any residual particulates that may be entrained in the primary gaseous product (pyrolysis vapors) **37** leaving the reactor **20** through outlet **32**. Distributor plate **52** may also serve to evenly distribute gases within the upgrading reactor **40**, such as when the upgrading catalyst **42** contained within comprises, for example, a fluidized bed (not depicted).

**[0023]** When the pyrolysis reactor described herein comprises an auger, the reactor is more efficient in char removal than a conventional fluidized bed reactor, which produces char fines by attrition that elutriate into the vapor product stream. The majority of char formed during pyrolysis is conveyed by the auger **22** along with heat carrier **15** towards the outlet end **28** of the pyrolysis reactor **20**. The majority of char and/or ash produced during pyrolysis of the feedstock exits the pyrolysis reactor **20** by force of gravity into char catch **31**. Thus, the char is diverted from entering the upgrading reactor **40** and coming in contact with the upgrading catalyst bed **42**, which dramatically enhances the longevity of the upgrading catalyst(s) **42**. As noted above, it is common for the biomass feedstock **12** to include measurable amounts of metals that act as poisons to desirable upgrading catalysts, and we have found that this metal content becomes concentrated in the char produced during pyrolysis. With the physical arrangement described herein, catalyst that are more susceptible to poisoning by metals may be used to upgrade the pyrolysis vapors, since the impact of metal poisoning and coke formation is dramatically reduced. In addition, the product leaving the upgrading bed is free of solids and metals, thereby removing the need for subsequent particle removal

[0024] The pyrolysis reactor preferably comprises at least one auger and may take many forms. In one embodiment, a single rotating auger transports sand, biomass and solid pyrolysis products through an elongated, cylindrical reactor. In the embodiment depicted in FIG. **1**, two rotating augers **22** operate in parallel. The first pyrolysis product exits through a first outlet **32** located on the upper side of the auger pyrolyzer **20**, preferably near the top of the reactor to prevent solids from leaving the reactor via this outlet. The outlet **32** conveys the primary gaseous product **37** immediately to contact an upgrading catalyst **42**, which is optionally contained within an upgrading reactor **40**.

[0025] The temperature within the pyrolysis reactor may be maintained via one or more of several mechanisms, such as heating of the reactor walls, heating of the at least one auger, microwave or inductive heating, addition of a heated sweep gas, and addition a of a solid particulate that has been preheated to a temperature of at least 900° F. (482° C.). Regardless of the heating mechanism utilized, preferably the pyrolysis reactor is maintained at a temperature of at least 600° F. (315° C.).

[0026] To reduce particle entrainment leading to heat carrier exiting the reactor via outlet **32**, the median heat carrier particle size is greater than about 100 microns, and preferably greater than about 250 microns. For similar reasons, the bulk density of the heat carrier particles is at least 500 kg/$m^3$, and preferably greater than about 1,000 kg/$m^3$.

[0027] Conventional pyrolysis methods and systems have suffered from either 1) char carry over in the pyrolysis vapors, which leads to upgrading catalyst deactivation, or 2) use of mechanical separation devices to remove char from pyrolysis vapors, which results in an undesirable delay prior to catalytic upgrading. This delay can allow secondary pyrolysis reactions to occur that produce products comprising 16 or more carbons that are difficult to upgrade into a bio-derived fuel. Again referring to the embodiment depicted in FIG. **1**, a "disengagement zone" **45** is located proximal to the outlet end **28** of the pyrolysis reactor, and near the first outlet **32**. This zone is designed to provide a space where the upward local velocity of the primary gaseous product **37** prior to passing through the first outlet **32** is sufficient to entrain less than 0.5% (by wt.) of the char produced by the pyrolysis of the biomass feedstock. In certain embodiments, the upward local velocity of the primary gaseous product **37** prior to passing through the first outlet **32** is sufficient to entrain less than 0.1% (by wt.) of the char produced by the pyrolysis of the biomass feedstock. Achieving this low percentage of char carryover requires designing the height and diameter of the disengagement zone **45** to allow the terminal falling velocity of the char and heat carrier particles to exceed the upward local velocity of the primary gaseous product **37** exiting the first outlet **32**. This results in nearly all char particles being retained in the pyrolysis reactor, thereby preventing these particles from contacting the upgrading catalyst.

[0028] FIG. **2** depicts an alternative embodiment, wherein the disengagement zone **45** may be smaller (or not present) and residual char particles may be instead be removed by passing the primary gaseous product **37** through an upgrading reactor **40** comprising a fluidized bed. In yet another embodiment depicted in FIG. **3**, the primary gaseous product **37** may raise through a reactor **55** comprising a moving bed granular filter that additionally comprises an initial upgrading catalyst **60**. Optionally, the catalyst may migrate downward in counter-current flow against the rising gases, and char **31** and spent catalyst **62** would leave out the bottom of the reactor **20**.

[0029] In certain embodiments, a sweep gas is employed that may comprise one or more of many gases that are either inert or reactive. For example, the sweep gas may comprise gases such as nitrogen, helium, argon, hydrogen, methane and mixtures thereof. If the sweep gas comprises a reactive gas, the reactive gas may optionally react with the biomass during pyrolysis, may serve as a reactant when the pyrolysis products are upgraded by contacting the upgrading catalyst(s), or both. The sweep gas may be injected into the system at more than one point, or injected simultaneously at multiple points. One point may comprise combining the sweep gas with the feedstock prior to entering the pyrolysis reactor, while another may comprise injecting sweep gas directly into the pyrolysis reactor proximal to the biomass feedstock inlet. A third point may comprise injecting the sweep gas proximal to the first outlet of the pyrolysis reactor. This may be preferable if the sweep gas is to be used as a reactant during upgrading of the primary gaseous product.

[0030] In certain embodiments, a gas may be injected just upstream of the pyrolysis reactor first outlet in order to 1) assist in preventing entrained char and heat carrier particles from leaving the pyrolysis reactor, 2) quench the primary gaseous product to a lower temperature, 3) heat the primary gaseous product to a higher temperature, or combinations thereof. In embodiments where the sweep gas serves to quench the primary gaseous product, such quenching may prevent coking. Embodiments where the sweep gas serves to heat the primary gaseous product may prevent formation of char and secondary pyrolysis reactions that may reduce the subsequent upgradability of the primary gaseous product to a bio-derived fuel. However, quenching is limited such that the quenched primary gaseous product does not condense prior to contacting the upgrading catalyst(s). Typically, this requires that the quenched primary gaseous product still maintains a temperature of at least 250° C. to prevent condensation.

[0031] The volumetric flow rate, or "standard gas hourly space velocity" (SGHSV) of the sweep gas is adjusted to minimize the time between pyrolysis and catalytic upgrading, such that the upgrading catalyst (or optionally, catalysts) contacts primary products of pyrolysis and not secondary pyrolysis products that comprise 16 or more carbons and are more difficult to upgrade to a bio-derived fuel. Volumetric flow rate for a given embodiment depends upon factors including, but not limited to, the volume of the pyrolysis reactor, the temperature and pressure at which the pyrolysis reactor is maintained, the feed rate of the biomass feedstock to the pyrolysis reactor, and the type of feedstock utilized. A paper by J. N. Brown, et al. provides one example of how these variables can be adjusted to determine an optimal volumetric flow rate for a desired pyrolysis outcome, including, for example, the pyrolysis liquid to pygas ratio, and the relative percentage of the feedstock converted to char.

[0032] The pressure maintained within the pyrolysis reactor is generally within a range of about 0 psig to 3000 psig. Preferably, the pyrolysis reactor is maintained at a pressure in the range of 100 psig to 500 psig to increase throughput of biomass feedstock, and in certain embodiments, facilitate catalytic upgrading of the primary gaseous product.

[0033] The primary gaseous product is driven by the sweep gas (or optionally, a pressure differential) from the pyrolysis reactor via the first outlet and enters an upgrading reactor and contacts an upgrading catalyst. Minimizing residence time of the primary gaseous product in the pyrolysis reactor is important for maximizing the percentage of primary gaseous product that is successfully upgraded to a bio-derived fuel. Conditions of temperature and pressure, as well as reactor dimensions are chosen to assure a residence time of the primary gaseous product in the pyrolysis reactor that is less than 5 seconds, preferably less than 3 seconds, more preferably less than 1 second, even more preferably less than 0.3 second and most preferably less than 0.1 second.

[0034] Minimizing residence time of the primary gaseous product in the pyrolysis reactor prevents the occurrence of secondary pyrolysis reactions that form larger oxygenated species comprising 16 or more carbon atoms. These larger oxygenated species are likely to form coke, which is extremely detrimental to the process by fouling process equipment and heat carrier. Additionally, diversion of the primary gaseous product into secondary pyrolysis reactions decreases the conversion efficiency of the feedstock into smaller species that are more easily upgraded into a bio-derived fuel.

[0035] The physical distance between the pyrolyzer and the upgrading catalyst(s) contained within the upgrading reactor may vary, but is preferably minimized, taking into consideration the space velocity of the primary gaseous product (optionally in a mixture with a sweep gas) out of the pyrolysis reactor. Minimizing this distance assists in decreasing the time between production of the primary gaseous product and subsequent contacting with one or more upgrading catalyst (s). Through optimizing the variables of distance and space velocity, the current invention assures that the upgrading catalyst sees primary products from pyrolysis and not secondary products created by reactions occurring after pyrolysis. Generally, the distance between the pyrolyzer and the upgrading catalyst(s) is less than 4 ft. More preferably, this distance is less than 1 ft., and most preferably, less than 6 inches.

[0036] Referring to FIG. **4**, we have found that reducing the total distance primary pyrolysis vapor must travel results in a decreased vapor residence time. Decreased residence time decreases the amount of time available for secondary pyrolysis reactions to occur. These reactions result in higher molecular weight species that can be difficult to upgrade. FIG. **4** illustrates the importance of minimizing residence time based on experiments in a micropyrolyzer. In those experiments, the sweep gas flow rate was adjusted to affect the overall gas residence time. Pyrolysis vapors (475° C., 1.5 mg red oak) and sweep gas (He) were sent from the pyrolyzer into a 4-mm I.D.×8 mm inlet liner, after which they entered a capillary column and were quenched with cold nitrogen to prevent further reaction. The total ion count was measured and normalized to the mass of sample and gas flow rate to eliminate the effect of sample dilution on the ion count.

[0037] Decreasing residence time is generally performed by increasing the sweep gas flow. However, increasing this flow can introduce significant particle entrainment that can be detrimental to pyrolysis vapor upgrading An example of this entrainment is shown in Table I, which shows the metal content of collected pyrolysis oil, and thus pyrolysis vapors, increases with increasing sweep rate.

TABLE I

Metal content in collected heavy pyrolysis oil at different sweep gas (hydrogen) flow rates. Si is present in the heat carrier (sand), while K and Ca are present in char. The metal content was determined by X-Ray analysis (KARNAK).

| Sweep Flow (sL/min) | Si in pyoil (ppm) | K in pyoil (ppm) | Ca in pyoil (ppm) |
|---|---|---|---|
| 5 | 460 | 40 | <5 |
| 50 | 755 | 75 | 45 |
| 100 | 2000 | 260 | 120 |

[0038] The increase is due to additional particle entrainment in the pyrolysis vapors. Furthermore, in the experiment, the pyrolysis vapors passed through a cyclone prior to collection, indicating that fine heat carrier particles were not collected by the cyclone, or the efficiency of their collection decreased as sweep flow increased. The present inventive disclosure does not employ a conventional cyclone, thus further reducing residence time by removing additional piping and a reactor vessel, and can be readily tailored to remove smaller particles while still maintaining short residence times.

[0039] Optionally, the disengagement zone between the pyrolyzer and the upgrading catalyst may include additional features to limit reactivity of the primary gaseous product prior to contact with the upgrading catalyst(s). These may include (but are not limited to) temperature control, introduction of a gas or fluid to quench the primary gaseous product (as mentioned previously), flow control through judicious choices in geometry (preferably, a geometry minimizing bends and small orifices to decrease the potential for vapor condensation, the presence of a pre-catalyst (such as zeolite monolith, or any of the above-mentioned upgrading catalysts) at the interface between reactors.

[0040] In some embodiments, a catalyst monolith may be utilized as a pre-catalyst bed, or guard bed, while in other embodiments, the pre-catalyst may comprise a fluidized bed of catalyst integrated with the distributor assembly to control reactivity in this region. The fluidized bed of catalyst may additionally function as a moving bed filter to remove residual particulates. Such methods may be as described in U.S. Pat. No. 8,268,271, which is hereby incorporated by reference.

[0041] The at least one upgrading bed may utilize any type of reactor configuration including, but not limited to, a fixed bed, a bubbling bed, a circulating bed, a moving bed, a counter current reactor or combinations of one or more of these configurations. The catalyst may be periodically removed from the upgrading reactor and passed through a regenerator for de-coking as needed, then returned to the pyrolysis reactor. Optionally, fresh catalyst may be added on a periodic or continuous basis to the pyrolysis reactor to account for catalyst attrition. In certain embodiments, there may be no means of introducing fresh catalyst.

[0042] Examples of some upgrading catalysts and typical reaction conditions are disclosed in U.S. patent application Ser. No. 13/416,533, although any catalyst known to catalyze the conversion of primary gaseous product to a bio-derived fuel may be utilized. The catalyst may include, but is not limited to zeolites, metal modified zeolites, and other modified zeolites. Other catalysts may include forms of alumina, silica-alumina, and silica, unmodified or modified with various metals, not limited but including, Nickel, Cobalt, Molybdenum, Tungsten, Cerium, Praseodymium, Iron, Platinum, Palladium, Ruthenium and Copper or mixtures thereof. Still other catalysts may include unsupported metals, supported or unsupported metal oxides or metal phosphides, and mixtures thereof. Catalyst types include deoxygenation catalysts, hydrogenation catalysts, hydrotreating catalysts, hydrocracking catalysts, water-gas-shift catalysts and condensation catalysts. Catalysts may be sulfided or un-sulfided. In certain embodiments, each catalyst bed may comprise mixtures of one or more catalysts of the types described above. Optionally, multiple catalyst beds may be placed within a single reactor, or multiple catalyst beds may be placed in different reactors to facilitate different reaction conditions. When multiple reactors are utilized, they may be arranged to either in parallel or series.

**[0043]** If multiple upgrading reactors are utilized, different conditions may be maintained in each reactor in order to facilitate a given catalytic reaction. To facilitate flow of the vapors through multiple reactors, a pressure differential may be maintained wherein the pressure in each successive reactor progressively decreases.

**[0044]** The residence time of the pyrolysis vapors in each upgrading reactor generally ranges from 0.01 sec to 1000 sec. preferably, the residence time is in a range from 0.05 sec to 400 secs. More preferably, the residence time is in a range from 0.1 sec to 200 sec. Most preferably, the residence time is in a range from 0.1 sec to 100 sec.

**[0045]** The temperature maintained within each upgrading reactor is generally in the range from 72° F. to 1500° F. Preferably, the temperature is in the range from 100° F. to 1000° F., although if multiple upgrading reactors are used, each may be maintained at a different temperature within this range.

**[0046]** Certain upgrading reactions are advantageously conducted at a pressure that is greater than atmospheric pressure. The pressure that is maintained in the one or more upgrading reactors may range from 0-3000 psig, although a preferred pressure range is zero to 1000 psig. In certain embodiments, the pressure may range from 10 to 800 psig, from 20 to 650 psig, from 100 to 500 psig. An exemplary pressure might be 400 psig.

**[0047]** The flow of gas and vapors within each upgrading reactor is preferably upward, although downward or lateral gas flow may also be utilized. Upon exiting the final upgrading reactor, the upgraded gas and/or vapors are directed to a condensation system that functions to reduce the temperature of upgraded product vapors to a temperature that is at or below the dew point for at least one component. Typically, the conditions utilized do not result in the condensation of methane, but preferably will condense C4+ hydrocarbons. Hydrogen may be separated from the non-condensed gas by a variety of conventional methods and recycled as the sweep gas. In certain embodiments, the recycled hydrogen may be added directly into, or just upstream from, an upgrading reactor to facilitate one or more upgrading reactions. Alternatively, the entirety, or some fraction, of the bulk non-condensable gas is used for the same purpose. In another embodiment, the entirety, or some fraction, of the bulk of the non-condensable gas is sent to a combustor or hydrogen generation unit (e.g., a reformer) to generate either heat or hydrogen, respectively. The resulting heat or hydrogen may then be partially or entirely recycled back to the process.

**[0048]** The following examples of certain embodiments of the invention are given. Each example is provided by way of explanation of the invention, one of many embodiments of the invention.

**[0049]** The following examples are intended to be illustrative of specific embodiments and should not be interpreted to limit, or define, the scope of the invention in any way.

## Example 1

**[0050]** FIG. **5** graphically depicts the relationship between residence time of the pyrolysis vapors in the pyrolysis reactor versus pyrolysis product size distribution (quantified as carbon number of the product). Product size distribution was first quantified at 0.3 seconds of residence time (white bars), then at 3 seconds of residence time (grey bars) in a 100 micron capillary maintained at pyrolysis temperatures (610° F.). At 3 seconds of vapor residence time, the proportion of C16+ species increased versus the relative abundance of levoglucosan, a key six carbon primary pyrolysis product. Furthermore, the proportion of phenolics, furans, and other carbohydrates/sugars comprising less than 16 carbon atoms decreased at the longer residence times, which was likely due to oligomerization of these primary compounds to heavier compounds of 16 carbons or greater, which are difficult to upgrade to fuel-range hydrocarbons.

## DEFINITIONS

**[0051]** As used herein, the term "entrainment" is defined as transport of a solid particle by a gas stream. Entrainment of a given solid particle typically occurs when the local velocity of a gas stream exceeds the terminal falling velocity of the particle.

**[0052]** As used herein, the term "standard gas hourly space velocity" or "SGHSV" refers to the gas hourly space velocity of a gas stream measured at standard conditions.

**[0053]** In closing, it should be noted that the discussion of any reference is not an admission that it is prior art to the present disclosure, in particular, any reference that may have a publication date after the priority date of this application. At the same time, each and every claim below is hereby incorporated into this detailed description or specification as an additional embodiment of the present invention.

**[0054]** Although the systems and processes described herein have been described in detail, it should be understood that various changes, substitutions, and alterations can be made without departing from the spirit and scope of the invention as defined by the following claims. Those skilled in the art may be able to study the preferred embodiments and identify other ways to practice the invention that are not exactly as described herein. It is the intent of the inventors that variations and equivalents of the invention are within the scope of the claims while the description, abstract and drawings are not to be used to limit the scope of the invention. The invention is specifically intended to be as broad as the claims below and their equivalents.

## REFERENCES

**[0055]** All of the references cited herein are expressly incorporated by reference. The discussion of any reference is not an admission that it is prior art to the present invention, especially any reference that may have a publication data after the priority date of this application. Incorporated references are listed again here for convenience:

**[0056]** 1. Brown, J. N., et al. "Process Optimization of an Auger Pyrolyzer with Heat Carrier Using Response Surface Methodology." Biores. Tech. 103:405-4141 (2012).

We claim:

**1**. A process for the production and upgrading of a pyrolysis product, comprising the steps of:

(a) pyrolyzing a biomass feedstock in a first reactor comprising at least one auger that conveys the feedstock through the reactor from a first end towards a second end, wherein said pyrolyzing forms primary pyrolysis products comprising a primary gaseous product and char;

(b) passing the primary gaseous product through a first outlet at or near the top of the first reactor and to a second reactor, wherein the primary gaseous product passing through the first outlet entrains less than 0.5 wt. % of the char produced by the pyrolyzing of step (a);

(c) contacting the primary gaseous product with an upgrading catalyst;

(d) removing the char from the first reactor via a second outlet located at or near the bottom of the first reactor.

**2**. The process of claim **1**, wherein the primary gaseous product passes upward through a disengagement zone prior to leaving the first reactor via the first outlet, wherein the terminal falling velocity of entrained char and heat carrier particles becomes greater than the upward local velocity of the primary gaseous product in the disengagement zone, thereby causing at least 99.5 wt. % of the char and heat carrier particles to be retained in the first reactor.

**3**. The process of claim **1**, wherein the first outlet is located closer to the second end of the first reactor relative to the second outlet, thereby decreasing entrainment of char in the primary gaseous product.

**4**. The process of claim **1**, wherein the first outlet is located closer to the first end of the first reactor relative to the second outlet, thereby decreasing entrainment of char in the primary gaseous product.

**5**. A system for the production and upgrading of a pyrolysis product, comprising a pyrolysis reactor adapted for pyrolyzing a biomass feedstock to produce a primary gaseous product, wherein the pyrolysis reactor comprises at least one auger, an inlet for a biomass feedstock and an outlet, wherein the pyrolysis reactor contains a solid particulate heat carrier and char, wherein the reactor is adapted to provide a disengagement zone that is, in turn, adapted to allow the terminal falling velocity of entrained char and heat carrier particles to become greater than the upward local velocity of the primary gaseous product in the disengagement zone prior to leaving the first reactor via the outlet such that the reactor retains at least 99.5 wt. % of the solid particulate heat carrier and char in the pyrolysis reactor.

* * * * *