



(51) International Patent Classification:

C10B 7/10 (2006.01) C10B 53/02 (2006.01)
C10B 49/16 (2006.01) C10B 57/06 (2006.01)
C10B 49/20 (2006.01)

(21) International Application Number:

PCT/US2013/045181

(22) International Filing Date:

11 June 2013 (11.06.2013)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

61/658,513 12 June 2012 (12.06.2012) US
13/914,146 10 June 2013 (10.06.2013) US

(71) Applicant: PHILLIPS 66 COMPANY [US/US]; Intellectual Property - Legal, P. O. Box 4428, Houston, Texas 77210 (US).

(72) Inventors; and

(71) Applicants : DAUGAARD, Daren E. [US/US]; 3378 E. 184th St. North, Skiatook, Oklahoma 74070 (US). JONES, Samuel T. [US/US]; 396491 W. 1300 Rd., Dewey, Oklahoma 74029 (US). PLATON, Alexandru [RO/US]; 5614 Meadow Dr., Bartlesville, Oklahoma 74006 (US). GONG, Kening [CN/US]; 120 Prairie Ridge

Court, Bartlesville, Oklahoma 74006 (US). LOTERO, Edgar [CO/US]; 901 North Cliff Drive, Cleveland, Oklahoma 74020 (US).

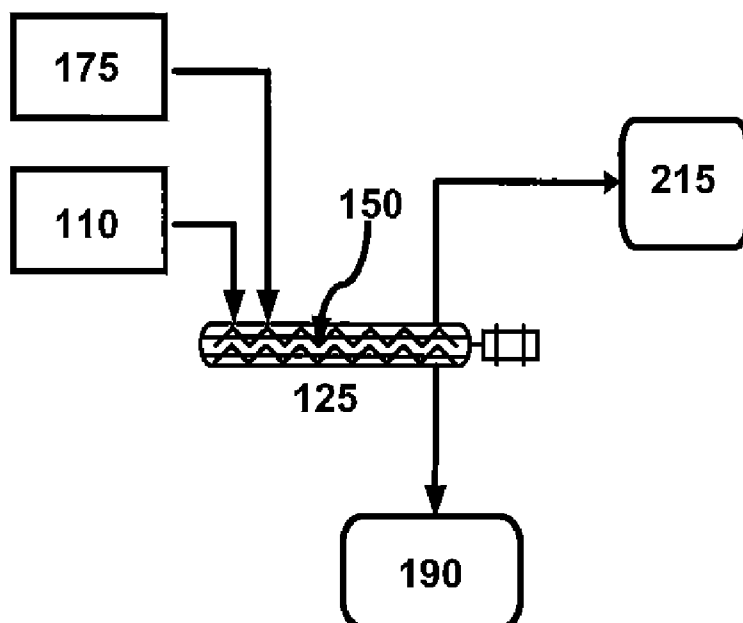
(74) Agent: SHERRILL, Kyle W.; Intellectual Property - Legal, P.O. Box 4428, Houston, Texas 77210 (US).

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

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

[Continued on next page]

(54) Title: CATALYTIC PYROLYSIS OF BIOMASS IN AN AUGER REACTOR



(57) Abstract: The present invention relates generally to the thermal conversion of biomass. Processes are disclosed for converting algal biomass to condensable vapor intermediates such as pyrolysis oil by means of pyrolysis in a reactor comprising at least one auger. The intermediates may be further processed for production of renewable hydrocarbon fuels. The disclosed processes assist in preventing premature devolatilization of algal biomass during pyrolysis, thereby increasing efficiency and commercial feasibility.



Published:

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

CATALYTIC PYROLYSIS OF BIOMASS IN AN AUGER REACTOR**CROSS REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims benefit of and priority to U.S. Provisional Application Serial No. 61/658,513 filed June 12, 2012, and U.S. Application Serial No. 13/914,146 filed June 10, 2013, entitled "CATALYTIC PYROLYSIS OF BIOMASS IN AN AUGER REACTOR," both of which are hereby incorporated by reference herein.

STATEMENT OF FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] None.

FIELD OF THE DISCLOSURE

[0003] The present invention relates generally to pyrolytic conversion of biomass in the presence of a catalyst and a heat carrier in a reactor comprising at least one auger.

BACKGROUND

[0004] The Renewable Fuels Standards (RFS) enacted by the US Government mandate the increased use of renewable energy sources to reduce emissions of carbon based fuels and provide alternatives to petroleum based energy and feedstock.

[0005] One of the alternatives being explored is the use of biomass. Biomass is any carbon containing material derived from living, or recently-living, organisms. The ability to convert biomass derived from plants, animals, and industrial waste provides a direct source for renewable fuels including gasoline, diesel, oils and other products that can substitute for fuel products produced from non-renewable fossil fuels.

[0006] Processes to convert renewable resources into transportation fuels usually involve several steps. One approach is to use acids to convert carbohydrates, starches, lignins, and other biomass into sugars such as glucose, lactose, fructose, sucrose, dextrose. Another approach is to utilize pyrolysis to convert biomass solids and liquids into pyrolysis oil, or bio-oil.

[0007] Pyrolysis is the chemical decomposition of organic materials by heating in the absence of oxygen or other reagents. Pyrolysis can be used to convert biomass into pyrolysis oil (or bio-oil). Bio-oil is typically produced by heating biomass to a temperature between 250°C to 1000°C in a predominantly inert atmosphere for a short time. The bio-oil thereby produced contains molecules derived from the original biomass feedstock, and is consequently a mixture of primarily oxygenated products. Bio-oil typically is thermally unstable, acidic, and not miscible with petroleum feedstocks. Thus, it is normally further processed to create hydrocarbon products that are fungible with current petroleum-based fuels.

[0008] A number of methods are known for the pyrolytic conversion of biomass; however, these conventional methods need to be further optimized to reduce the overall costs associated with biofuels production, thereby making the use of these fuels more attractive. What is needed are methods for converting a biomass-derived feedstock to biofuels that can reduce cost, increase throughput, and require less maintenance of process equipment.

BRIEF DESCRIPTION OF THE DISCLOSURE

[0009] The present disclosure provides novel processes for converting biomass to bio-oil by means of pyrolysis. Certain embodiments comprise a process for pyrolysis in the presence of a catalyst, wherein the catalyst may be combined with a heat carrier in a reactor comprising at least one auger.

[0010] In certain embodiments, the process comprises providing a thermal reactor containing at least one auger, as well as a first mixture comprising a heat carrier and at least one catalyst. A biomass feedstock is introduced to the thermal reactor and conveyed through the reactor via at least one auger for a defined residence time prior to removal from the reactor. In certain embodiments, the at least one auger increases contact between the heat carrier and the feedstock to increase the heating rate of the feedstock. In certain embodiments, the rotation of the at least one auger may increase contact between the catalyst and the feedstock to increase the catalytic pyrolysis of the feedstock.

[0011] The feedstock contacts the heat carrier and at least one catalyst to convert at least a portion of the feedstock to condensable vapor intermediates via pyrolysis. The catalyst facilitates the rate at which the feedstock is converted, and rotation of the auger increases heat transfer to the feedstock and increases contact between the feedstock and the catalyst. In

certain embodiments, the thermal reactor is maintained at a pressure in a range from about 50 psig to about 500 psig and a temperature in a range from about 250°C to about 1000°C. In certain alternative embodiments, the thermal reactor is maintained at a pressure in a range from about 15 psig to about 50 psig and a temperature in a range from about 350°C to about 700°C.

[0012] In certain embodiments, the heat carrier and at least one catalyst is introduced proximal to a reactor first end and is conveyed by at least one auger to a point downstream where the feedstock is introduced to combine with the first mixture to form a second mixture. Upon introducing the feedstock to the reactor, the feedstock is heated at a rate from about 100°C per second to about 10,000°C per second.

[0013] Generally, the presence of at least one catalyst increases the rate of pyrolysis, such that the temperature required for pyrolysis is lowered, the required residence time of the feedstock is decreased, or combinations thereof. In certain embodiments, the atmosphere maintained inside the thermal reactor comprises an inert gas and less than 0.5 mol% oxygen gas. In certain alternative embodiments, the atmosphere maintained inside the thermal reactor comprises a reactive gas selected from a group consisting of hydrogen, synthesis gas (i.e., CO + H₂), steam/water, ammonia, methane, ethane, propane, butane, pentane, and natural gas, etc., and any combinations of these gases. In certain embodiments, the catalyst comprises at least one of Co, Ni, Mo, W, Zn, Ga a zeolite, a metal-impregnated zeolite, and combinations of these catalysts.

BRIEF DESCRIPTION OF THE FIGURE

[0014] Figure 1 is a simplified flow-chart representing an embodiment of the inventive processes disclosed herein.

DETAILED DESCRIPTION

[0015] Pyrolysis is the chemical decomposition of biomass by heating in the absence of oxygen or other reagents. Intermediates produced via pyrolysis may be further processed by one or more refining means for production of renewable hydrocarbon fuels. Pyrolysis has been studied extensively, and a variety of pyrolysis processes and conditions are known. Pyrolysis may be conducted at a variety of temperatures and pressures, in the presence (or absence) of an inert gaseous atmosphere and may be facilitated by a catalyst or a heat-carrier.

[0016] The biomass to be pyrolyzed according the methods disclosed herein may be any type of biomass derived from plants or animals. The biomass to be utilized as feedstock is selected according to its pyrolysis characteristics and ash fusion point. Typically, biomass (or a mixture of biomass derived from different sources) with an ash fusion point no less than 700°C is fed into a pyrolysis reactor after being collected, screened, dried and crushed. The pyrolysis temperature and reaction time are carefully controlled to rapidly decompose the reactant by heat to form a gas, at least a portion of which is condensed to form a liquid intermediate product comprising pyrolysis oil.

[0017] Examples of biomass feedstock may include, but are not limited to biomass derived from plants, protists (including micro-algae and macro algae), and animal biomass. Lignocellulosic biomass is commonly utilized as a feedstock for production of biofuels, and may be comprised of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are carbohydrate polymers. The carbohydrate polymers are tightly bound to the lignin. Lignocellulosic biomass may be grouped into four main categories: (1) agricultural residues, (2) dedicated energy crops, (3) wood residues, and (4) municipal solid waste. The agricultural residues may include, but not limited to, corn stover, wheat straw and sugarcane bagasse. Many energy crops may also be of interest for their ability to provide high yields of biomass and may be harvested multiple times each year. These may include, but not limited to, poplar trees, switchgrass, and miscanthus giganteus. The premier energy crop is sugarcane, which is a source of the readily fermentable sucrose and the lignocellulosic side product bagasse. The wood residues may include, but are not limited to, sawmill and paper mill discards.

[0018] In the pyrolysis processes disclosed herein, the feedstock is rapidly heated to produce one or more volatile gases. In certain embodiments, the feedstock is heated in a reactor comprising at least one auger, where the reactor is maintained in a range from about 250°C to 1000°C. In certain embodiments, the feedstock is heated in a reactor maintained in a range from about 350°C to about 750°C.

[0019] In some embodiments, the feedstock is heated in an atmosphere comprising an inert gas and in the absence of oxygen. The inert gas may be, but is not limited to, nitrogen, argon, helium, or carbon dioxide, or combinations of these gases. In certain embodiments, the feedstock is heated in an atmosphere comprising an inert gas and oxygen, where the concentration of oxygen is in the range from about 0.0 mol % to about 0.5 mol%. In another embodiment, the gaseous atmosphere may comprise oxygen in the range from about 0.5 mol % to about 5 mol%.

[0020] Alternatively, the feedstock is heated in the presence of an atmosphere comprising a one or more gaseous compounds that can donate hydrogen. These gases may include, but are not limited to, hydrogen, synthesis gas (i.e., $\text{CO} + \text{H}_2$), steam/water, ammonia, methane, ethane, propane, butane, pentane, and natural gas. Certain embodiments may combine one of these gases with an inert gas. Not intending to be bound by theory, it is believed that these various mixtures may create a reducing atmosphere and quench any unstable radical species formed during heating of the feedstock. When using a hydrogen donor compound or hydrocarbon, mass ratios for feedstock to hydrogen donor compound or hydrocarbon may be in the order of 0.1-to-2.

[0021] One or more catalysts may be utilized for the pyrolysis reaction to promote hydrogenation/hydrogenolysis reactions. These catalysts may comprise, but are not limited to, those conventionally used in hydroprocessing of hydrocarbons, such as, for example, those comprising metals such as Co, Ni, Mo and W. More specific examples of catalysts that have been utilized in catalytic pyrolysis include various zeolites as well as metal-impregnated zeolites, such as, for example HUSY, REY, HZSM-5, Ni-Mo-HUSY, Ni-Mo-REY. The catalyst may be placed on any solid material known to be suitable as a solid catalyst support. In certain embodiments, the solid support is gamma alumina.

[0022] Additional examples of zeolites suitable for use as catalysts for the inventive processes disclosed herein include, but are not limited to, those disclosed in Kirk-Othmer Encyclopedia of Chemical Technology, third edition, volume 15, pages 638-669 (John Wiley & Sons, New York, 1981). Generally, zeolites useful in the present invention have a constraint index (as defined in U.S. Pat. No. 4,097,367, which is incorporated herein by reference) in the range of from about 0.4 to about 12, and preferably in the range of from about 2 to about 9. In addition, the molar ratio of SiO_2 to Al_2O_3 in the crystalline framework of the zeolite is at least about 5:1 and can range up to infinity. In one embodiment of the present invention, the molar ratio of SiO_2 to Al_2O_3 in the crystalline framework of the zeolite is in the range of from about 8:1 to about 200:1. In another embodiment of the present invention, SiO_2 to Al_2O_3 in the crystalline framework of the zeolite is in the range of from about 12:1 to about 100:1. Zeolites useful in the present invention include but are not limited to ZSM-5, ZSM-8, ZSM-11, ZSM-12, ZSM-35, ZSM-38 and combinations thereof. Some of these zeolites are also known as "MFI" or "Pentasil" zeolites. In one embodiment of the present invention, the zeolite is ZSM-5. Modified zeolites can also be used. Modified zeolites can include zeolites modified by metal cations, such as, for example, zinc, gallium, or nickel.

Zeolites can also be modified by steam treatment and/or acid treatment. In addition, zeolites of the present invention may be combined with a clay, promoter, and/or a binder. Zeolites useful in the present invention may also contain an inorganic binder (also referred to as matrix material) selected from the group consisting of alumina, silica, alumina-silica, aluminum phosphate, clays (such as bentonite), and combinations thereof. The type of zeolite used will cause the final product to vary considerably.

[0023] The conventional pyrolysis of biomass is often conducted in fluidized bed reactors. A heated carrier gas is mixed with the biomass feedstock, and bubbles through the biomass to cause mixing, thereby facilitating heat transfer through the feedstock. The methods described herein instead utilize a reactor comprising at least one mechanical auger (hereby termed “auger reactor”) to mechanically mixing the feedstock (or a mixture of feedstock and a heat-carrier) to facilitate a high rate of heat transfer to the feedstock. This requires that only moderate temperatures be maintained within the reactor to effectively promote pyrolysis of the feedstock, while also preventing premature devolatilization of the feedstock. The current disclosure discloses novel processes that additionally comprise a catalyst to further facilitate pyrolysis in an auger reactor.

[0024] Figure 1 provides a general flow diagram for one embodiment of the inventive process disclosed herein. A first mixture 110 comprising at least one particulate solid catalyst and a particulate solid heat carrier is heated in an oven, then introduced near a first end of a reactor 125 comprising at least one auger 150 (or auger reactor). As the at least one auger rotates, the first mixture is conveyed through the auger reactor away from the first end and mechanically mixed to assure even and rapid heat transfer. At a point downstream from the entry point of the first mixture, a biomass feedstock 175 is introduced to the auger reactor at a ratio of heat carrier to feedstock of between about 1:1 and about 50:1. Rotation of the at least one auger mechanically mixes the first mixture with the biomass feedstock, thereby producing a second mixture that is conveyed through the reactor away from the first end. Mechanically mixing by the auger also assures even and rapid heat transfer from the heat carrier to the feedstock. In certain alternative embodiments, the feedstock may be introduced upstream from the first mixture. In such cases, a portion of the heating of the feedstock may occur inside the reactor prior to contacting the first mixture.

[0025] In certain alternative embodiments, the biomass feedstock and the catalyst may be mixed prior to heating, and then added to a pre-heated heat carrier. In still other alternative embodiments, the catalyst may be heated separately from the heat carrier, for example, to a

temperature approximately equal to or less than the temperature maintained within the reactor, then combined with heat carrier immediately 1) prior to, 2) after, or 3) simultaneous with entry into the reactor. Separate heating of the catalyst may preserve the activity of catalysts having a propensity to sinter at temperatures higher than those maintained inside the reactor, as oftentimes the heat carrier in pyrolysis reactions is heated to a temperature that is from about 150°C to 300°C greater than the reactor temperature.

[0026] In certain embodiments, the conditions maintained within the auger reactor 125 include a temperature of between about 250°C and about 1000°C. Preferably, the auger reactor is maintained at a temperature of between about 350°C and about 700°C. Upon introduction to the reactor, the biomass feedstock is rapidly heated at a rate in the range of about 100°C sec⁻¹ to about 10,000°C sec⁻¹. Heating of the biomass feedstock may be performed by heat transfer from a carrier gas, through direct contact with the reactor walls, through contact with a solid heat carrier (as discussed above). Pressure within the reactor is generally maintained between about atmospheric pressure to about 500 psig, and in certain embodiments is maintained at a pressure of between about 15 psig to about 50 psig. The total residence time of the feedstock within the reactor is maintained in a range of between about 0.1 sec and about 10 sec. In certain embodiments, the total residence time within the reactor is maintained between 1 sec and about 40 sec.

[0027] While not wishing to be bound by theory, the processes disclosed herein are believed to facilitate rapid and even heating of the feedstock while also continuously moving the first and second mixture downstream toward the second end of the reactor, thereby assuring a constant residence time for the second mixture within the reactor. The residence time can be adjusted by adjusting the rotational speed of the at least one auger. An additional advantage is that as the biomass feedstock enters the pyrolysis reactor, it always contacts fresh (or freshly regenerated) catalyst, thus, which allows more efficient catalytic pyrolysis, thereby and improving the quality of the produced bio-oil, and decreasing the formation of char and coke. More efficient pyrolysis enabled by the presence of a catalyst potentially allows a lower temperature to be maintained in the reactor, a higher throughput of feedstock by decreasing required residence time, or combinations of these benefits. Additionally, certain embodiments of the present disclosure may preserve the activity of catalysts having a propensity to sinter at temperatures higher than those maintained inside the reactor. This can be achieved by allowing separate preheating of the catalyst and the heat carrier. This allows the catalyst to be pre-heated to a lower temperature than the temperature to which the heat carrier is pre-heated.

[0028] Additional benefits of the processes disclosed herein include a decreased requirement for carrier gas (i.e., inert carrier gas or reactive carrier gas) to be mixed with the feedstock prior to entering the pyrolysis reactor, because the auger reactor does not utilize carrier gas as the method of primary heat transfer. Instead, the auger reactor achieves efficient heat transfer via constant mechanical mixing via the at least one auger. The decreased requirement for carrier gas also allows for easier collection of the liquid intermediate product.

[0029] A heat carrier is often utilized to increase the heating rate of the feedstock during pyrolysis and thereby reduce the amount of char formed. Any material capable of absorbing and transferring heat to a biomass feedstock may be utilized in the processes disclosed herein. Conventional heat carriers include, for example silica and granulated metal, such as steel shot, alumina, magnesium oxide, a zeolite and combinations thereof, although any other known solid heat carrier material or mixture of heat carrier materials may be useful.

[0030] Again referring to Figure 1, upon reaching the second end of the auger reactor, the heat carrier, catalyst, and any char and ash remaining after pyrolysis of the biomass are removed from the reactor and collected 190. The char and ash may then be separated from the mixture of heat carrier and catalyst by conventional methods. The char may be further separated and used for combustion, while the catalyst and (optionally) the heat carrier may be conveyed to a regeneration reactor (not depicted) for regeneration of the catalyst at a temperature generally ranging from 400°C to 1200°C in the presence of oxygen, such that any coke deposits on the catalyst are removed by combustion. In certain embodiments, the catalyst and the heat carrier may be conveyed to the regeneration reactor as a mixture. In these embodiments, the catalyst, or the regenerated mixture of catalyst and heat carrier is then conveyed to a chamber that is maintained at a temperature approximately equal to or higher than the temperature inside the auger reactor. As discussed previously, in alternative embodiments, fresh catalyst may be pre-heated separately from heat carrier (usually to a lower temperature) then co-fed to the reactor or combined with the biomass feedstock and co-fed into the reactor. In embodiments where the catalyst is relatively inexpensive to obtain or synthesize, regeneration may not be cost-effective. In these embodiments, the catalyst and heat carrier may be discarded and replaced with fresh heat carrier and catalyst. In certain embodiments, oxygen may be at least partially replaced (or mostly replaced) by an inert gas atmosphere prior to returning the regenerated mixture to the auger reactor.

[0031] The volatile gases created during pyrolysis are conveyed from the reactor 125, and are rapidly quenched. At least a portion of the vapors are condensed to generate a

mixture of hydrocarbons and oxygenates 215. The mixture generated by condensation of these volatile gases is generally termed as bio-oil. In certain embodiments, the quenching may be carried out at a pressure in the range from about 1.4 psig to about 100 psig and at a temperature in a range from about -20°C to about 80°C.

[0032] Depending on the degree of deoxygenation achieved and the components of the heating atmosphere, three or four product phases are obtained, i.e., solid, liquid and gas. The solid phase is composed mainly of char and used catalyst, if the latter is used. The gas phase contains mainly carbon oxides and light hydrocarbons. The liquid phase may be one or two phases. When two phases are formed, one phase is mainly aqueous with some polar organics dissolved. The other phase has a lower concentration of water and is mainly a mixture of organic compounds, such as those named above. Separation of the organic phase can be carried out by decantation when two separated liquid phases are obtained. The recovered gases produced during catalytic pyrolysis can optionally be used for hydrogen production using conventional technologies as described in that art.

[0033] The processes disclosed herein result in the production of a bio-oil (pyrolysis oil), which is a mixed liquid product derived from biomass pyrolyzed by heating in the absence (or near absence) of O₂. Bio-oil components vary relative to the composition of the original biomass. Typically, bio-oil contains molecules derived from the cellulose, hemicellulose, lignin and other biological molecules in the biomass feedstock, and is consequently a mixture of a variety of oxygenated products. The bio-oil comprises a mixture of several organic compounds, including hydrocarbons, sugar and derivatives, alcohols or polyols (such as glycerol, sorbitol, xylitol, for example), esters, alcohols, ketones, aldehydes, carboxylic acids, phenolics and polymers, along with tars, oils and water-insoluble solids. Bio-oil is thermally unstable, acidic, and is not typically miscible with petroleum feedstocks.

[0034] The bio-oil produced by the catalytic pyrolysis processes described herein may be further processed by one or more refining means to produce biofuels or hydrocarbons that can be used in blends with conventional fuels such as gasoline and diesel. The one or more refining means may include, but are not limited to, hydro-treating, fluidized catalytic cracking, hydro-cracking and coking. These are all conventional methods understood by one having skill in the art. The refining may be carried by any conventional methods and the scope of the present invention should not be limited to the examples provided herein.

[0035] The following example is provided by way to better explain one or more of the various embodiments, and should not be interpreted as limiting, or defining the scope of the invention.

EXAMPLE 1:

[0036] Either micro-algal or lignin biomass was dried at 70 °C for 12 hours, then pyrolyzed with and without zeolite catalyst in inert (He) atmosphere. Pyrolysis was conducted at 475 °C pyrolysis temperature, heating rate ~10,000 °C/s and a 5:1 catalyst ratio (when used). Vapors were analyzed by gas chromatography/mass spectrometry (GC/MS). Char was measured by gravimetric difference. All yields are on a mass basis.

[0037] The data (see Tables 1 and 2) show a greater than 60% yield of condensable vapors from both micro-algal (Table 1) and lignin (Table 2) biomass in un-catalyzed pyrolysis and 50% or greater yield during catalyzed pyrolysis. Adding a zeolite catalyst improved yield of hydrocarbons in the vapor phase, while also increasing char yield.

Table I. Yield of pyrolysis products from dried, whole microalgae.

Product	Yield %, no catalyst	Yield %, zeolite catalyst
Noncondensable gas*	6	17
Char*	19	28
Condensable vapors*	74	55
Hydrocarbons in vapor**	9	44

* Yield based on total biomass

** Yield based on condensable vapors only

Table II. Yield of pyrolysis products using lignin from corn stover hydrolysate:

Product	Yield %, no catalyst	Yield %, zeolite catalyst
Noncondensable gas*	2	6
Char*	37	44
Condensable vapors*	61	50
Hydrocarbons in vapor**	3	40

* Yield based on total biomass

** Yield based on condensable vapors only

[0038] As used herein, the term “auger reactor” is defined as any cylindrical, oval, or frusto-conically shaped reactor comprising at least one auger, which in turn, comprises a shaft passing axially therethrough, wherein each shaft is attached to one edge of a continuous blade having a non-perpendicular angle, or pitch, relative to the shaft, wherein rotation of the shaft causes the continuous blade to rotate, such that a material fed into one end of the reactor is mechanically conveyed through the reactor by the screw-like movement of at least one blade. Certain embodiments of an auger reactor may comprise multiple augers, wherein the augers may act in concert to mechanically mix the material passed through the reactor.

[0039] In closing, it should be noted that the discussion of any reference is not an admission that it is prior art to the present invention, in particular references that have a publication date after the priority date of this application. The claims listed below are hereby incorporated into this detailed description or specification as additional embodiments of the present inventive disclosure.

[0040] 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 disclosed embodiments and identify other ways to practice the invention that are not exactly as described herein, but are equivalent. 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.

REFERENCES

[0041] 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:

1. US Ser. No. 7,578,927, US Ser. No. 2008/0053870, WO2008/027699, Marker, et al., “Gasoline And Diesel Production From Pyrolytic Lignin Produced From Pyrolysis Of Cellulosic Waste,” UOP L.L.C. (2006).

2. USSN 13/274754, Lotero Alegria, et al., "Hydrocarbons From Pyrolysis Oil," ConocoPhillips Company (2011).
3. USSN 13/280982, Gong, et al., "Process For Producing High Quality Pyrolysis Oil From Biomass," ConocoPhillips Company (2011).
4. USSN 61/411531, Gong, et al., "Heat Integrated Process For Producing High Quality Pyrolysis Oil From Biomass," ConocoPhillips Company (2010).
5. USSN 61/427270, Gong, et al., "Integrated FCC Biomass Pyrolysis/Upgrading," ConocoPhillips Company (2010).
6. Lu, Changbo, et al. "Kinetics of Biomass Catalytic Pyrolysis" Biotech Advances 27 (2009) 583-587.

CLAIMS

1. A process comprising:
 - (a) providing a thermal reactor comprising at least one auger, and a first mixture comprising a heat carrier and at least one catalyst;
 - (b) introducing a feedstock comprising biomass to the thermal reactor and contacting therein with the first mixture to produce a second mixture,
wherein at least a portion of the feedstock is converted to condensable vapor intermediates via pyrolysis,
wherein the catalyst facilitates the rate at which the feedstock is converted,
wherein rotation of the at least one auger increases heat transfer from the heat carrier to the feedstock and increases contact between the feedstock and the first mixture,
 - (c) conveying the second mixture through the reactor for a defined residence time prior to removal from the reactor.
2. The process of claim 1, wherein said thermal reactor is maintained at a pressure in a range from about 50 psig to about 500 psig and a temperature in a range from about 250°C to about 1000°C.
3. The process of claim 1, wherein said thermal reactor is maintained at a pressure in a range from about 15 psig to about 50 psig and a temperature in a range from about 350°C to about 700°C.
4. The process of claim 1, wherein upon introducing the feedstock to the reactor, the feedstock is heated at a rate from about 100°C per second to about 10,000°C per second.
5. The process of claim 1, wherein the first mixture is introduced at a first location that is proximal to a reactor first end and is conveyed by the at least one auger to a second location located downstream, wherein the feedstock is introduced at the second location and combines with the first mixture to form a second mixture.

6. The process of claim 1, wherein the feedstock is introduced at a first location that is proximal to a reactor first end and is conveyed by the at least one auger to a second location located downstream, wherein the first mixture is introduced at the second point and combines with the feedstock to form a second mixture
7. The process of claim 1, wherein the defined residence time is decreased as a result of step (b)
8. The process of claim 1, wherein the heat carrier and the at least one catalyst are particulate solids, thereby increasing the surface area available for direct contact with the feedstock.
9. The process of claim 1, wherein the at least one catalyst increases the rate of pyrolysis, such that the temperature required for pyrolysis is lowered, the required residence time of the feedstock is decreased, or combinations thereof.
10. The process of claim 1, wherein the feedstock is converted in an atmosphere comprising an inert gas and less than 0.5 mol% oxygen gas.
11. The process of claim 1, wherein the feedstock is converted to condensable vapor intermediates in the presence of a reactive gas selected from a group consisting of hydrogen, synthesis gas (i.e., CO + H₂), steam/water, ammonia, methane, ethane, propane, butane, pentane, and natural gas, etc., and any combinations thereof.
12. The process of claim 1, wherein rotation of the at least one auger increases contact between the heat carrier and the feedstock to increase the heating rate of the feedstock.
13. The process of claim 1, wherein rotation of the at least one auger increases contact between the catalyst and the feedstock to increase the catalytic pyrolysis of the feedstock.
14. The process of claim 1, wherein the at least one catalyst comprises at least one of Co, Ni, Mo, W, Zn, Ga a zeolite, a metal-impregnated zeolite, and combinations thereof.

