

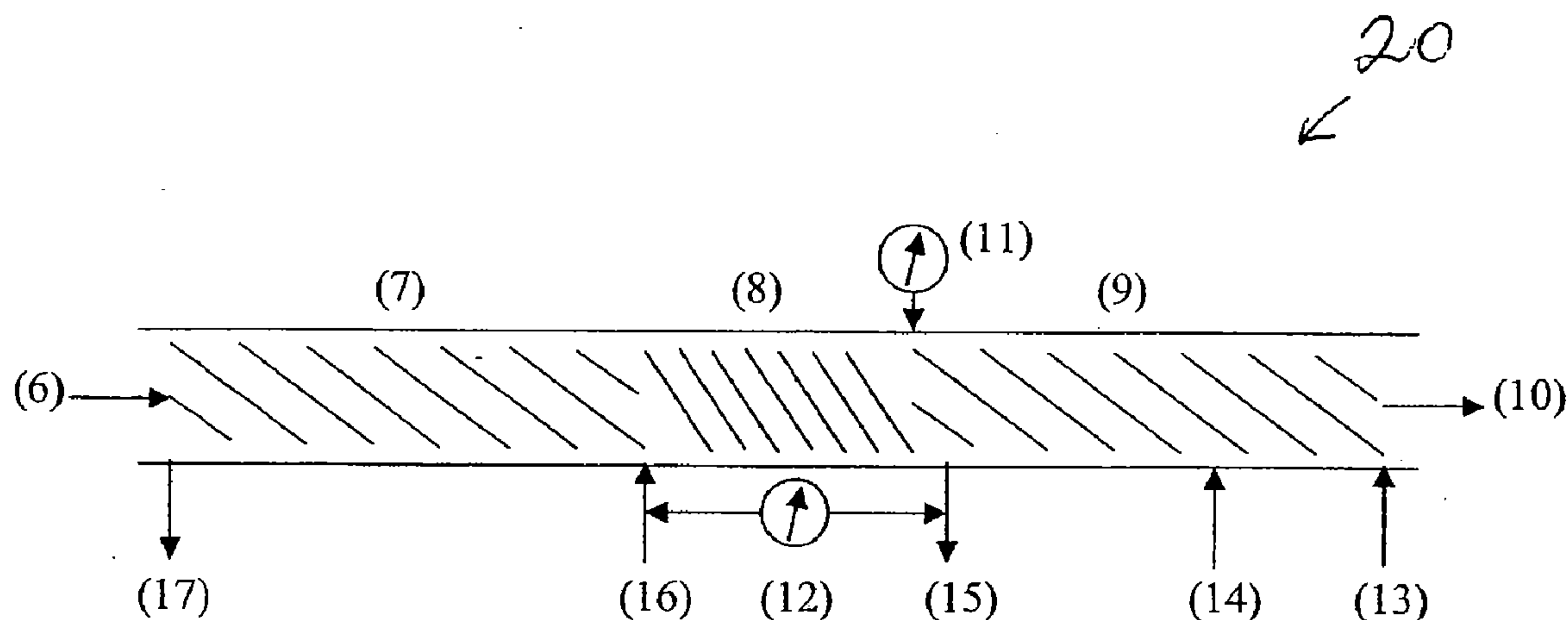
US 20080029233A1

(19) **United States**(12) **Patent Application Publication**
Wingerson et al.(10) **Pub. No.: US 2008/0029233 A1**(43) **Pub. Date: Feb. 7, 2008**(54) **MOVING BED BIOMASS FRACTIONATION
SYSTEM AND METHOD****Publication Classification**(75) Inventors: **Richard C. Wingerson**, Sandpoint,
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D21C 7/00 (2006.01)(52) **U.S. Cl. 162/60; 162/233; 162/238; 162/246**

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Lupton, CO (US)(21) Appl. No.: **11/462,207**(22) Filed: **Aug. 3, 2006**(57) **ABSTRACT**

Countercurrent extraction of lignocellulosic biomass such as trees, grasses, shrubs, and agricultural residues or waste involves the separation of cellulose fibers from other constituents, for subsequent use in the manufacture of paper, plastics, ethanol, and other industrial chemicals. Systems and methods involve continuous, multiple processing steps that may include chemical reactions with mixing at elevated temperature and/or pressure, efficient reagent or solvent utilization, filtration at elevated temperature and/or pressure, controlled discharge of liquid and solid products, and energy recuperation.



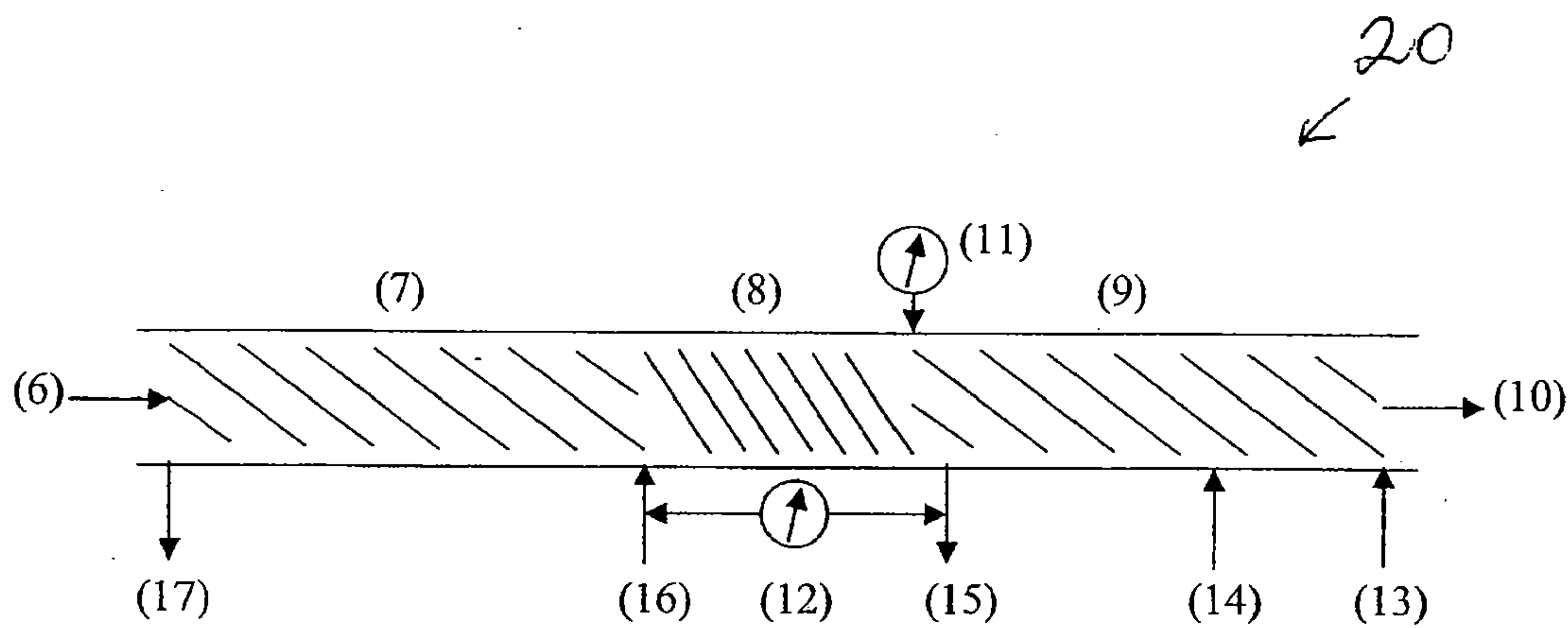


FIG. 1A

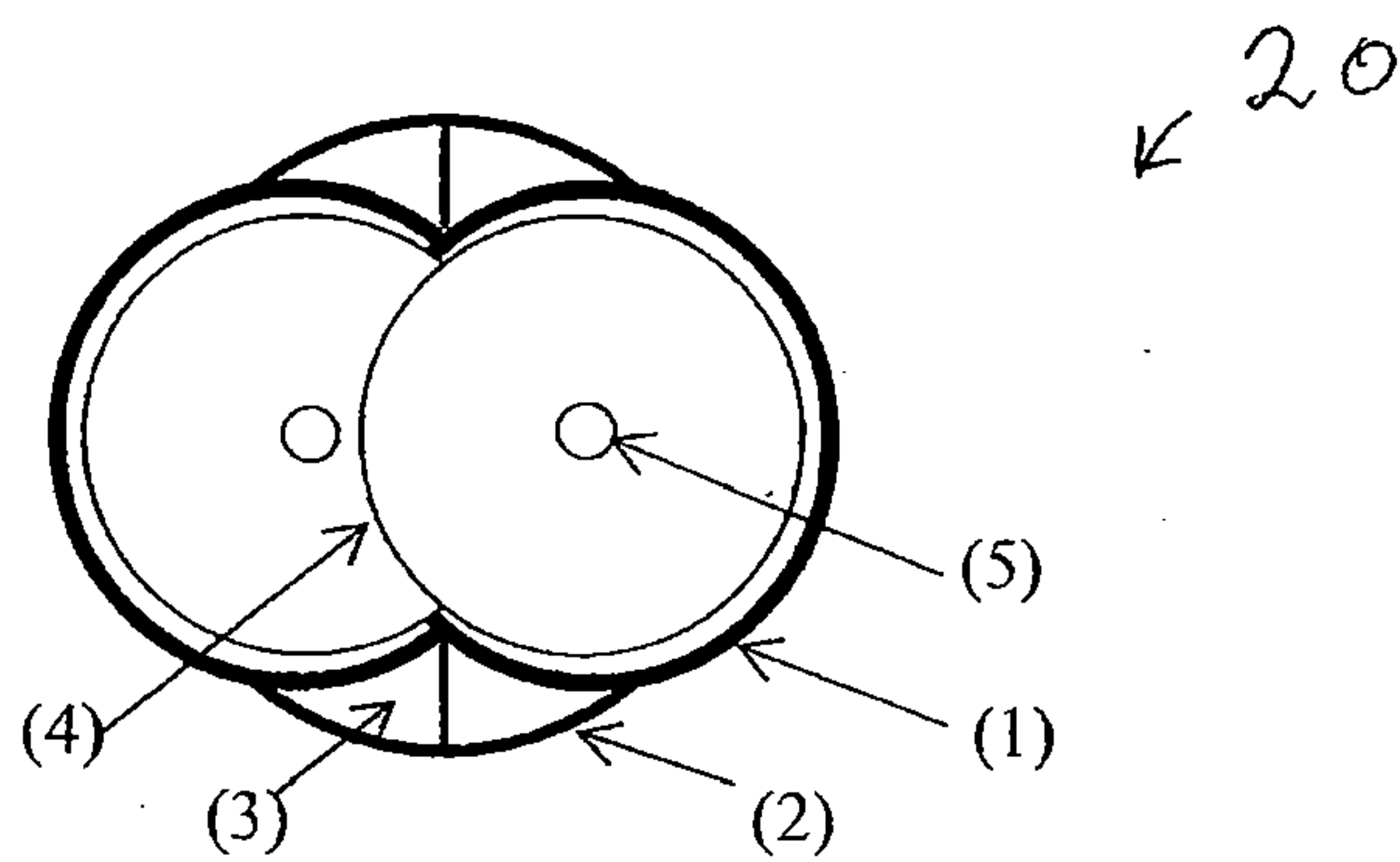
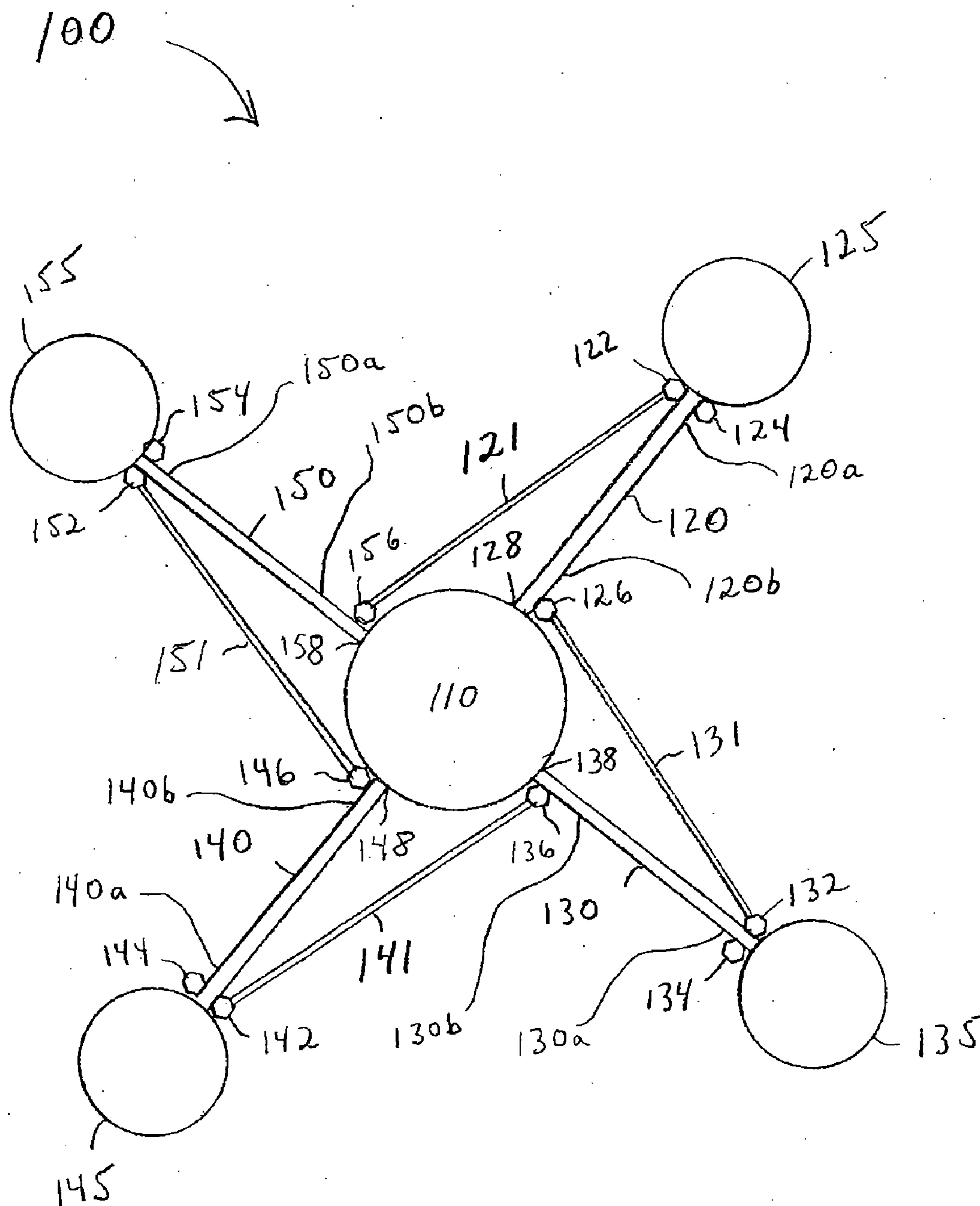
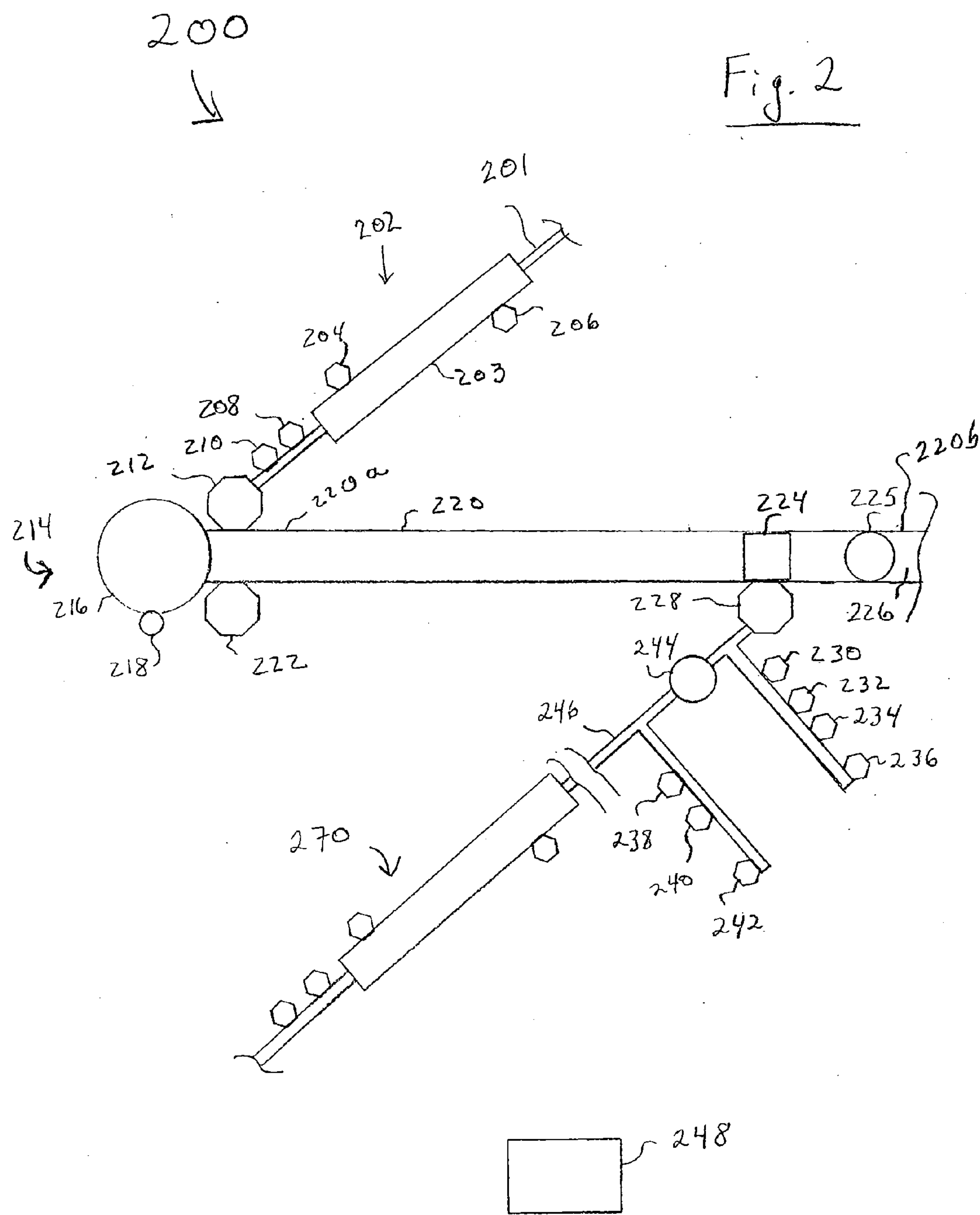
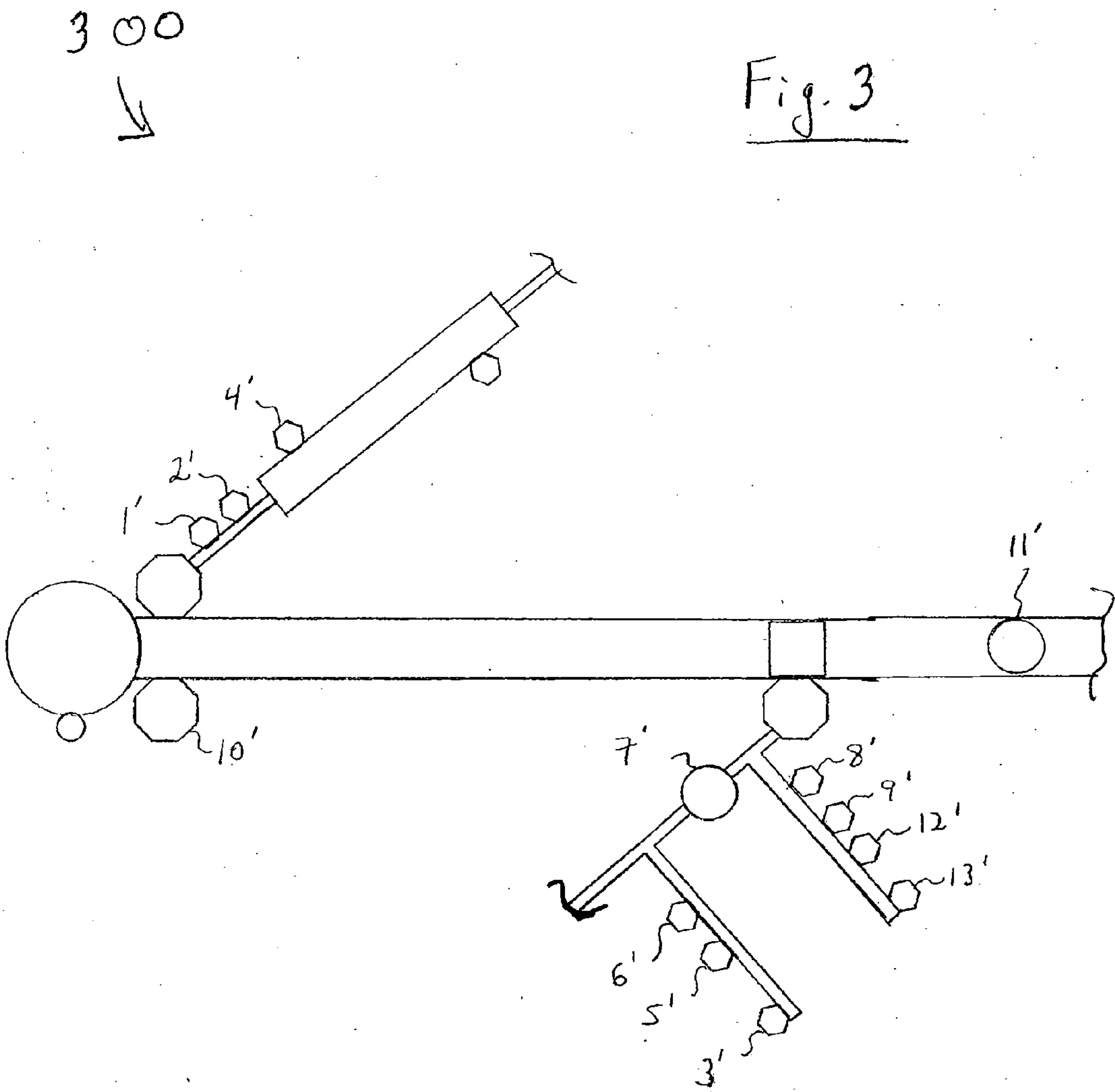


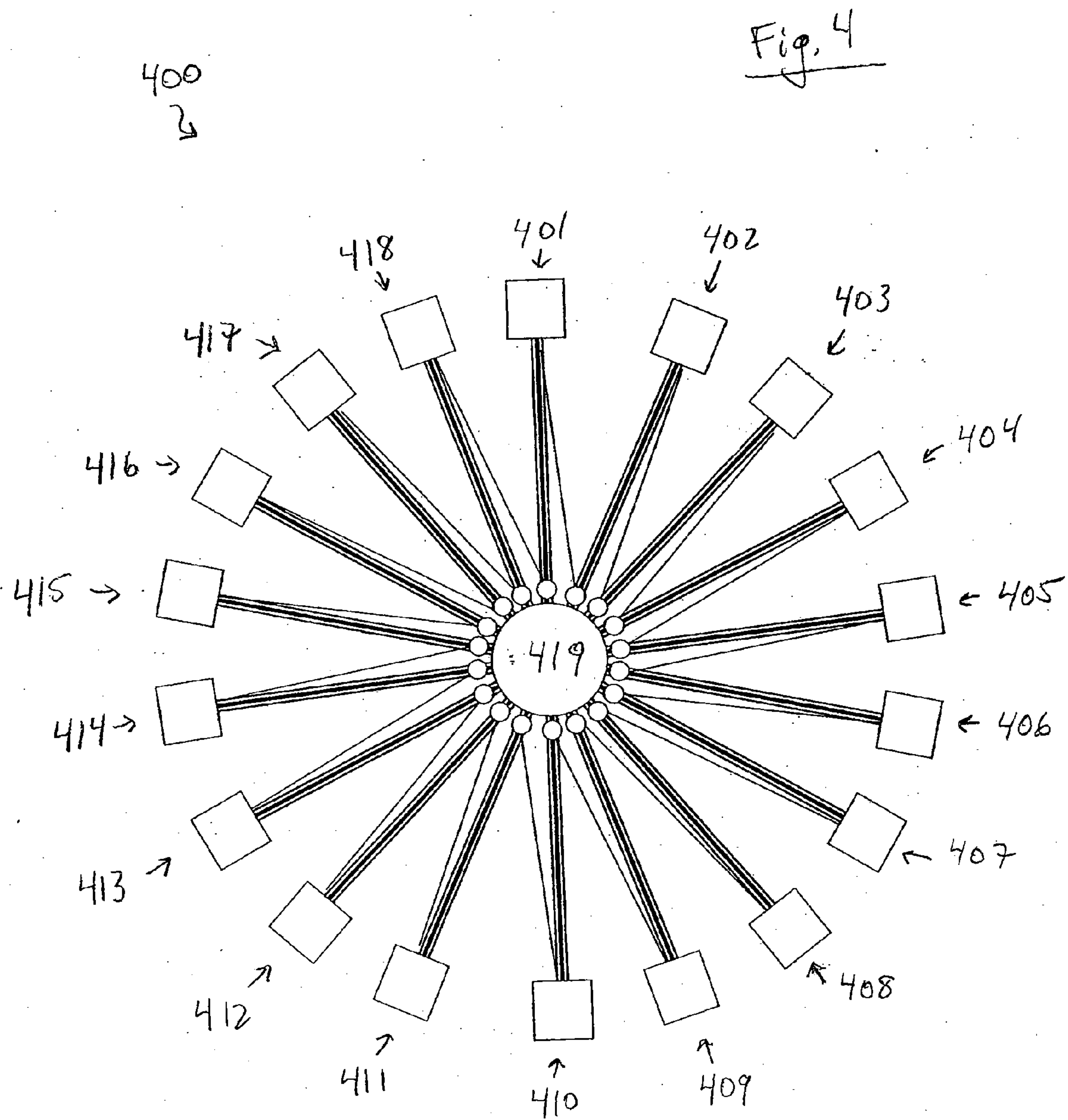
FIG. 1B

Fig. 1C









MOVING BED BIOMASS FRACTIONATION SYSTEM AND METHOD

BACKGROUND OF THE INVENTION

[0001] Embodiments of the present invention relate to systems and methods for the fractionation of lignocellulosic biomass into its components, including extractives, hemicellulose, lignin, and cellulose.

[0002] Natural cellulosic feedstocks typically are referred to as “biomass”. Many types of biomass, including wood, paper, agricultural residues, herbaceous crops, and lignocellulosic municipal and industrial solid wastes have been considered as feedstocks for the manufacture of a wide range of goods. These biomass materials consist primarily of cellulose, hemicellulose, and lignin bound together in a complex gel-like structure along with small quantities of extractives, pectins, proteins, and ash. Due to the complex chemical structure of the biomass material, microorganisms and enzymes cannot effectively attack the cellulose without prior treatment because the cellulose is highly inaccessible to enzymes or bacteria. This inaccessibility is illustrated by the inability of cattle to digest wood with its high lignin content even though they can digest cellulose from such material as grass. Successful commercial use of biomass as a chemical feedstock depends on the separation of cellulose from other constituents.

[0003] The possibility of producing sugar and other products from cellulose has received much attention. This attention is due to the availability of large amounts of cellulosic feedstock, the need to minimize burning or landfilling of waste cellulosic materials, and the usefulness of sugar and cellulose as raw materials substituting for oil-based products. Other biomass constituents also have potential market values. A wide variety of biomass processing techniques have been proposed, as further discussed below.

NREL Process

[0004] The NREL process involves biomass utilization in the production of fuel ethanol. At the front of the NREL process, a 3-reactor train is used comprising a pre-steamer, pretreatment reactor, and flash tank. Corn stover is steamed with low-pressure steam in a pre-steamer at 100 C for 20 min. After the stover is pre-steamed, concentrated H₂SO₄ is added to the pretreatment reactor (Sunds hydrolyzer). The resultant acid concentration is 1.1% and the insoluble solids loading is 30%. The reactor operates at 190° C. and 12.1 atm (177 psia), and the residence time is 2 min. The exiting material is flash cooled to 1 atm in the flash tank. After a residence time of 15 min in the flash tank, the hydrolyzate slurry containing about 21% insoluble solids is filtered to yield a solid stream and a liquid stream. The solid cake is washed, and the wash liquor is mixed with the hydrolyzate liquor. The combined liquid stream is overlimed and the resulting gypsum is filtered off. The solid cake and the conditioned hydrolyzate liquor are mixed and fermented to ethanol using a recombinant organism. A hybrid hydrolysis and fermentation (HHF) mode is used. The NREL process does not emphasize the lignin component of biomass as a potential marketable product. Pretreatment, saccharification, and co-fermentation conditions are provided in Tables 1-3, respectively.

[0005] Pretreatment conditions

TABLE 1

Parameter	Value
Acid concentration	1.1%
Residence time	2 min
Temperature	190° C.
Pressure	12.1 atm
Insoluble solids loading	30%

[0006] Saccharification conditions (as part of HHF)

TABLE 2

Parameter	Value
Temperature	65° C.
Initial total solids loading	20%
Residence time	1.5 days
Cellulose loading	12 FPU/g cellulose

[0007] Co-fermentation conditions (as part of HHF)

TABLE 3

Parameter	Value
Organism	Recombinant <i>Z. mobilis</i>
Temperature	41° C.
Initial total solids loading	20%
Residence time	1.5 days
Inoculum level	10%

Solvent Extraction of Lignin

[0008] Pulping is another way of exposing the cellulose via delignification, the Kraft process being standard industry practice. Pulping with alcohols has also been known for several decades. Although methanol, ethanol, propanol, isopropanol, butanol, and glycols can be used for pulping, ethanol has been reported to yield the highest ratio of

$$\frac{\text{lignin removal}}{\text{carbohydrate removal}}$$

Ethanol actually protects cellulose during delignification. Aqueous ethanol penetrates with ease into the structure of hardwoods and softwoods resulting in uniform delignification; however, delignification rates of the former are much higher. The reasons for differences in lignin hydrolysis rates are related to variations and heterogeneity in structure and the chemical composition of cellulosic materials. The process dissociates lignin and xylan in the middle lamella and the primary wall of the lignocellulosic material while substantially preserving the structural integrity of the fiber core, also referred to as the S2 layer, which is the strongest component of the fiber. The usual objective of pulping is to produce a strong and “pure” fiber. For chemical applications, however, the resultant cellulose product should be easy to digest enzymatically.

[0009] During conventional aqueous ethanol pulping, the liquor pH drops from 7 to about 4 due to the cleavage of acetyl groups from the hemicellulose. In most cases several hours of treatment is required to accomplish delignification. U.S. Pat. No. 4,100,016 to Diebold et al. [“Diebold”]

describes what later became known as the Alcell® process. Using a 40-60% (wt/wt) ethanol-water mixture, and temperature of 190-200° C. (corresponding pressure of 400-500 psig), the Alcell® process produces pulps that are similar to kraft pulps in physical properties. However, the lignin recovered is different from kraft lignins or lignosulfonates in terms of containing no sulfur and very low ash. It is reported to be “natural” lignin. Ethanol is recycled, hence, requiring only make-up quantities, about 1% on wood.

[0010] Lignin produced from Alcell® pulping of hardwoods is a polyphenol of high purity, low MW, low polydispersity, low glass transition temperature, and relatively high decomposition temperature. It can be used industrially as a partial replacement for phenolic resins, e.g., waferboards. See Lora et al., “Industrial scale production of organosolv lignins: characteristics and applications” *Cellulose: chemical, biochemical and material aspects*. Chichester, UK: Ellis Horwood Ltd. pp. 251-256 (1993).

[0011] Commercial processes for producing cellulose pulp from wood generally depend on inorganic chemicals as the extracting agent and do not yield lignin as a valuable byproduct. In order to yield high-quality lignin byproduct, an organosolv type process is used, in which the cooking liquor is an aqueous solution of an organic solvent. U.S. Pat. No. 3,585,104 to Kleinert describes pulping with an aqueous mixture of lower aliphatic alcohols such as methanol, ethanol, propanol or aqueous mixtures of the lower aliphatic ketones such as acetone, with pulping temperature of 150-200° C. and a residence time of 1-2 h. Other variations of the organosolv process are discussed below.

[0012] Diebold describes a solvent pulping process in which lignin is extracted from fibrous plant material by a lower aliphatic alcohol, such as ethanol, at an elevated pulping temperature and pressure. This is an example of a simulated countercurrent system using a batch mode. The pulping liquor is an aqueous solution of ethanol, and several batch extractors are used in carrying out the following sequential steps in each extractor: (1) Feeding an initial charge of fibrous material to a first extractor. (2) Filling the first extractor with a first used pulping liquor. (3) Introducing a second used pulping liquor of relatively high dissolved solids content at an elevated temperature and pressure into first extractor so as to displace first used pulping liquor, and recirculating second used pulping liquor without separation of lignin at a relatively high velocity through said first extractor. Achieving a pulping temperature of 160-220° C. The second used pulping liquor is obtained from step 5 (described below) during pulping of another charge in a second extractor and is supplied from second extractor to said first extractor without separation of lignin. (4) Continuing recirculation of second used pulping liquor without separation of lignin to effect essentially isothermal initial extraction of first charge at desired pulping temperature and pressure, and thereafter withdrawing second used pulping liquor from first extractor. (5) Flowing at least one additional used pulping liquor through first charge in first extractor on a once-through basis, additional used pulping liquor having a lower dissolved solids content than second used pulping liquor and being obtained from step 6 (described below) during pulping of still another charge in a third extractor and being supplied from third extractor to first extractor without separation of lignin. (6) Flowing heated fresh pulping liquor through first charge in first extractor on a once-through basis

to effect essentially isothermal final extraction of said first charge. (7) Discharging crude cellulose pulp from first extractor.

[0013] The solvent extraction can be carried out at ethanol concentrations (in aqueous solution) of 40-60% by weight, at pressures ranging from 20-35 atm, and at temperatures ranging from 180-210° C. To assure maximum lignin extraction efficiency with a minimum degree of redeposition of undesirable condensed fractions, the extraction vessel is to be designed to minimize channeling and/or back-mixing of the alcohol-water solvent. This then dictates a vessel with high aspect ratio (height to diameter ratio) of about 10:1.

[0014] U.S. Pat. Nos. 4,409,032 and 4,470,851 to Paszner et al. [“Paszner ’032 and ’851”] discuss organosolv delignification and saccharification of lignocellulosic plant materials. Cellulosic material is cooked under pressure at 180 C-220° C. to convert pentosans and hexosans to their respective sugar constituents. The cooking is done with acetone-water solvent mixture containing 0.05-0.25 wt % of phosphoric, sulfuric or hydrochloric acids. A delignified pulp containing predominantly cellulose is hydrolyzed to yield relatively pure glucose within an elapsed time of a minute or less.

[0015] Paszner ’851 reports that acetone at high concentration forms stable complexes with sugars, thereby minimizing their degradation. They employed an aqueous mixture containing 60-70% acetone by volume, and hydrochloric acid at 0.05-0.25 wt % of the mixture or phosphoric/sulfuric acids at 0.15-0.25 wt % of the mixture. The vessel under pressure provides a retention time for the solvent mixture of ≤ 7 min to minimize sugar degradation. However, the examples provided use longer retention times: 25 min for Douglas-Fir sawdust or Aspen wood cooked at 200° C. with 60:40 acetone-water containing 0.08% by weight of HCl, with liquor circulation to pass six times the volume of the cooking vessel through the charge in 25 minutes. The liquor is removed from the vessel which initially contains lignin and is separated from the liquor collected subsequently which contains the sugars. Hydrolysis of β -glycosidic chains characterizing amorphous and crystalline cellulose is reported.

[0016] U.S. Pat. No. 4,496,426 to Baumeister et al. describes a two-stage process for continuous extraction of fibrous material such as wood chips. The process comprises impregnating the fiber with organic solvents followed by reaction at elevated temperatures. In the first stage, extraction is conducted at 180-210° C. using an aqueous mixture containing about 90% methanol by weight with a reaction time of 40-120 min and a pH of 3.8-4.9. Additional extraction is achieved in the second stage at 150-190° C. for a period of 10-80 min. The second stage is different from the first stage in that the methanol concentration is lower and there is addition of sodium hydroxide and anthraquinone (5-30% by weight of sodium hydroxide to dry wood and 0.01-0.15% by weight of anthraquinone to dry wood). The extraction liquid, which gets saturated by leached substances, is removed continuously at each stage. In this process, the essential constituents of the fiber material such as cellulose, hemicellulose and lignin may all be recovered in pure form.

[0017] U.S. Pat. No. 4,746,401 to Roberts et al. describes a delignification process using an aqueous organic solvent and an acid neutralizing agent which yields cellulose pulp and reactive lignin of low molecular weight as byproduct.

This process comprises degassing lignocellulosic material followed by rapidly heating in an aqueous mixture of an organic solvent and a buffer to maintain a neutral pH during solvent extraction. The cooked temperature ranges from 150-280° C. The mixture is rapidly cooled to a temperature of <150° C. Additional cooking can take place in an optional third stage. A last or final stage, in which the liquor is cooled to a temperature of <150° C., should proceed at a fastest possible cooling rate. The operating conditions are controlled so as to maximize reactive lignin salvation while suppressing cellulose degradation in order to enable recovery of high quality cellulose pulp and of reactive lignin. Using an acid neutralizing agent is thought to aid the liquor in attaining and maintaining a mostly neutral pH (6.8-7.5) during an early or first stage of the cooking process.

[0018] U.S. Pat. No. 4,520,105 to Sinner et al. discusses a process for the production of sugars, cellulose, and lignin from lignocellulosic materials. The process comprises subjecting cellulosic materials to pretreatment with a mixture of water and lower aliphatic alcohols and/or ketones at a temperature of 100-190° C. for a period of 4 h to 2 min. This is followed by separation of residue and subsequent chemical treatment with a similar solvent mixture at elevated temperatures for a further period of from 2-180 min. The cellulosic material is treated under elevated pressure with an aqueous mixture containing 30-70% acetone by volume and an acid catalyst in a concentration 0.001-1N at a temperature of 170-220° C. Substantially all of lignin and hemicelluloses are dissolved in the first solution leaving a residue of microcrystalline cellulose. After separating the residue from the mixture, it is treated with a similar water-acetone mixture at a temperature of 170-220° C. This almost completely hydrolyzes the microcrystalline cellulose to glucose. Oligosaccharides and polysaccharides, which may still be present in the solution after separation from fibrous materials, are subjected to acid hydrolysis. The organic solvent and lignin are subsequently separated.

[0019] U.S. Pat. No. 4,941,944 to Chang describes a method for continuous countercurrent organosolv saccharification of lignocellulosic biomass. Continuous countercurrent production of lignins and sugars from wood and other lignocellulosic materials by organosolv delignification or saccharification at elevated temperatures and pressures is discussed. This method involves continuously feeding biomass (30-70% moisture by weight) and cooking liquor into a reaction vessel at opposite ends to achieve countercurrent flow. The cooking liquor, consisting of ethanol, water, and a catalytic amount of inorganic acid, is continuously withdrawn from the reaction vessel. It contains dissolved sugars and lignin and other substances released from the lignocellulosic material. The reaction is conducted at the following conditions: temperatures ranging from 150-210° C., residence times of 2-5 min, and initial insoluble solids loading of 12.5%. Mainly lignin and hemicellulosic sugars are dissolved in the first zone of the vessel. The cooking liquor in the first zone is removed from the vessel and rapidly cooled; lignin remains dissolved during the cooling step. The resultant cellulose-rich solids are then hydrolyzed in the second zone of the vessel by acid to mainly form oligomers of glucose. The objective is to obtain pentose sugars and lignin under relatively mild conditions in one part of the reactor, and to yield hexoses under more severe conditions in the other part of the reactor. This is accomplished by

designing a reactor that has different operating conditions and thus produces different reaction products for the two stages.

Countercurrent Batch Systems

[0020] An example of a countercurrent system using a batch mode is described in Diebold. Another such example is discussed in U.S. Pat. No. 4,123,318 to Sherman. In this three-vessel system, fiber material is impregnated with the liquid, sent to a separate digesting vessel, and from the digesting vessel sent to separate washing vessels without a significant reduction in pressure. Countercurrent operation is simulated in the washing vessels in a manner similar to that described in Diebold.

Continuous Countercurrent Digesters

[0021] An example of a countercurrent system using a batch mode was discussed above. Pulping with continuous countercurrent digesters is also possible. U.S. Pat. No. 5,716,497 to Richter et al. describes a device for continuous production of pulp. This process relates principally to pulp and involves impregnating the chips with the aid of hot black liquor, which can improve the strength properties of the fibers, due to the fiber-sparing effect of the black liquor, i.e., a milder treatment. If a large proportion of white liquor is used in connection with the impregnation, this exposes fibers to the aggressive effect of the white liquor, with carbohydrates degradation and loss of fiber strength. The aim of the impregnation step is to thoroughly soak each chip to render it susceptible, by diffusion, to the active cooking chemicals. In this continuous cooking process, hot impregnated chips are fed at the top of a countercurrent steam digester. The digester has a bottom outlet and at least one draw-off point for discharging the black liquor. About 70% of the cooking liquor is fed to the top of the digester as finely divided droplets.

[0022] U.S. Pat. No. 5,882,477 to Laakso et al. describes the use of a continuous digester with a low temperature gas phase. The continuous pulp digester is operated so that it has the advantages of a hydraulic digester yet has a gas-filled zone over the liquid level. A slurry of chips and cooking liquor is introduced into the top of the digester vessel. A gas-filled zone above the liquid level includes compressed gas and is at a temperature of >120° C. and at a pressure of 80-150 psig. The chips are heated by heating liquid using a recirculation loop below the chips level, and a countercurrent flow zone is provided. Kraft pulp from the bottom of the digester is withdrawn.

[0023] U.S. Pat. No. 5,192,396 to Backlund discusses a process for continuously digesting cellulosic fiber material, which employs both cocurrent and countercurrent modes. The fiber material is impregnated with liquid in a closed system comprising a cocurrent zone and a countercurrent zone. The liquid in the cocurrent zone includes black liquor and possibly some white liquor, and the liquid in the countercurrent zone is fresh white liquor. A liquid stream is withdrawn from the impregnation system at an exit situated between the two zones.

[0024] U.S. Pat. No. 5,401,361 to Prough et al. discusses a completely countercurrent digester for continuous cooking. A conventional continuous digester can be modified to achieve a countercurrent cook throughout the entire height of the digester. The process utilizes an upright digester, and

the operation is comprised of the following steps: (1) Continuously introducing cellulosic material steeped in cooking liquor into the top of the digester so that the material continuously travels downwardly in the digester. (2) Establishing a countercurrent flow between cooking liquor and solids throughout the entire height of the digester, from the top where the cellulosic material is introduced to the bottom where the pulp is withdrawn. (3) Continuously withdrawing liquid from the digester at different points along the height of the digester, and reintroducing the withdrawn liquid. (4) Continuously withdrawing cellulose pulp from the bottom of the digester.

[0025] U.S. Pat. No. 4,668,340 to Sherman discusses countercurrent acid hydrolysis of cellulosic materials. After prehydrolysis treatment of cellulosic fibrous material, subsequent kraft digestion can be conducted to produce paper pulp. The material is steeped with cooking liquor, steamed, and transferred by a high pressure feeder to the top of a first vertical vessel. Liquid is withdrawn from the top of the first vessel via a liquid/solids separator. This recovered hydrolyzate contains hemicellulose, sugars, etc. Countercurrent acid hydrolysis takes place in the top section of the vessel, and a countercurrent wash is effected in the bottom section of the vessel. After hydrolysis and washing, the resultant material is withdrawn from the bottom of the first vessel and sent to the top of a kraft digester.

Biomass Fractionation

[0026] Many steps are required in production, harvesting, storage, transporting, and processing of biomass to yield useful products. One step in the processing is the separation of biomass into its major components: extractives, hemicellulose, lignin, and cellulose. This separation process is called fractionation. Biomass can be viewed as an intermingled structure of three complex polymers saturated with mobile extractives. Many approaches have been investigated for disentangling this complex structure. Once this separation has been achieved, a variety of paths are opened for further processing of each component into marketable products. The separation of cellulose from other biomass constituents is difficult, in part because the chemical structure of lignocellulosic biomass is so complex. See, e.g., ACS Symposium Series 397, "Lignin Properties and Materials", edited by G. W. Glasser and S. Sarkanen, published by the American Chemical Society, 1989, which includes the statement that "[L]ignin in the true middle lamella of wood is a random, three-dimensional network polymer comprised of phenylpropane monomers linked together in different ways. Lignin in the secondary wall is a nonrandom two-dimensional network polymer. The chemical structure of the monomers and linkages which constitute these networks differ in different morphological regions (middle lamella vs secondary wall) different types of cell (vessels vs fibers) and different types of wood (softwoods vs hardwoods). When wood is delignified, the properties of the macromolecules made soluble reflect the properties of the network from which they are derived." The separation of cellulose from other biomass constituents is further complicated by the fact that lignin is intertwined and linked in various ways with cellulose and hemicellulose both of which are polymers of sugars. Thus there is a need for systems and methods for separating solid biomass, such as lignocellulosic biomass, into its constituent components, for example by chemical fractionation, and treating the components to make useful

products. Biomass is widely recognized as a potential raw material for the production of transportation fuel and industrial chemicals, but an economically competitive commercial biorefinery has yet to be devised. Much research and development has been conducted toward this goal over the past 30 years or more, and there is in addition a century of experience working with biomass for the production of paper pulp at commercial scale, yet there remains a need for an economically viable path to a commercial biorefinery. These and other needs are addressed by the present invention.

BRIEF SUMMARY OF THE INVENTION

[0027] Embodiments of the present invention include methods and systems that involve the continuous countercurrent flow of biomass and reactive liquids, and the control of degradation reactions to increase product yields. Design features include elevated temperature and pressure to minimize processing time, and the efficient use of chemical reagents and/or solvents as well as heat energy. Other features provide for the in-situ separation of liquids and solids for discharge, and the optional linking of multiple processing steps.

[0028] Embodiments of the present invention provide ethanol-water mixture techniques that may differ in one or more aspects from known approaches (e.g. Alcell® process of Diebold). For example, in some cases, embodiments include a prehydrolysis step to remove a desired amount of hemicellulose in a two-stage approach, where hemicellulose can be removed in a first stage. Embodiments may also include the use of a regime of high temperature and short residence time during delignification. For example, the residence time may be on the order of minutes, whereas other known approaches may involve a residence time on the order of hours. Embodiments may also provide the ability to produce low-hemicellulose pulp (suitable, for example, in making dissolving pulp) using a two-stage approach, whereas some known approaches may remove about 50% of the hemicellulose. Embodiments may also provide the ability to produce high-yield pulp using a single-stage approach, whereas other known approaches may remove about 50% of the hemicellulose, thereby lowering pulp yield.

[0029] In one aspect, embodiments of the present invention provide a continuous, countercurrent process of one or more stages for the fractionation of a lignocellulosic biomass feedstock. The process includes feeding the biomass feedstock into a first stage of a pressurized reaction vessel, injecting a first wash liquid into the first stage countercurrently to the biomass feedstock, discharging the first wash liquid from the first stage, and discharging a solid biomass product from the reaction vessel in slurry form. The process can also include conveying a first stage biomass product from the first stage to a second stage of the reaction vessel, injecting a second wash liquid into the second stage countercurrently to the first stage biomass product, and discharging the second wash liquid from the second stage. The first wash liquid can include water or a solution of water and a mineral acid for hemicellulose hydrolysis, and the second wash liquid can include water and a sodium or ammonium hydroxide base for lignin hydrolysis. The second wash liquid can include about 40% to about 60% ethanol by weight. The first wash liquid can include a water rinse and a concentrated chemical reagent that mix to form the first

wash liquid. In some cases, the first wash liquid provides optimal recovery of oils, proteins, and other extractives. The process can also include maintaining a temperature of at least one of the stages in a range from about 190° C. to about 240° C.

[0030] In another aspect, embodiments provide a continuous, countercurrent system of one or more stages for the fractionation of a lignocellulosic biomass. The system can include means for feeding the biomass into an elongated, pressurized reaction vessel, means for conveying the biomass through the length of the reaction vessel, means for discharging a processed biomass from the reaction vessel, means for injecting concurrently a flow of pressurized wash liquid into each stage of the reaction vessel, means for discharging the wash liquid from each stage of the reaction vessel, means for separating liquids from solids in each stage of the reaction vessel prior to discharging the wash liquid, means for maintaining a desired temperature in each stage of the reaction vessel, means for transferring heat from the liquid being discharged to the liquid being injected, and means for controlling pressure throughout each stage of the reaction vessel such that boiling nowhere occurs, separate counter-flows are established in each stage where desired, and mixing of liquids between stages is minimized. The pressurized reaction vessel can include an elongated barrel accommodating twin screws for conveying the biomass, the screws being driven by a gearbox and motor. In some cases, the means for discharging a processed biomass from the reaction vessel includes a processed biomass discharge progressive cavity pump configured to reduce pressure while avoiding clogging from settling solids, and the means for discharging the wash liquid from each stage of the reaction vessel includes a wash liquid discharge progressive cavity pump configured to reduce pressure while avoiding clogging from settling solids. The means for separating liquids from solids in each stage of the reaction vessel prior to discharging the wash liquid can include at least one twin-screw extruder configured to force solids back into the reaction vessel.

[0031] In another aspect, embodiments of the present invention provide a simulated moving bed system of one or more stages for the countercurrent fractionation of lignocellulosic biomass. The system can include a plurality of elongated, pressurized reactors or reaction columns interconnected with a plumbing system for controlling and directing one or more fluid flows, means for sequential loading of the plurality of reactors with a biomass feedstock and for sequential unloading of a processed biomass, means for injecting countercurrently a flow of pressurized wash liquid into each stage of the simulated moving bed system, means for discharging the wash liquid from each stage of the simulated moving bed system, means for separating liquids from solids prior to discharging the wash liquid and transferring the wash liquid between reactors, means for maintaining a desired temperature in each of the plurality of reactors of the simulated moving bed system, means for transferring heat from the wash liquid being discharged to the wash liquid being injected, means for controlling a pressure in each of the plurality of reactors to prevent boiling and to maintain a desired liquid flow throughout the simulated moving bed system, and means for sequential switching of a plurality of valves to create a desired countercurrent moving bed simulation. In some cases, the means for sequential loading of the plurality of reactors with a biomass

feedstock and for sequential unloading of a processed biomass includes one or more augers configured to load the biomass feedstock into the plurality of reactors, and means for slurring and washing the processed biomass with water. In some cases, the means for sequential loading of the plurality of reactors with a biomass feedstock and for sequential unloading of a processed biomass includes a plurality of baskets. The means for discharging the wash liquid from each stage of the reaction vessel can include a wash liquid discharge progressive cavity pump configured to reduce pressure while avoiding clogging from liquid-solid separation. The means for separating liquids from solids in each stage of the reaction vessel prior to discharging the wash liquid can include at least one twin-screw extruder configured to force solids back into the reaction vessel. The means for sequential switching of a plurality of valves to create a desired countercurrent moving bed simulation can include an electronic computer. The plumbing system for controlling and directing one or more fluid flows comprises a first reactor outlet port coupled with a second reactor inlet port. In some cases, the first reactor outlet port is coupled with the second reactor inlet port via a heat exchanger. In some embodiments, the means for sequential loading of the plurality of reactors with a biomass feedstock and for sequential unloading of a processed biomass includes a common feedstock hopper in operative association with the plurality of elongated, pressurized reactors.

[0032] In still another aspect, embodiments of the present invention provide a simulated moving bed system for processing a lignocellulosic feedstock. The system can include a common feedstock hopper to provide the lignocellulosic feedstock, a first reactor having a first fluid inlet port, a first discharge port, a first fluid outlet port, and a first feedstock inlet port that is coupled with the common feedstock hopper. The system can also include a second reactor having a second fluid inlet port, a second discharge port, a second fluid outlet port, and a second feedstock inlet port that is coupled with the common feedstock hopper. The first fluid outlet port of the first reactor can be coupled with the second fluid inlet port of the second reactor. In some cases, the first fluid inlet port and the first discharge port are disposed toward a distal end of the first reactor, and the first fluid outlet port and the first feedstock inlet port are disposed toward a proximal end of the first reactor. In some cases, at least one of the first or second reactors includes a threaded shaft. The system may also include a motor coupled with the threaded shaft, wherein the motor is configured to rotate the threaded shaft. The system may also include a positioning system coupled with the threaded shaft. The positioning system may be configured to move the threaded shaft into and out of the common feedstock hopper. The first fluid outlet port of the first reactor can be coupled with the second fluid inlet port of the second reactor via a heat exchanger. At least one of the first or second feedstock inlet ports can include a ball valve.

[0033] In yet another aspect, embodiments provide a method for processing a lignocellulosic feedstock. The method can include passing a first amount of the lignocellulosic feedstock from a common feedstock hopper to a first reactor, passing a second amount of the lignocellulosic feedstock from the common feedstock hopper to a second reactor, passing a first reaction fluid to the first reactor, reacting the first reaction fluid with the first amount of the lignocellulosic feedstock in the first reactor to form a first

fractionate and a first discharge, and passing the first fractionate from the first reactor to the second reactor. The first amount of feedstock can be passed from the common feedstock hopper to the first reactor in a first direction, and the first reaction fluid can be passed to the first reactor in a second direction that is countercurrent to the first direction. The first amount of the lignocellulosic feedstock can be passed from the common feedstock hopper to the first reactor with a threaded shaft. The first amount of the lignocellulosic feedstock can be passed from the common feedstock hopper to the first reactor by advancing the threaded shaft into the common feedstock hopper, and rotating the threaded shaft with a motor so as to draw the first amount of feedstock out of the common feedstock hopper. In some cases, the threaded shaft is advanced into and withdrawn from the common feedstock with a positioning system. In some cases, the first amount of the lignocellulosic feedstock is passed from the common feedstock hopper to the first reactor via a first feedstock inlet port. The second amount of the lignocellulosic feedstock can be passed from the common feedstock hopper to the second reactor via a second feedstock inlet port. The first reaction fluid can be passed to the first reactor via a first fluid inlet port. In some cases, the first discharge is passed out of the first reactor via a first discharge port. The first fractionate can be passed from the first reactor to the second reactor via a first fluid outlet port and a second fluid inlet port. The method can also include reacting the first fractionate with the second amount of feedstock in the second reactor to form a second fractionate and a second discharge. In some cases, the first fractionate is passed from the first reactor to the second reactor via a heat exchanger. The method may also include capturing particles from the first fractionate as the first fractionate passes from the first reactor to the second reactor, and returning the particles to the first reactor. The first reaction fluid may include an alkaline solution. In some cases, the reaction fluid has a pH of about 8 to about 13. In some cases, the first reaction fluid has a temperature of about 180° C. to about 240° C. The first fractionate may include lignin. The first discharge may include cellulose.

[0034] Simulated moving bed systems for processing a lignocellulosic feedstock are provided. The systems may include a common feedstock hopper to provide the lignocellulosic feedstock, and a first reactor having a first fluid inlet port, a first discharge port, a first fluid outlet port, and a first feedstock inlet port that is coupled with the common feedstock hopper. The systems may also include a second reactor having a second fluid inlet port, a second discharge port, a second fluid outlet port, and a second feedstock inlet port that is coupled with the common feedstock hopper. The first fluid outlet port of the first reactor is coupled with the second fluid inlet port of the second reactor.

[0035] Embodiments of the invention may also include methods for processing a lignocellulosic feedstock. The methods may include the steps of passing a first amount of the lignocellulosic feedstock from a common feedstock hopper to a first reactor, and passing a second amount of the lignocellulosic feedstock from the common feedstock hopper to a second reactor. The methods may also include passing a first reaction fluid to the first reactor, and reacting the first reaction fluid with the first amount of the lignocellulosic feedstock in the first reactor to form a first fractionate

and a first discharge. In addition, the methods may include passing the first fractionate from the first reactor to the second reactor.

[0036] Additional embodiments and features are set forth in part in the description that follows, and in part will become apparent to those skilled in the art upon examination of the specification or may be learned by the practice of the invention. The features and advantages of the invention may be realized and attained by means of the instrumentalities, combinations, and methods described in the specification.

BRIEF DESCRIPTION OF THE DRAWINGS

[0037] A further understanding of the nature and advantages of the present invention may be realized by reference to the remaining portions of the specification and the drawings wherein like reference numerals are used throughout the several drawings to refer to similar components. In some instances, a sublabel is associated with a reference numeral and follows a hyphen to denote one of multiple similar components. When reference is made to a reference numeral without specification to an existing sublabel, it is intended to refer to all such multiple similar components.

[0038] FIG. 1A is a schematic representation of a pressure controlled, two-stage, twin-screw, countercurrent apparatus illustrating one embodiment of this invention.

[0039] FIG. 1B is a schematic representation of a cross section of the apparatus of FIG. 1A.

[0040] FIG. 1C is a schematic illustrating a simulated moving bed biomass fractionation system according to one embodiment of the present invention.

[0041] FIG. 2 is a schematic detailing a reaction section of a simulated moving bed biomass fractionation system according to one embodiment of the present invention.

[0042] FIG. 3 is a schematic of a reaction section of a simulated moving bed biomass fractionation system according to one embodiment of the present invention.

[0043] FIG. 4 shows a simulated moving bed biomass fractionation system according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0044] Systems and methods for processing lignocellulosic feedstocks are described. The feedstocks may be processed to separate cellulose fibers from other constituents of a lignocellulosic biomass, such as found in trees, grasses, shrubs, agricultural waste, and waste paper. The separated cellulose fibers may be used as a component in the manufacture of paper, plastics, ethanol, and a variety of other materials and chemicals.

[0045] Counter-flow operation provides for the efficient use of processing reagents. Processed solids encounter fresh reagents just before discharge, while the fresh and reactive feedstock first meets with nearly exhausted liquid reagent about to be discharged. Advantageously, countercurrent flow can establish a non-equilibrium steady state in which the reacting liquids and solids experience different histories. In combination with temperature gradients, this permits manipulation of reaction rates for competing chemical interactions to improve yields by minimizing degradation reactions. Elevated temperatures reduce processing times for fractionation. As a rough rule, every ten degrees Celsius rise in temperature reduces processing time by a factor of two

and can thus increase materials throughput by this same factor for similarly sized apparatus. In many cases, however, with increased temperature comes increased pressure to prevent liquid boiling. Further, increased temperature can result in undesirable degradation of biomass. Both of these considerations may have an effect in the temperature range from 210 to 230° C., depending on details of the fractionation chemistry.

[0046] In a countercurrent system, it is possible to incorporate a rinsing feature that provides in-situ recovery and full use of reagents that might otherwise be discharged with the processed solids. This additional processing can occur at the elevated temperature and pressure where reaction rates are high and mobilized components remain in solution. A rinse liquid can even be used to cool the solid product with in-situ recuperation of the heat energy in the solid product. Reagents and energy needed for biomass fractionation can be costly and efficient utilization may be required if the fractionation process is to be economically viable. Advantageously, embodiments of the present invention provide efficient utilization as a process feature. In-situ separation of liquid and solid flows in a countercurrent system provide opportunities for significant savings in downstream processing. Processed solids can thus be discharged in a clean, cooled condition as a fully prepared intermediate product. Depending on the particulars of the biomass and the intermediate products desired from the fractionation, one or more processing steps may be involved. For example, a simple extraction of oils or other extractables might involve only a single stage, while a more complete fractionation might involve multiple stages for sequential recovery of extractives, hemicellulose, lignin, and cellulose with intermediate rinsing. Embodiments of the present invention provide the ability to carry out such multiple processing steps while maintaining operating temperatures and flows.

[0047] Embodiments provided herein include various implementing devices, however, knowledgeable readers will readily see the applicability of the techniques described herein in a broad range of related situations depending on such factors as the particular biomass feedstock, the marketable fractionation products to be recovered, the scale of the operation, and the availability of certain manufactured components. Embodiments of the present invention involve the fractionation of biomass, and in some cases it is assumed that certain feedstock preparation steps such as cleaning, sizing, and wetting have already been accomplished, as needed. Fractionation chemistry can be carried out in a sequence of steps in a reactor configured to provide a plurality of countercurrent zones. Although applicable for a single or multi-stage fractionation process, the following steps would characterize one embodiment of a two-stage, countercurrent fractionation process: (1) Feed prepared (cleaned and/or size-reduced) biomass into the pressurized reactor. (2) Discharge a first liquid with dissolved extractives, hemicellulose, etc. (3) Provide a zone for chemical reaction at elevated temperature. (4) Inject a first reagent, liquid or solvent to mix with rinse liquid. (5) Provide a zone for countercurrent rinsing of the solids. (6) Input a rinse liquid (e.g. water). (7) Provide an interstage separation zone with negligible liquid flow. (8) Discharge a second liquid with dissolved hemicellulose, lignin, etc. (9) Provide a zone for chemical reaction at elevated temperature. (10) Inject a second reagent, liquid or solvent to mix with rinse liquid. (11) Provide a zone for countercurrent rinsing of the solids.

(12) Input a rinse liquid (e.g. water). (13) Discharge the solid product. In some embodiments, hemicellulose and extractives can be removed in the first stage, and thus an ethanol extraction in the second stage can be more efficient.

[0048] Further details of the fractionation chemistry are provided herein. For aqueous based biomass processing, the first reagent will often be either water itself or a dilute mineral acid. The second reagent will often be a solution of water and an alkali such as sodium or ammonium hydroxide. Some of the water may be replaced by ethanol. Many process variations are contemplated by embodiments of the present invention. For example, fractionation can begin with an additional stage optimized for the recovery of extractives before proceeding to hemi-cellulose extraction. Another example might involve an alternative to discharging the solid product in which an additional stage is optimized for rapid acid hydrolysis of the cellulose and discharge of the resulting sugars for further processing. Embodiments described herein can provide precise control of the movement of liquids and solids in the reactor, and maintenance of desired pressures and temperatures throughout, to enhance the performance of the implementing apparatus.

[0049] The present systems integrate a plurality of processing steps, which may include chemical reactions, mixing steps at elevated temperatures and/or pressures, liquid/solid separation steps at elevated temperatures and/or pressures, and controlled discharge of liquid and solid products, among other steps. A description of other apparatuses and methods for processing lignocellulosic feedstocks are described in co-assigned, U.S. Pat. No. 6,419,788, issued Jul. 16, 2002; U.S. Pat. No. 6,620,292, issued Sep. 16, 2003, and U.S. patent application Ser. No. 11/158,831, filed Jun. 21, 2005, the entire contents of which are all herein incorporated by reference for all purposes.

[0050] An exemplary implementing apparatus includes a twin-screw conveyor with housing designed for operating pressures of 400 psi or more and with metallurgy compatible with the reagents expected to be used. This conveyor is the reaction vessel and is sized for the desired throughput and reaction time. A crammer-feeder with a safety shutoff can be used to take biomass from a feed hopper and inject it continuously into the reaction vessel. The screw conveyor creates a moving bed of solids while liquid is forced countercurrently. Pressure pumps with flow sensors and pressure gauges are required for each of the liquid inputs. Positive displacement pumps (e.g. Moyno type pumps) run in reverse are used for each of the liquid discharges and for the solid product discharge. In some applications, a double valve system can be used instead of a pump to discharge product while maintaining pressure. Liquid/solid separators are used on each of the liquid discharge ports to extract liquid while keeping solids in the reactor. A heating system with temperature sensors is used to achieve necessary reaction temperatures (up to 230° C.). Heat exchangers are used between liquid feed and discharge lines for energy conservation and to prevent flashing of liquid discharges. A control system is used to use temperature, flow, and pressure information to maintain desired operating conditions throughout the reactor.

[0051] In some embodiments, the present invention provides continuous, countercurrent processes of one or more stages for the fractionation of lignocellulosic biomass feedstock. Processes may include, for example, feeding biomass into the first stage of a pressurized reaction vessel, injecting

a first wash liquid into said first stage countercurrently to said biomass, discharging said first wash liquid from said first stage, optionally conveying said biomass into a second stage of said reaction vessel, injecting a second wash liquid into said second stage countercurrently to said biomass, discharging said second wash liquid from said second stage, optionally conveying said biomass into additional stages of said reaction vessel with provision for injecting and discharge wash liquids, and finally discharging a solid biomass product in slurry form. In some cases, one or more wash liquids are injected into the reaction vessel as two streams; a water rinse and a concentrated chemical reagent that mix to form the working wash liquid. The wash liquid for the first stage may be selected for optimal recovery of oils, proteins, and other extractives. Embodiments encompass multi-stage processing in which the wash liquid in one stage is water or a solution of water and a mineral acid to emphasize hydrolysis of hemicellulose, and the wash liquid in the following stage is a solution of water and a strong base such as sodium or ammonium hydroxide and may include 40 to 60% ethanol by weight to emphasize hydrolysis of lignin. The temperature in one or more stages may be maintained in the range 190° C. to 240° C.

[0052] In related embodiments, continuous, countercurrent systems of one or more stages for the fractionation of lignocellulosic biomass may include means for feeding said biomass into an elongated, pressurized reaction vessel, means for conveying said biomass through the length of said reaction vessel, means for discharging processed biomass from said reaction vessel, means for injecting a countercurrent flow of pressurized wash liquid into each stage of said reaction vessel, means for discharging wash liquid from each stage of said reaction vessel, means for separating liquids from solids prior to discharging wash liquids, means for maintaining desired temperatures in each stage of said reaction vessel, means for transferring heat from liquid being discharged to liquid being injected, means for controlling pressures throughout said reaction vessel such that boiling nowhere occurs, separate countercurrent flows are established in each stage where desired, and mixing of liquids between stages is minimized. A pressurized reaction vessel may include an elongated barrel accommodating twin screws for conveying the biomass, the screws being driven by a gearbox and motor. The length of the barrel and screws, the rotation rate of the screws, and the diameter of the screws may be determined by the number of stages, the time necessary for processing, and the biomass throughput desired. Systems may be configured to discharge liquid and solid slurry products by means of progressive cavity pumps operated in reverse to reduce pressure while avoiding clogging from liquid-solid separation. Liquids may be separated from solids prior to liquid discharge by means of small, twin-screw extruders operated so as to force solids back into the reaction vessel.

[0053] For various reasons (e.g. feedstock characteristics or economics) moving bed fractionation systems may not always provide an optimal or preferred solution. In such cases, a simulated moving bed (SMB) system may be used to implement the fractionation chemistry. An SMB system can be thought of as an actual moving bed system, such as previously described herein, that is physically divided into a series of segments (from one or two to up to more than a dozen for each stage of the process) within which the solids remain fixed. Liquid feed and discharge flows and liquid

flows between segments are then switched by valves from one segment to the next such that both the solids and liquids experience a time history similar to what would be experienced in an actual moving bed system. The larger the number of segments in each process stage, the more closely an SMB operation can match an actual moving bed system, but at an increasing capital investment cost. Reactor segments are loaded and unloaded sequentially to accompany the switching of liquid flows. One advantage of the SMB system is that reactor segments can be loaded and unloaded at atmospheric pressure and temperature thereby avoiding the shear forces and physical degradation encountered when solids must be injected, transported, and discharged under pressure in screw based, continuous flow apparatus. SMB fractionation systems are also advantageous because they have great versatility and flexibility in adapting to different feedstocks through computer-based reconfiguration. They also can make use of previously developed product discharge technology, and allow countercurrent operation in multiple stages with all the benefits such operation provides in terms of process control and product purity. What is more, SMB systems allow operation at lower temperatures and longer residence times such as may be needed to get sufficient chemical diffusion when processing large feedstock chips such as are customary in wood pulping. SMB system designs can be easily modified by addition of more reactor sections to provide for additional processing stages (e.g. more than two) as desired.

[0054] Turning now to the drawings, FIG. 1A is a schematic representation of a pressure controlled, multi-stage, twin-screw, countercurrent vessel or apparatus **20** according to one embodiment of the present invention. Although from one to many-stage processes may apply, this two-stage, countercurrent, biomass fractionation apparatus allows both the liquid flow rate and the pressure to be controlled in each of the two stages. FIG. 1B is a schematic representation of a cross section of this vessel **20** that includes an outer wall **1** for pressure containment (e.g. rated to at least 1000 psi). Additional reinforcement **2** is provided to aid in meeting the pressure rating. This reinforcement **2** also creates passages **3** that can be used to circulate fluid for temperature regulation. Within the pressure vessel **1** are overlapping twin screws **4** affixed to drive shafts **5**.

[0055] Embodiments of the present invention provide for the maintenance of independent countercurrent flows of liquid in each of the stages or processing zones. This can involve variable speed pumps with speed controllers that respond to signals from pressure or flow sensors. A multi-stage countercurrent system can have pressure differentials in each stage to drive the liquid flows, in addition to zones of constant pressure between stages to separate flows. FIG. 1A is a conceptual schematic of a two-stage system having a first stage **7** and a second stage **9**, including a solids feed **6** and a discharge **10**. In some embodiments, the entire system is maintained at an elevated pressure sufficient to prevent boiling of any liquids. Solids can be transported by twin screws, which can have a pitch equal to the screw diameter. The pitch of the screws can be shortened (e.g. by half) in the compression zone **8** to squeeze out some of the water and thereby minimize dilution of the second stage liquid product. A second compression zone (not shown) may be included as an option just before the solids discharge.

[0056] Liquid feed rate can be controlled by pumps as described above. In some cases, the first stage is a simple,

countercurrent water wash **16** with auto-catalyzed hemicellulose hydrolysis. The second stage ends with a countercurrent water rinse **13** before discharge of solids **10**. The countercurrently flowing rinse water is then augmented with countercurrently flowing ethanol and alkali **14** to mobilize lignin. The flow of liquid input **13**, **14**, and **16** is controlled by variable speed pressure pumps that are, in turn, controlled by flow sensors on these input lines with manual set points determined by the details of the chemistry desired. Solids discharge **10** from the second stage **9** may be controlled by a variable speed, positive displacement pump of the Moyno type whose speed is set manually to accommodate the solids feed (after processing) plus sufficient water to provide a manageable slurry. Liquid discharge from the second stage **15** is controlled by a second Moyno type pump with variable speed drive controlled by a pressure sensor **11** having an electrical output proportional to pressure. The pressure signal is compared to a manually set reference voltage. If the pressure is too high, the continuous Moyno speed is increased; if the pressure is too low, the Moyno speed is decreased. A small “dead zone” minimizes hunting. The reference pressure (voltage) is set manually to prevent boiling of the ethanol-water mixture at the highest temperature in the second stage. Liquid discharge **17** from the first stage is controlled by a third Moyno type pump with variable speed drive controlled by a differential pressure sensor **12** having a bi-polar electrical output proportional to the deviation from zero of the pressure differential across the compression zone **8**. This signal is then used to speed up or slow down the Moyno type pump. In some embodiments, the goal is to have no pressure differential across the compression zone, to prevent or inhibit liquid flow and mixing of liquids between the two stages. For applications involving additional chemical processing stages, the first stage configuration (including compression zone, pumps, and controls) can be replicated for each additional stage.

[0057] The twin-screw embodiment creates a moving bed of solids that is then subjected to countercurrent flows of liquid. The continuous solids feeder, the action of the screws, and the continuous pump discharge all act mechanically to degrade the physical structure of the feedstock. In some applications, this can be an advantage by promoting mixing and degradation action and increasing the rate of chemical reaction. In other applications, however, the breakdown of the fibrous biomass structure may be undesirable. In such cases, the advantages of multi-stage, countercurrent flow can be achieved by use of apparatus in which the moving bed of solids is simulated rather than actual. A simulated moving bed (SMB) system for biomass fractionation is similar to conventional SMB systems for separation of components of a liquid in the sense that there are multiple reactor sections (e.g. columns or barrels) and a complex array of valves to direct liquid flows. It differs however in that full fractionation occurs in a single pass and the “stationary phase” (biomass) is replaced at an appropriate place in the processing cycle rather than being regenerated.

[0058] FIG. 1C illustrates a layout plan view of a simulated moving bed biomass fractionation system **100** according to one embodiment of the present invention. Fractionation system **100** includes a common feedstock hopper **110** and four reactors **120**, **130**, **140**, and **150**. First reactor **120** includes a first fluid inlet port **122**, a first discharge port **124**, a first fluid outlet port **126**, and a first feedstock inlet port **128** that is coupled with common feedstock hopper **110**.

Second reactor **130** includes a second fluid inlet port **132**, a second discharge port **134**, a second fluid outlet port **136**, and a second feedstock inlet port **138** that is coupled with common feedstock hopper **110**. Third reactor **140** includes a third fluid inlet port **142**, a third discharge port **144**, a third fluid outlet port **146**, and a third feedstock inlet port **148** that is coupled with common feedstock hopper **110**. Fourth reactor **150** includes a fourth fluid inlet port **152**, a fourth discharge port **154**, a fourth fluid outlet port **156**, and a fourth feedstock inlet port **158** that is coupled with common feedstock hopper **110**. First fluid outlet port **126** is coupled with second fluid inlet port **132** via a second fluid passage **131**. Second fluid outlet port **136** is coupled with third fluid inlet port **142** via a third fluid passage **141**. Third fluid outlet port **146** is coupled with fourth fluid inlet port **152** via a fourth fluid passage **151**. Fourth fluid outlet port **156** is coupled with first fluid inlet port **122** via a first fluid passage **121**.

[0059] In the embodiment illustrated in FIG. 1C, first fluid inlet port **122** and first discharge port **124** are disposed toward a distal end **120a** of first reactor **120**, and first fluid outlet port **126** and first feedstock inlet port **128** are disposed toward a proximal end **120b** of first reactor **120**. Second fluid inlet port **132** and second discharge port **134** are disposed toward a distal end **130a** of second reactor **130**, and second fluid outlet port **136** and second feedstock inlet port **138** are disposed toward a proximal end **130b** of second reactor **130**. Third fluid inlet port **142** and third discharge port **144** are disposed toward a distal end **140a** of third reactor **140**, and third fluid outlet port **146** and third feedstock inlet port **148** are disposed toward a proximal end **140b** of third reactor **140**. Fourth fluid inlet port **152** and fourth discharge port **154** are disposed toward a distal end **150a** of fourth reactor **150**, and fourth fluid outlet port **156** and fourth feedstock inlet port **158** are disposed toward a proximal end **150b** of fourth reactor **150**. Simulated moving bed biomass fractionation system **100** also includes a first motor **125**, a second motor **135**, a third motor **145**, and a fourth motor **155**.

[0060] FIG. 2 shows a schematic of an exemplary reaction section **200** of a simulated moving bed biomass fractionation system according to one embodiment of the present invention. Reaction section **200** can include any suitable combination of passages, inlet valves, discharge valves, reagent valves, water valves, vents, thermal units, motors, and the like. In the embodiment shown here, reaction section **200** includes a first fluid passage **201** and a thermal unit **202**. In this embodiment, thermal unit **202** includes a tube-in-tube heat exchanger **203** having a heat exchange inlet valve **204** and a heat exchange outlet valve **206**. Reaction section **200** also includes fluid inlet valves such as a warm water valve **208** and a cold water valve **210**, a fluid inlet port **212**, a motor **214** having a screw drive **216** and a screw positioning system **218**, a reactor **220**, a discharge port **222**, a vacuum stuffer **224** (to separate solids from discharged liquid), a ball valve **225**, a feedstock inlet port **226** coupled with a feedstock hopper (not shown), and a fluid outlet port **228**. Reaction section **200** also includes a stage 1 liquid discharge valve **230**, a stage 2 liquid discharge valve **232**, a cold water valve **234**, an air vent **236**, a base reagent valve **238**, an acid reagent valve **240**, a hot water valve **242**, a passage valve

244, and a second fluid passage **246**. In some embodiments, a simulated moving bed biomass fractionation system may also include a computer **248** or other control means in operative association with the thermal unit or any of the valves, vents, motor components, or other reaction section elements, where the computer includes or is configured to implement instructions for regulating these elements as desired. A simulated moving bed fractionation system can include any desired number of reaction sections. As shown here, reaction section **200** can be coupled with an adjoining reaction section **270**. Each of the sections in a simulated moving bed biomass fractionation system may be plumbed identically. The simulated moving bed can be created by changing the settings, for example via computer control, of the numerous valves and by sequential activation of other features.

[0061] In some embodiments, the present invention provides a simulated moving bed system of one or more stages for the countercurrent fractionation of lignocellulosic biomass. The system may include a plurality of elongated pressurized reactors interconnected with plumbing for controlling and directing fluid flows, means for sequential loading of the reactors with biomass feedstock and for sequential unloading of processed biomass, means for injecting countercurrently pressurized wash liquid into each stage of the simulated moving bed system, means for discharging wash liquid from each stage of the simulated moving bed system, means for separating liquids from solids prior to discharging wash liquids and transferring wash liquids between reactors, means for maintaining desired temperatures in each reactor of said simulated moving bed system, means for transferring heat from liquid being discharged to liquid being injected, means for controlling pressures to prevent boiling and to maintain desired liquid flows throughout the SMB system, and means for sequential switching of valves to create the desired countercurrent, moving bed simulation. Biomass feedstock can be loaded into reactors by means of one or more augers and processed biomass can be unloaded by slurring and washing with water. In some instances, biomass feedstock may be loaded into and unloaded from reactors while contained in full-length baskets. Liquid products can be discharged by means of progressive cavity pumps operated in reverse to reduce pressure while avoiding clogging from liquid-solid separation. Liquids can be separated from solids prior to liquid discharge by means of small, twin-screw extruders operated so as to force solids back into the reactors. In some cases, an electronic computer can be used to configure an SMB for a particular application and to automate the sequential switching of valves.

[0062] FIG. 3 provides a schematic view of a reaction section **300** having valves **1'-13'**. The valves shown in FIG. 3 correspond to certain reaction section elements of FIG. 2 as described in Table 4 below.

TABLE 4

Valve Number (of FIG. 3)	Reaction Section Element (of FIG. 2)
valve 1'	cold water valve 210
valve 2'	warm water valve 208
valve 3'	hot water valve 242
valve 4'	heat exchange inlet valve 204
valve 5'	acid reagent valve 240
valve 6'	base reagent valve 238
valve 7'	passage valve 244
valve 8'	stage 1 liquid discharge valve 230
valve 9'	stage 2 liquid discharge valve 232
valve 10'	discharge port 222
valve 11'	ball valve 225
valve 12'	cold water valve 234
valve 13'	air vent 236

[0063] In the FIG. 3 schematic, simple shutoff valves are shown for clarity and ease of description. Embodiments of the present invention also encompass fractionation systems having multi-port valves as well, which may reduce the number of valve units. FIG. 4 shows a layout plan of an exemplary simulated moving bed biomass fractionation system **400** having eighteen reaction sections **401-418** arranged in a radial constellation similar to that shown in FIG. 1C, such that the distal end of each of the reactors is coupled with and radiates from a common feedstock hopper **419**. Each of the reaction sections includes a screw and drive, and each section is linked to an adjoining section, for example via liquid discharge units to the outer ends of the barrels. Hoppers can receive finished solid product. Valves, connections to common features, and other details are not shown in this simplified layout view. In practice, the barrels of the SMB system can be mounted vertically around the central feed hopper. The horizontal arrangement shown here is merely for clarity in illustrating the interconnections, which may be vertical, horizontal, or any combination thereof. In some embodiments, each of the repeating sections is identical. Operation of fractionation system **400** can be described in terms of sequential valve settings for various valves in the reaction sections as provided in Table 5. Thus, the simulated moving bed can be created by changing the settings of the various valves and activating other features. Often, operation of these system components is controlled by a computer. Although only three steps are shown, it is appreciated that a fractionation progression can be continued for any number of steps.

TABLE 5

Section No. (of FIG. 4) Step No.			Valve No. (of FIG. 3)												Action
1	2	3	1'	2'	3'	4'	5'	6'	7'	8'	9'	10'	11'	12'	
401	418	417	C	C	C	C	C	C	C	C	C	C	O	C	Load Feedstock
402	401	418	C	O	C	C	C	C	C	C	C	C	C	C	Soak Feedstock
403	402	401	C	C	C	O	C	C	C	O	C	C	C	C	Stage 1 Liquid Discharge
404	403	402	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Fractionation
405	404	403	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Fractionation
406	405	404	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Fractionation
407	406	405	C	C	C	O	O	C	O	C	C	C	C	C	Stage 1 Reagent In
408	407	406	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Rinse
409	408	407	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Rinse
410	409	408	C	C	O	O	C	C	C	C	O	C	C	C	Stage 2 Liquid Discharge
411	410	409	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Fractionation
412	411	410	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Fractionation
413	412	411	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Fractionation
414	413	412	C	C	C	O	C	O	O	C	C	C	C	C	Stage 2 Reagent In
415	414	413	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Rinse
416	415	414	C	C	C	O	C	C	O	C	C	C	C	C	Counter-Flow Rinse
417	416	415	O	C	C	C	C	C	O	C	C	C	C	C	Stage 2 Cold Rinse In
418	417	416	C	C	C	C	C	C	C	C	C	O	C	O	Cellulose Discharge

[0064] Table 5 describes the action occurring in each reaction section and the settings of the valves in each reaction section at each step. The valves can be described as open (O) or closed (C). The valve settings for each step can be maintained for any desired period of time. For example, Step 1 may involve maintaining valve settings for a period of three minutes. Similar time periods may be maintained for Step 2, Step 3, and so on. This progression may be continued continuously, or for any desired length of time or number of steps. With reference to FIG. 4, the reaction sections can be numbered clockwise in accordance to with “Step 1” in Table 5. In an exemplary lignocellulosic feedstock processing method embodiment, Step 1 involves loading feedstock into reaction section 401, carrying out various processing steps in reaction sections 402-417, and discharging cellulose from reaction section 418. Step 2 involves loading feedstock into reaction section 418, carrying out various processing steps in reaction sections 401-416, and discharging cellulose from reaction 417, and so on. A detailed status of each of the reaction sections (401-418) at Step 1 can be described as follows, where specific elements of the reaction sections are described by reference numerals as provided in FIGS. 2 and 3. It is appreciated that in some embodiments, each of the reaction sections is identical. The description below discusses a sequential processing of the feedstock, following the solids in a clockwise manner through the fractionation system. Typically, however, all section descriptions occur simultaneously or in parallel in the various reaction sections of the fractionation system.

[0065] Step 1: Reaction Section 401—Load Feedstock: When loading feedstock from the common feedstock hopper into reactor 220, an adjustable closure such as a ball valve 225 (valve 11'), which typically has an inner diameter that matches an inner diameter of the reactor, is opened to create a passage between the feedstock hopper and reactor 220. All other valves are closed, so that no other materials are introduced into reactor 220. Screw drive 216 is turned on to enable screw penetration, and screw positioning system 218 pushes at least a portion of a screw or threaded shaft (not

shown) into the feedstock hopper. The screw continues to turn and draws feedstock from the hopper into reactor 220. After an appropriate time, the screw rotation is stopped and screw positioning system 218 withdraws the screw from the hopper back into reactor 220. Ball valve 225 is then closed.

[0066] In an alternative vertical configuration, feedstock can be loaded into baskets (e.g. in a loading operation external to the simulated moving bed) to be inserted into the reactors by opening and then closing covers on the reactors. At the end of processing, the cover can be opened, the basket of finished product removed, and a new basket of feedstock inserted, in an endless cycle. In some embodiments, ball valves, screws, motors, or positioning units may not be included or involved.

[0067] Step 1: Reaction Section 402—Soak Feedstock: Warm water valve 208 (valve 2') and air vent 236 (valve 13') are opened and reactor 220 of reaction section is filled with warm or heated water which mixes with the feedstock. In some embodiments, air vent 236 may include a liquid sensor that can trigger closure of valve 208 and vent 236. Optionally, warm water can be obtained via a heat exchange process involving liquid discharge originating from reaction section 403.

[0068] Step 1: Reaction Section 403—Stage 1 Liquid Discharge: Stage 1 liquid discharge valve 230 (valve 8') is opened to allow stage 1 liquid discharge (e.g. with mobilized biomass constituents including extractives and hemicellulose) to exit reactor 220. Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction section 404 as it passes through thermal unit 202. In some embodiments, heat exchange inlet valve 204 may be coupled with a steam source. Optionally, operation of heat exchange inlet valve 204 may be modulated with a thermocouple control. In one example, the temperature of contents passing through thermal unit 202 are heated to a temperature of about 2300C. It may be desirable to avoid high pressure regulatory requirements. For example, in some embodiments pressure is maintained below 600 psi. Relatedly, the temperature of reactors con-

taining ethanol may be limited to 220° C. or lower. Other reactors may operate at 230° C. or more to meet chemical processing requirements, limited primarily by destructive degradation of the material being processed. Prior to solid product discharge, a reactor is often cooled below 100° C. to avoid flashing. This cooling can be accomplished with full recovery of heat values by countercurrent rinsing with cold water in the step just prior to discharge. The screw motor can be started in an oscillating mode, to provide a turning of the screw. In some embodiments, this may involve, for example, a turn or two of the screw in one direction and a turn or two in the other direction, for perhaps a duration of two seconds in each direction. This action can generate some stirring and can prevent channeling or uneven fluid flow at certain points within reactor 220. A steam jacket or other thermal device may be coupled with reactor 220 or any other appropriate element of the fractionation system to achieve a desired temperature control.

[0069] Step 1: Reaction Section 404—Countercurrent Fractionation: Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction section 405. Passage valve 244 (valve 7') is opened to provide countercurrent fractionate from reactor 220 to the adjacent reaction section 403. In some embodiments, this countercurrent fractionate comprises hemicellulose. The term countercurrent or counter-flow can be used to describe the flow of fractionate from a reactor containing more processed solids into a reactor containing less processed solids. Specifically, feedstock is passed from the common feedstock hopper into reactor 220 in a radially outward direction, via feedstock inlet port 226, passing from proximal end 220b toward distal end 220a of reactor 220. In contrast, fractionate from section 404 passes into reactor 220 in a radially inward direction, via fluid inlet port 212, passing from distal end 220a toward proximal end 220b of reactor 220.

[0070] Step 1: Reaction Sections 405 and 406—Countercurrent Fractionation: All valves retain their settings. Heat exchange inlet valve 204 (valve 4') of reaction section 405 is opened so as to heat material that is being transferred from reaction section 406. Passage valve 244 (valve 7') of reaction section 405 is opened to provide countercurrent fractionate from reaction section 405 to reaction section 404. In some embodiments, the fractionate may contain hemicellulose. Heat exchange inlet valve 204 (valve 4') of reaction section 406 is opened so as to heat material that is being transferred from reaction section 407. Passage valve 244 (valve 7') of reaction section 406 is opened to provide countercurrent fractionate from reaction section 406 to reaction section 405. In some embodiments, the fractionate may contain hemicellulose. More reaction sections can be added here with the same valve settings if desired for additional processing.

[0071] Step 1: Reaction Section 407—Reagent Feed: Acid reagent valve 240 (valve 5') may be opened to provide acid or another reagent to enhance hydrolysis in countercurrent fractionation reaction sections 406, 405, and 404. Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction section 408. Passage valve 244 (valve 7') is opened to provide transfer of material to adjacent reaction section 406. The contents of this material, in some cases, is similar to that as described above except that it contains less hemicellulose and more acid. In some embodiments, the acid reagent has a pH within

the range from about 2 to about 4. In some embodiments, the acid reagent has a temperature within the range from about 210° C. to about 230° C.

[0072] Step 1: Reaction Section 408—Countercurrent Rinse: Acid reagent valve 240 (valve 5') is closed. Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction section 409. Passage valve 244 (valve 7') is opened to provide transfer of material to adjacent reaction section 407. In some cases, this involves a water rinse that contains residues from what was section 408 in the previous step. All other valves retain their settings for a countercurrent rinse.

[0073] Step 1: Reaction Section 409—Countercurrent Rinse: Passage valve 244 (valve 7') is opened to provide transfer of material to adjacent reaction section 408. In some cases, this involves a water rinse that contains residues from what was section 409 in the previous step. All valves retain their settings as the countercurrent rinse continues. Heat exchange inlet valve 204 (valve 4') may be opened, and water coming from valve 3 of section 410 can be heated. Although valve 3' is for “hot” water, in some cases this water may not be hot enough for the desired process.

[0074] Step 1: Reaction Section 410—Stage 2 Liquid Discharge: Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction section 411. Passage valve 244 (valve 7') is closed, thus preventing passage of material to reaction section 409. Hot water valve 242 (valve 3') is opened to provide Stage 1 rinse flow (replacing valve 7' flow). With valve 7' closed, water can pass to the previous section 409. Stage 2 liquid discharge valve 232 (valve 9') is opened to allow stage 2 liquid discharge, which may contain for example primarily lignin in addition to stage 2 wash chemicals, to exit reactor 220.

[0075] Step 1: Reaction Section 411—Countercurrent Fractionation: Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction section 412. Hot water valve 242 (valve 3') and Stage 2 liquid discharge valve 232 (valve 9') are closed. Passage valve 244 (valve 7') is opened to provide transfer of countercurrent fractionate to adjacent reaction section 410. This fractionate may contain, for example, primarily lignin along with stage 2 wash chemicals. Progressing from section 410 through section 413, the lignin concentration may become lower and the chemical concentration may become higher.

[0076] Step 1: Reaction Sections 412 and 413—Countercurrent Fractionation: All valves retain their settings as fractionation continues. Heat exchange inlet valve 204 (valve 4') of reaction section 412 is opened so as to heat material that is being transferred from reaction section 413. Passage valve 244 (valve 7') of reaction section 412 is opened to provide countercurrent fractionate from reaction section 412 to reaction section 411. Heat exchange inlet valve 204 (valve 4') of reaction section 413 is opened so as to heat material that is being transferred from reaction section 414. Passage valve 244 (valve 7') of reaction section 413 is opened to provide countercurrent fractionate from reaction section 413 to reaction section 412. More reaction sections can be added here with the same valve settings if desired for additional processing.

[0077] Step 1: Reaction Section 414—Stage 2 Reagent Feed: Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction

section 415. Passage valve 244 (valve 7') is opened to provide transfer of material to adjacent reaction section 413. Base reagent valve 238 (valve 6') is opened to provide alkali or another reagent for Stage 2 processing in the countercurrent fractionation reaction sections 413, 412, and 411. In some embodiments, the alkali or base reagent has a pH within the range from about 8 to about 13. In some embodiments, the base reagent has a temperature within the range from about 180° C. to about 240° C. In some cases, the maximum may be about 220° C. when 50% ethanol is used.

[0078] Step 1: Reaction Section 415—Countercurrent Rinse: Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction section 416. Passage valve 244 (valve 7') is opened to provide transfer of material to adjacent reaction section 414. This may involve a water rinse that contains residues from section 414 in the previous step. Base reagent valve 238 (valve 6') is closed. All other valves retain their settings for a countercurrent rinse.

[0079] Step 1: Reaction Section 416—Countercurrent Rinse: Heat exchange inlet valve 204 (valve 4') is opened so as to heat material that is being transferred from reaction section 417. Passage valve 244 (valve 7') is opened to provide transfer of material to adjacent reaction section 415. This may involve the continued washing out of residual chemicals. All other valves retain their settings as the countercurrent rinse continues.

[0080] Step 1: Reaction Section 417—Stage 2 Cold Water Rinse In: Passage valve 244 (valve 7') is opened to provide transfer of material to adjacent reaction section 416. Heat exchange inlet valve 204 (valve 4') is closed so as to reduce the temperature in reactor 220. Cold water valve 210 (valve 1') is opened allowing cool water to enter and cool reactor 220, in preparation for the cellulose discharge. At the same time, this water is heated for energy recuperation and further use in the Stage 2 counter-flow rinse. In some cases, as the cold water flows into the section, the hot water in the section is forced out the other end as rinse for section 416. At the same time, the cold water is cooling the solids and being warmed. This process may continue, for example, until the temperature at the top or inner section of section 417 falls below 100° C.

[0081] Step 1: Reaction Section 418—Cellulose Discharge: Passage valve 244 (valve 7') to reaction section 417 is closed to retain pressure downstream. Discharge port 222 (valve 10') is opened to discharge cellulose product from reactor 220. Cold water valve 234 (valve 12') is opened to flush the cellulose with cold water. The screw drive is activated to move cellulose toward discharge port 222. In some embodiments, cold water valve 210 (valve 1') is opened for additional washing action. At the end of the cellulose discharge period, reactor 220 can be emptied and made available for filling with feedstock in Step 2.

[0082] In some embodiments, a vacuum stuffer operates at all times except when a section is being emptied and filled. The vacuum stuffer can retain solids within a section while allowing liquid to discharge. In a vertical configuration using a basket system for filling, a vacuum stuffer may be replaced by a large, washable filter.

[0083] In one embodiment, a simulated moving bed fractionation system includes reactors having an inside diameter of 4 inches and a length of 80 inches (L/D=20). The empty volume of an individual reactor of the system is about 1000 cubic inches, less the screw volume or about 0.5 cubic feet

or about 14 liters. The bulk density of corn stover, a source of cellulose, is about 76 grams per liter. Thus, a single reaction section will contain about one kilogram of corn stover feedstock. If the SMB is on a two minute cycle, this would result in a processing throughput of about 720 kilograms of corn stover per day, or about 0.8 English tons per day. With the reactor utilization shown in Table 5, a two minute cycle time would give about 8 minutes of maximum severity processing (for example sections 404-407 and 411-414) in each of the two stages. In contrast, a 100 ton/day commercial system with an L/D of 20 and the same two minute cycle time would require reactor sections of about 20 inches in diameter and 400 inches (33.3 feet) long. This illustrates the feasibility of a simulated moving bed system for scale-up to a small commercial configuration having similar proportions and reaction times. Although an L/D of 20 may be arbitrary, a slender reaction vessel may have advantages in handling expected pressures and minimizing undesirable mixing and channeling of the countercurrent liquid flow.

[0084] Having described several embodiments, it will be recognized by those of skill in the art that various modifications, alternative constructions, and equivalents may be used without departing from the spirit of the invention. Additionally, a number of well known processes and elements have not been described in order to avoid unnecessarily obscuring the present invention. Accordingly, the above description should not be taken as limiting the scope of the invention.

[0085] Where a range of values is provided, it is understood that each intervening value, to the tenth of the unit of the lower limit unless the context clearly dictates otherwise, between the upper and lower limits of that range is also specifically disclosed. Each smaller range between any stated value or intervening value in a stated range and any other stated or intervening value in that stated range is encompassed. The upper and lower limits of these smaller ranges may independently be included or excluded in the range, and each range where either, neither or both limits are included in the smaller ranges is also encompassed within the invention, subject to any specifically excluded limit in the stated range. Where the stated range includes one or both of the limits, ranges excluding either or both of those included limits are also included.

[0086] As used herein and in the appended claims, the singular forms “a”, “an”, and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a process” includes a plurality of such processes and reference to “the electrode” includes reference to one or more electrodes and equivalents thereof known to those skilled in the art, and so forth.

[0087] Also, the words “comprise,” “comprising,” “include,” “including,” and “includes” when used in this specification and in the following claims are intended to specify the presence of stated features, integers, components, or steps, but they do not preclude the presence or addition of one or more other features, integers, components, steps, acts, or groups.

What is claimed is:

1. A continuous, countercurrent process of one or more stages for the fractionation of a lignocellulosic biomass feedstock, comprising:

feeding the biomass feedstock into a first stage of a pressurized reaction vessel;

injecting a first wash liquid into the first stage counter-currently to the biomass feedstock;
 discharging the first wash liquid from the first stage; and
 discharging a solid biomass product from the reaction vessel in slurry form.

2. The process of claim 1, further comprising conveying a first stage biomass product from the first stage to a second stage of the reaction vessel, injecting a second wash liquid into the second stage countercurrently to the first stage biomass product, and discharging the second wash liquid from the second stage.

3. The process of claim 1, wherein the first wash liquid comprises water or a solution of water and a mineral acid for hemicellulose hydrolysis, and the second wash liquid comprises water and a sodium or ammonium hydroxide base for lignin hydrolysis.

4. The process of claim 3, wherein the second wash liquid comprises about 40% to about 60% ethanol by weight.

5. The process of claim 1, wherein the first wash liquid comprises a water rinse and a concentrated chemical reagent that mix to form the first wash liquid.

6. The process of claim 1, wherein the first wash liquid provides optimal recovery of oils, proteins, and other extractions.

7. The process of claim 1, further comprising maintaining a temperature of at least one of the stages in a range from about 190° C. to about 240° C.

8. A continuous, countercurrent system of one or more stages for the fractionation of a lignocellulosic biomass, the system comprising:

- means for feeding the biomass into an elongated, pressurized reaction vessel;
- means for conveying the biomass through the length of the reaction vessel;
- means for discharging a processed biomass from the reaction vessel;
- means for injecting a counter-flow of pressurized wash liquid into each stage of the reaction vessel;
- means for discharging the wash liquid from each stage of the reaction vessel;
- means for separating liquids from solids in each stage of the reaction vessel prior to discharging the wash liquid;
- means for maintaining a desired temperature in each stage of the reaction vessel;
- means for transferring heat from the liquid being discharged to the liquid being injected; and
- means for controlling pressure throughout each stage of the reaction vessel such that boiling nowhere occurs, separate countercurrent flows are established in each stage where desired, and mixing of liquids between stages is minimized.

9. The system of claim 8, wherein the pressurized reaction vessel comprises an elongated barrel accommodating twin screws for conveying the biomass, the screws being driven by a gearbox and motor.

10. The system of claim 8, wherein the means for discharging a processed biomass from the reaction vessel comprises a processed biomass discharge progressive cavity pump configured to reduce pressure while avoiding clogging from liquid-solid separation, and the means for discharging the wash liquid from each stage of the reaction vessel comprises a wash liquid discharge progressive cavity pump configured to reduce pressure while avoiding clogging from liquid-solid separation.

11. The system of claim 8, wherein the means for separating liquids from solids in each stage of the reaction vessel prior to discharging the wash liquid comprises at least one twin-screw extruder configured to force solids back into the reaction vessel.

12. A simulated moving bed (SMB) system of one or more stages for the countercurrent fractionation of lignocellulosic biomass, the system comprising:

a plurality of elongated, pressurized reactors interconnected with a plumbing system for controlling and directing one or more fluid flows;

means for sequential loading of the plurality of reactors with a biomass feedstock and for sequential unloading of a processed biomass;

means for injecting countercurrently a pressurized wash liquid into each stage of the simulated moving bed system;

means for discharging the wash liquid from each stage of the simulated moving bed system;

means for separating liquids from solids prior to discharging the wash liquid and transferring the wash liquid between reactors;

means for maintaining a desired temperature in each of the plurality of reactors of the simulated moving bed system;

means for transferring heat from the wash liquid being discharged to the wash liquid being injected;

means for controlling a pressure in each of the plurality of reactors to prevent boiling and to maintain a desired liquid flow throughout the simulated moving bed system; and

means for sequential switching of a plurality of valves to create a desired countercurrent, moving bed simulation.

13. The system of claim 12, wherein the means for sequential loading of the plurality of reactors with a biomass feedstock and for sequential unloading of a processed biomass comprises:

one or more augers configured to load the biomass feedstock into the plurality of reactors; and

means for slurring and washing out the processed biomass with water.

14. The system of claim 12, wherein the means for sequential loading of the plurality of reactors with a biomass feedstock and for sequential unloading of a processed biomass comprises a plurality of baskets.

15. The system of claim 12, wherein the means for discharging the wash liquid from each stage of the SMB comprises a wash liquid discharge progressive cavity pump configured to reduce pressure while avoiding clogging from liquid-solid separation.

16. The system of claim 12, wherein the means for separating liquids from solids in each stage of the SMB prior to discharging the wash liquid comprises at least one twin-screw extruder configured to force solids back into the reaction vessel.

17. The system of claim 12, wherein the means for sequential switching of a plurality of valves to create a desired countercurrent, moving bed simulation comprises an electronic computer.

18. The system of claim 12, wherein the plumbing system for controlling and directing one or more fluid flows comprises a first reactor outlet port coupled with a second reactor inlet port.

19. The system of claim **18**, wherein the first reactor outlet port is coupled with the second reactor inlet port via a heat exchanger.

20. The system of claim **12**, wherein the means for sequential loading of the plurality of reactors with a biomass

feedstock and for sequential unloading of a processed biomass comprises a common feedstock hopper in operative association with the plurality of elongated, pressurized reactors.

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