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(54) **Title:** REDUCING ETHYL ACETATE CONCENTRATION IN RECYCLE STREAMS FOR ETHANOL PRODUCTION PROCESSES

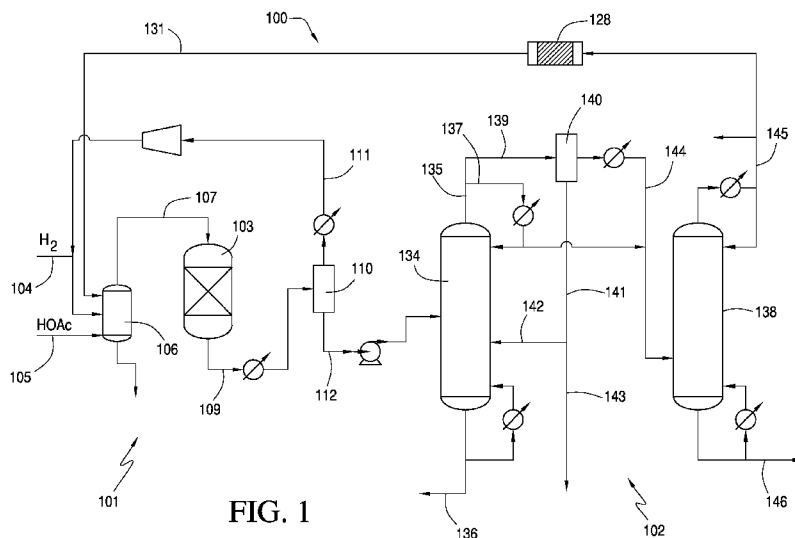


FIG. 1

(57) **Abstract:** Recycle streams in an ethanol production process are hydrolyzed to reduce ethyl acetate concentration. In the process, acetic acid is hydrogenated to form a crude ethanol product, which undergoes a separation or purification process. Ethyl acetate is formed as a byproduct of the hydrogenation of acetic acid. The hydrolysis of recycle streams from the separation process can reduce the concentration of ethyl acetate, converting some or all of the ethyl acetate to acetic acid and ethanol.

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REDUCING ETHYL ACETATE CONCENTRATION IN RECYCLE STREAMS FOR ETHANOL PRODUCTION PROCESSES

PRIORITY CLAIM

[0001] This application claims priority to U.S. App. No. 13/339,872, filed on December 29, 2011, U.S. App. No. 13/094,588, filed on April 26, 2011, and U.S. App. No. 13/094,657, filed on April 26, 2011, the entireties of which are incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates generally to processes for producing ethanol and, in particular, to reducing ethyl acetate concentration in recycle streams, preferably by hydrolysis.

BACKGROUND OF THE INVENTION

[0003] Ethanol for industrial use is conventionally produced from organic feed stocks, such as petroleum oil, natural gas, or coal, from feed stock intermediates, such as syngas, or from starchy materials or cellulose materials, such as corn or sugar cane. Conventional methods for producing ethanol from organic feed stocks, as well as from cellulose materials, include the acid-catalyzed hydration of ethylene, methanol homologation, direct alcohol synthesis, and Fischer-Tropsch synthesis. Instability in organic feed stock prices contributes to fluctuations in the cost of conventionally produced ethanol, making the need for alternative sources of ethanol production all the greater when feed stock prices rise. Starchy materials, as well as cellulosic materials, are converted to ethanol by fermentation. However, fermentation is typically used for consumer production of ethanol, which is suitable for fuels or human consumption. In addition, fermentation of starchy or cellulosic materials competes with food sources and places restraints on the amount of ethanol that can be produced for industrial use.

[0004] Ethanol production via the reduction of alkanolic acids and/or other carbonyl group-containing compounds has been widely studied, and a variety of combinations of catalysts, supports, and operating conditions have been mentioned in the literature. During the reduction of alkanolic acid, e.g., acetic acid, other compounds are formed with ethanol or are formed in side reactions. These impurities limit the production and recovery of ethanol from such reaction mixtures. For example, during hydrogenation, esters are produced that together with ethanol

and/or water form azeotropes, which are difficult to separate. In addition when conversion is incomplete, unreacted acid remains in the crude ethanol product, which must be removed to recover ethanol.

[0005] EP02060553 describes a process for converting hydrocarbons to ethanol involving converting the hydrocarbons to ethanoic acid and hydrogenating the ethanoic acid to ethanol. The stream from the hydrogenation reactor is separated to obtain an ethanol product and a stream of acetic acid and ethyl acetate, which is recycled to the hydrogenation reactor.

[0006] US Pat. No. 7,842,844 describes a process for improving selectivity and catalyst activity and operating life for the conversion of hydrocarbons to ethanol and optionally acetic acid in the presence of a particulate catalyst, said conversion proceeding via a syngas generation intermediate step.

[0007] Therefore, a need remains for improving the recovery of ethanol from a crude product obtained by reducing alkanolic acids, such as acetic acid, and/or other carbonyl group-containing compounds.

SUMMARY OF THE INVENTION

[0008] In a first embodiment, the present invention is directed to a process for producing ethanol, comprising hydrogenating an acetic acid and ethyl acetate stream in a reactor in the presence of a catalyst to form a crude ethanol product, and separating a portion of the crude ethanol product in a first distillation column to yield a first distillate comprising ethyl acetate and acetaldehyde, and a first residue comprising ethanol, ethyl acetate, acetic acid and water. Preferably, the first residue comprises a majority of the ethanol, acetic acid, and water from the crude ethanol product. The process further comprises separating a portion of the first residue in a second distillation column to yield a second residue comprising acetic acid and water and a second distillate comprising ethanol and ethyl acetate, separating a portion of the second distillate in a third distillation column to yield a third residue comprising ethanol and a third distillate comprising ethyl acetate, and hydrolyzing, preferably in the presence of a strongly acidic heterogeneous or homogeneous catalyst, at least a portion of the first distillate or third distillate to form a hydrolyzed stream. In one embodiment, the first distillate and/or third distillate may be condensed and the hydrolysis is carried out in the liquid phase. The process further comprises forming a hydrolyzed stream, comprising acetic acid and ethanol, from the

first distillate and/or third distillate. The molar ratio of water to ethyl acetate in the hydrolyzed stream may be at least 1:10. When the first distillate and/or third distillate is hydrolyzed, the hydrolyzed stream may be introduced, directly or indirectly, to the reactor or first column. In one embodiment, a portion of both the first distillate and third distillate are hydrolyzed.

[0009] In another embodiment, a portion of the water may be removed from the second distillate using a water removal unit selected from the group consisting of adsorption unit, membrane, molecular sieves, extractive column distillation, and combinations thereof.

[0010] In an optional embodiment, the first column may be an extractive agent. The extractive agent may be water, which is preferably obtained from a portion of the second residue.

[0011] In a second embodiment, the present invention is directed to a process for producing ethanol, comprising hydrogenating an acetic acid and ethyl acetate stream in a reactor in the presence of a catalyst to form a crude ethanol product, separating a portion of the crude ethanol product in a first distillation column to yield a first distillate comprising ethyl acetate and acetaldehyde, and a first residue comprising ethanol, ethyl acetate, acetic acid and water, wherein the first residue comprises a majority of the ethanol, acetic acid, and water from the crude ethanol product, separating a portion of the first residue in a second distillation column to yield a second residue comprising acetic acid and water and a second distillate comprising ethanol and ethyl acetate, separating a portion of the second distillate in a third distillation column to yield a third residue comprising ethanol and a third distillate comprising ethyl acetate, and hydrolyzing, preferably in the presence of a strongly acidic heterogeneous or homogenous catalyst, at least a portion of the first distillate to form a hydrolyzed stream that is introduced to the reactor.

[0012] In a third embodiment, the present invention is directed to a process for producing ethanol, comprising hydrogenating an acetic acid and ethyl acetate stream in a reactor in the presence of a catalyst to form a crude ethanol product, separating a portion of the crude ethanol product in a first distillation column to yield a first distillate comprising ethyl acetate and acetaldehyde, and a first residue comprising ethanol, ethyl acetate, acetic acid and water, wherein the first residue comprises a majority of the ethanol, acetic acid, and water from the crude ethanol product, separating a portion of the first residue in a second distillation column to yield a second residue comprising acetic acid and water and a second distillate comprising ethanol and ethyl acetate, separating a portion of the second distillate in a third distillation column to yield a third residue comprising ethanol and a third distillate comprising ethyl acetate, and hydrolyzing,

preferably in the presence of a strongly acidic heterogeneous or homogenous catalyst, at least a portion of the third distillate to form a hydrolyzed stream that is introduced to the first column.

[0013] In a fourth embodiment, the present invention is directed to a process for producing ethanol, comprising hydrogenating an acetic acid and ethyl acetate stream in a reactor in the presence of a catalyst to form a crude ethanol product, separating at least a portion of the crude ethanol product in a first distillation column to yield a first residue comprising acetic acid and a first distillate comprising ethanol, ethyl acetate, and water, removing water from at least a portion of the first distillate to yield an ethanol mixture stream comprising less than 10 wt.% water, separating a portion of the ethanol mixture stream in a second distillation column to yield a second residue comprising ethanol and a second distillate comprising ethyl acetate, and hydrolyzing at least a portion of the second distillate to form a hydrolyzed stream.

[0014] In a fifth embodiment, the present invention is directed to a process for producing ethanol, comprising hydrogenating an acetic acid and ethyl acetate stream in a reactor in the presence of a catalyst to form a crude ethanol product, separating a portion of the crude ethanol product in a first distillation column to yield a first distillate comprising ethyl acetate, and a first residue comprising ethanol, ethyl acetate, acetic acid and water, hydrolyzing at least a portion of the first distillate to form a hydrolyzed stream, and recovering ethanol from the first residue.

BRIEF DESCRIPTION OF DRAWINGS

[0015] The invention may be more completely understood in consideration of the following detailed description of various embodiments of the invention in connection with the accompanying drawings, wherein like numerals designate similar parts.

[0016] FIG. 1 is a schematic diagram of an ethanol production system having one or more hydrolysis units for a two column distillation system having an intervening water removal in accordance with one embodiment of the present invention.

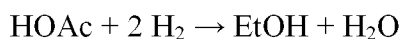
[0017] FIG. 2 is a schematic diagram of an ethanol production system having one or more hydrolysis units for a two column distillation system in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0018] In general, the present invention relates to processes for recovering ethanol produced by hydrogenating acetic acid in the presence of a catalyst. The hydrogenation reaction produces a crude ethanol product that comprises ethanol, water, ethyl acetate, acetic acid, and other impurities. Water is co-produced with ethanol in the hydrogenation reaction in about a 1:1 molar ratio, and thus producing ethanol also results in the production of water. This makes recovering industrial grade ethanol or fuel grade ethanol difficult due to the excess water. The present invention relates generally to processes in ethanol production systems wherein a recycle stream is hydrolyzed to reduce the ethyl acetate concentration. The hydrolysis of ethyl acetate may produce acetic acid and ethanol. Embodiments of the present invention preferably maximize ethanol yields and may also reduce waste streams that are purged from the system.

[0019] In embodiments of the present invention, ethyl acetate is formed as a byproduct and is recycled to a reactor having a catalyst that can convert both acetic acid and ethyl acetate to ethanol. Preferably, the process introduces fresh acetic acid and recycled ethyl acetate to the reactor. Depending on the reactor conditions, there may be more ethyl acetate than is desired in the reactor due to the production of ethyl acetate from converting acetic acid. To reduce the ethyl acetate concentrations in the reactor, the recycle streams, or a portion thereof, may be hydrolyzed. The resulting acetic acid may be converted to ethanol and the resulting ethanol may pass through the reactor. Preferably, the processes of the present invention operate at high conversions and an acetic acid enriched stream is not recovered and recycled to the reactor. Thus, the recycle streams to the reactor may reduce the ethyl acetate concentration through hydrolysis prior to returning to the reactor. Advantageously this may be useful when the amount of ethyl acetate recycled to the reactor exceeds the ability of the catalyst to convert ethyl acetate.

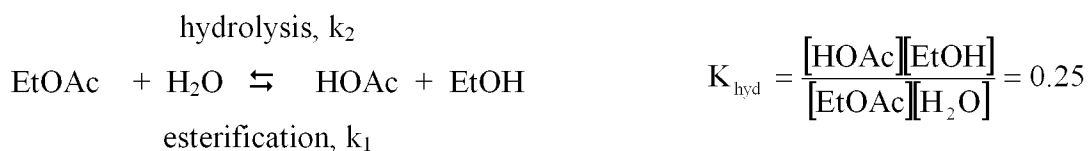
[0020] The hydrogenation of acetic acid to form ethanol and water may be represented by the following reaction:



[0021] In theoretical embodiments where ethanol and water are the only products of the hydrogenation reaction, the crude ethanol product comprises 71.9 wt.% ethanol and 28.1 wt.% water. However, not all of the acetic acid fed to the hydrogenation reactor is typically converted to ethanol. Subsequent reactions of ethanol, such as esterification, may form other byproducts

such as ethyl acetate. Ethyl acetate is a byproduct that reduces the yield of ethanol of the process and increases the waste that must be taken out of the system.

[0022] The esterification reaction that produces ethyl acetate has liquid phase equilibrium constant of $K_{\text{est}} = 4.0$. (See, for example, Witzeman and Agreda in, "Acetic Acid and its Derivatives", Marcel Dekker, NY, 1992, p. 271, the entirety of which is incorporated herein by reference.) The hydrolysis of ethyl acetate has an equilibrium constant, $K_{\text{hyd}} = 0.25$, which is the reciprocal of the K_{est} .



[0023] Excess acetic acid may be removed along with a substantial portion of water or a substantial portion of the ethanol and water in an initial column. Until the excess acetic acid, which is not converted to products in the hydrogenation reactor, is substantially removed from the crude ethanol product, the crude ethanol product is not at chemical equilibrium and the composition favors esterification of ethanol with acetic acid to form ethyl acetate and water. In one embodiment of the present invention, substantially all of the excess acetic acid is removed. One or more derivative streams that are formed in the separation system may contain small amounts of acetic acid. As such, any mixture of ethanol, ethyl acetate and water in the derivative streams are not at chemical equilibrium, and the hydrolysis of ethyl acetate is thermodynamically favored.

[0024] In one embodiment, one or more of the derivative streams obtained by recovering and/or purifying a crude ethanol product is hydrolyzed. In preferred embodiments, the derivative stream to be hydrolyzed comprises ethyl acetate, ethanol, and water. Each of the components in the derivative stream may be obtained from separate streams and mixed. In addition, the one or more derivative streams to be hydrolyzed preferably comprise substantially no acetic acid, e.g., less than 2 wt.% or less than 0.5 wt%. Although ethyl acetate may be hydrolyzed in the absence of a catalyst, it is preferred that a catalyst is employed to increase reaction rate. In one embodiment, the hydrolysis of the ethyl acetate is performed under liquid phase or gas phase

conditions. In one embodiment, the hydrolysis of the ethyl acetate is performed continuously under liquid phase conditions.

[0025] According to one embodiment of the invention, the derivative stream is passed through a hydrolysis unit comprising an ion exchange resin reactor bed. The ion exchange resin reactor bed may comprise a strongly acidic heterogeneous or homogenous catalyst, such as for example a Lewis acid, strongly acidic ion exchange catalyst, inorganic acids, and methanesulfonic acid. Exemplary catalysts include Amberlyst™ 15 (Dow Chemical Company), Amberlyst™ 70, Dowex-M-31 (Dow Chemical Company), Dowex Monosphere M-31 (Dow Chemical Company), and Purolite CT type Catalysts (Purolite International SRL). The ion exchange resin reactor bed preferably is a gel or macro-reticular bed. Ion exchange resin reactor beds may be located externally to the distillation columns or within a distillation column. In some embodiments, the outflow of the ion exchange resin reactor bed may be directly or indirectly returned to one of the flashers and/or one of the distillation columns, e.g., the acid removal column. In one embodiment, when the system employs two or more flashers, the outflow of the ion exchange resin reactor bed is preferably directed to the low pressure flasher. In other embodiments, a portion of the outflow of the ion exchange resin reactor bed is fed, along with acetic acid, to the reaction zone.

[0026] In one embodiment, the crude ethanol product is fed to a distillation column and ethyl acetate present in the crude ethanol product is hydrolyzed within the distillation column. The distillation column may comprise a reactive distillation column. The distillation column may comprise a hydrolyzing section, preferably in the upper portion of the column or near the top of the column. The hydrolyzing section may comprise an internal ion exchange resin reactor bed. In another embodiment, the hydrolyzing section is an enlarged portion of the column, i.e., has a greater cross-sectional diameter than the lower half of the column. This may increase the residence time of the light boiling point materials in the column to facilitate further hydrolysis of ethyl acetate.

[0027] In further embodiments, one or more of the derivative streams may also be fed to the distillation column having the hydrolyzing section. This may allow a derivative stream containing ethyl acetate to be hydrolyzed along with the crude ethanol product. Optionally, the derivative stream may be passed through an external ion exchange resin reactor bed before being fed to the distillation column having the hydrolyzing section.

[0028] In one embodiment of the invention, other compounds may also be hydrolyzed with the ethyl acetate, such as diethyl acetate (DEA).

[0029] The process of the present invention may be used with any hydrogenation process for producing ethanol. The materials, catalysts, reaction conditions, and separation processes that may be used in the hydrogenation of acetic acid are described further below.

[0030] The raw materials, acetic acid and hydrogen, fed to the reactor used in connection with the process of this invention may be derived from any suitable source including natural gas, petroleum, coal, biomass, and so forth. As examples, acetic acid may be produced via methanol carbonylation, acetaldehyde oxidation, ethane oxidation, oxidative fermentation, and anaerobic fermentation. Methanol carbonylation processes suitable for production of acetic acid are described in U.S. Pat. Nos. 7,208,624; 7,115,772; 7,005,541; 6,657,078; 6,627,770; 6,143,930; 5,599,976; 5,144,068; 5,026,908; 5,001,259; and 4,994,608, the entire disclosures of which are incorporated herein by reference. Optionally, the production of ethanol may be integrated with such methanol carbonylation processes.

[0031] As petroleum and natural gas prices fluctuate becoming either more or less expensive, methods for producing acetic acid and intermediates such as methanol and carbon monoxide from other carbon sources have drawn increasing interest. In particular, when petroleum is relatively expensive, it may become advantageous to produce acetic acid from synthesis gas (“syngas”) that is derived from more available carbon sources. U.S. Pat. No. 6,232,352, the entirety of which is incorporated herein by reference, for example, teaches a method of retrofitting a methanol plant for the manufacture of acetic acid. By retrofitting a methanol plant, the large capital costs associated with CO generation for a new acetic acid plant are significantly reduced or largely eliminated. All or part of the syngas is diverted from the methanol synthesis loop and supplied to a separator unit to recover CO, which is then used to produce acetic acid. In a similar manner, hydrogen for the hydrogenation step may be supplied from syngas.

[0032] In some embodiments, some or all of the raw materials for the above-described acetic acid hydrogenation process may be derived partially or entirely from syngas. For example, the acetic acid may be formed from methanol and carbon monoxide, both of which may be derived from syngas. The syngas may be formed by partial oxidation reforming or steam reforming, and the carbon monoxide may be separated from syngas. Similarly, hydrogen that is used in the step of hydrogenating the acetic acid to form the crude ethanol product may be separated from

syngas. The syngas, in turn, may be derived from a variety of carbon sources. The carbon source, for example, may be selected from the group consisting of natural gas, oil, petroleum, coal, biomass, and combinations thereof. Syngas or hydrogen may also be obtained from bio-derived methane gas, such as bio-derived methane gas produced by landfills or agricultural waste.

[0033] Biomass-derived syngas has a detectable ^{14}C isotope content as compared to fossil fuels such as coal or natural gas. An equilibrium forms in the Earth's atmosphere between constant new formation and constant degradation, and so the proportion of the ^{14}C nuclei in the carbon in the atmosphere on Earth is constant over long periods. The same distribution ratio $n^{14}\text{C}:n^{12}\text{C}$ ratio is established in living organisms as is present in the surrounding atmosphere, which stops at death and ^{14}C decomposes at a half life of about 6000 years. Methanol, acetic acid and/or ethanol formed from biomass-derived syngas would be expected to have a ^{14}C content that is substantially similar to living organisms. For example, the $^{14}\text{C}:^{12}\text{C}$ ratio of the methanol, acetic acid and/or ethanol may be from one half to about 1 of the $^{14}\text{C}:^{12}\text{C}$ ratio for living organisms. In other embodiments, the syngas, methanol, acetic acid and/or ethanol described herein are derived wholly from fossil fuels, i.e. carbon sources produced over 60,000 years ago, may have no detectable ^{14}C content.

[0034] In another embodiment, the acetic acid used in the hydrogenation step may be formed from the fermentation of biomass. The fermentation process preferably utilizes an acetogenic process or a homoacetogenic microorganism to ferment sugars to acetic acid producing little, if any, carbon dioxide as a by-product. The carbon efficiency for the fermentation process preferably is greater than 70%, greater than 80% or greater than 90% as compared to conventional yeast processing, which typically has a carbon efficiency of about 67%. Optionally, the microorganism employed in the fermentation process is of a genus selected from the group consisting of *Clostridium*, *Lactobacillus*, *Moorella*, *Thermoanaerobacter*, *Propionibacterium*, *Propionispora*, *Anaerobiospirillum*, and *Bacteriodes*, and in particular, species selected from the group consisting of *Clostridium formicoaceticum*, *Clostridium butyricum*, *Moorella thermoacetica*, *Thermoanaerobacter kivui*, *Lactobacillus delbrukii*, *Propionibacterium acidipropionici*, *Propionispora arboris*, *Anaerobiospirillum succinicproduens*, *Bacteriodes amylophilus* and *Bacteriodes ruminicola*. Optionally in this process, all or a portion of the unfermented residue from the biomass, e.g., lignans, may be

gasified to form hydrogen that may be used in the hydrogenation step of the present invention. Exemplary fermentation processes for forming acetic acid are disclosed in U.S. Pat. Nos. 6,509,180 and U.S. Pub. Nos. 2008/0193989 and 2009/0281354, the entireties of which are incorporated herein by reference.

[0035] Examples of biomass include, but are not limited to, agricultural wastes, forest products, grasses, and other cellulosic material, timber harvesting residues, softwood chips, hardwood chips, tree branches, tree stumps, leaves, bark, sawdust, off-spec paper pulp, corn, corn stover, wheat straw, rice straw, sugarcane bagasse, switchgrass, miscanthus, animal manure, municipal garbage, municipal sewage, commercial waste, grape pumice, almond shells, pecan shells, coconut shells, coffee grounds, grass pellets, hay pellets, wood pellets, cardboard, paper, plastic, and cloth. Another biomass source is black liquor which is an aqueous solution of lignin residues, hemicellulose, and inorganic chemicals.

[0036] U.S. Pat. No. RE 35,377, also incorporated herein by reference, provides a method for the production of methanol by conversion of carbonaceous materials such as oil, coal, natural gas and biomass materials. The process includes hydrogasification of solid and/or liquid carbonaceous materials to obtain a process gas which is steam pyrolyzed with additional natural gas to form syngas. The syngas is converted to methanol which may be carbonylated to acetic acid. The method likewise produces hydrogen which may be used in connection with this invention as noted above. U.S. Pat. No. 5,821,111, which discloses a process for converting waste biomass through gasification into synthesis gas, and U.S. Pat. No. 6,685,754, which discloses a method for the production of a hydrogen-containing gas composition, such as a syngas including hydrogen and carbon monoxide, are incorporated herein by reference in their entireties.

[0037] Acetic acid fed to the hydrogenation reaction may also comprise other carboxylic acids and anhydrides, as well as aldehyde and/or ketones, such as acetaldehyde and acetone. Preferably, a suitable acetic acid feed stream comprises one or more of the compounds selected from the group consisting of acetic acid, acetic anhydride, acetaldehyde, ethyl acetate, and mixtures thereof. These other compounds may also be hydrogenated in the processes of the present invention. In some embodiments, the presence of carboxylic acids, such as propanoic acid or its aldehyde, may be beneficial in producing propanol. Water may also be present in the acetic acid feed.

[0038] Alternatively, acetic acid in vapor form may be taken directly as crude product from the flash vessel of a methanol carbonylation unit of the class described in U.S. Pat. No. 6,657,078, the entirety of which is incorporated herein by reference. The crude vapor product, for example, may be fed directly to the hydrogenation reactor without the need for condensing the acetic acid and light ends or removing water, saving overall processing costs.

[0039] The acetic acid may be vaporized at the reaction temperature, following which the vaporized acetic acid may be fed along with hydrogen in an undiluted state or diluted with a relatively inert carrier gas, such as nitrogen, argon, helium, carbon dioxide and the like. For reactions run in the vapor phase, the temperature should be controlled in the system such that it does not fall below the dew point of acetic acid. In one embodiment, the acetic acid may be vaporized at the boiling point of acetic acid at the particular pressure, and then the vaporized acetic acid may be further heated to the reactor inlet temperature. In another embodiment, the acetic acid is mixed with other gases before vaporizing, followed by heating the mixed vapors up to the reactor inlet temperature. Preferably, the acetic acid is transferred to the vapor state by passing hydrogen and/or recycle gas through the acetic acid at a temperature at or below 125°C, followed by heating of the combined gaseous stream to the reactor inlet temperature.

[0040] The reactor, in some embodiments, may include a variety of configurations using a fixed bed reactor or a fluidized bed reactor. In many embodiments of the present invention, an “adiabatic” reactor can be used; that is, there is little or no need for internal plumbing through the reaction zone to add or remove heat. In other embodiments, a radial flow reactor or reactors may be employed as the reactor, or a series of reactors may be employed with or without heat exchange, quenching, or introduction of additional feed material. Alternatively, a shell and tube reactor provided with a heat transfer medium may be used. In many cases, the reaction zone may be housed in a single vessel or in a series of vessels with heat exchangers therebetween.

[0041] In preferred embodiments, the catalyst is employed in a fixed bed reactor, e.g., in the shape of a pipe or tube, where the reactants, typically in the vapor form, are passed over or through the catalyst. Other reactors, such as fluid or ebullient bed reactors, can be employed. In some instances, the hydrogenation catalysts may be used in conjunction with an inert material to regulate the pressure drop of the reactant stream through the catalyst bed and the contact time of the reactant compounds with the catalyst particles.

[0042] The hydrogenation in the reactor may be carried out in either the liquid phase or vapor

phase. Preferably, the reaction is carried out in the vapor phase under the following conditions. The reaction temperature may range from 125°C to 350°C, e.g., from 200°C to 325°C, from 225°C to 300°C, or from 250°C to 300°C. The pressure may range from 10 kPa to 3000 kPa, e.g., from 50 kPa to 2300 kPa, or from 100 kPa to 2100 kPa. The reactants may be fed to the reactor at a gas hourly space velocity (GHSV) from 50 hr⁻¹ to 50,000 hr⁻¹, e.g., from 500 hr⁻¹ to 30,000 hr⁻¹, from 1000 hr⁻¹ to 10,000 hr⁻¹, or from 1000 hr⁻¹ to 6500 hr⁻¹.

[0043] Although the reaction consumes two moles of hydrogen per mole of acetic acid to produce one mole of ethanol, the actual molar ratio of hydrogen to acetic acid in the feed stream may vary from about 100:1 to 1:100, e.g., from 50:1 to 1:50, from 20:1 to 1:2, or from 18:1 to 2:1.

[0044] Contact or residence time can also vary widely, depending upon such variables as amount of acetic acid, catalyst, reactor, temperature, and pressure. Typical contact times range from a fraction of a second to more than several hours when a catalyst system other than a fixed bed is used, with preferred contact times, at least for vapor phase reactions, of from 0.1 to 100 seconds.

[0045] The hydrogenation of acetic acid to form ethanol is preferably conducted in the presence of a hydrogenation catalyst in the reactor. Exemplary catalysts are further described in U.S. Pat. Nos. 7,608,744 and 7,863,489, and U.S. Pub. Nos. 2010/0121114 and 2010/0197985, the entireties of which are incorporated herein by reference. In another embodiment, the catalyst comprises a Co/Mo/S catalyst of the type described in U.S. Pub. No. 2009/0069609, the entirety of which is incorporated herein by reference. In some embodiments the catalyst may be a bulk catalyst.

[0046] In one embodiment, the catalyst comprises a first metal selected from the group consisting of copper, iron, cobalt, nickel, ruthenium, rhodium, palladium, osmium, iridium, platinum, titanium, zinc, chromium, rhenium, molybdenum, and tungsten. Preferably, the first metal is selected from the group consisting of platinum, palladium, cobalt, nickel, and ruthenium.

[0047] As indicated above, in some embodiments, the catalyst further comprises a second metal, which typically would function as a promoter. If present, the second metal preferably is selected from the group consisting of copper, molybdenum, tin, chromium, iron, cobalt, vanadium, tungsten, palladium, platinum, lanthanum, cerium, manganese, ruthenium, rhenium, gold, and nickel. More preferably, the second metal is selected from the group consisting of

copper, tin, cobalt, rhenium, and nickel.

[0048] In certain embodiments where the catalyst includes two or more metals, e.g., a first metal and a second metal, the first metal is present in the catalyst in an amount from 0.1 to 10 wt.%, e.g., from 0.1 to 5 wt.%, or from 0.1 to 3 wt.%. The second metal preferably is present in an amount from 0.1 to 20 wt.%, e.g., from 0.1 to 10 wt.%, or from 0.1 to 7.5 wt.%.

[0049] Preferred metal combinations for exemplary catalyst compositions include platinum/tin, platinum/ruthenium, platinum/rhenium, palladium/ruthenium, palladium/rhenium, cobalt/palladium, cobalt/platinum, cobalt/chromium, cobalt/ruthenium, cobalt/tin, silver/palladium, copper/palladium, copper/zinc, nickel/palladium, gold/palladium, ruthenium/rhenium, or ruthenium/iron.

[0050] The catalyst may also comprise a third metal selected from any of the metals listed above in connection with the first or second metal, so long as the third metal is different from the first and second metals. In preferred aspects, the third metal is selected from the group consisting of cobalt, palladium, ruthenium, copper, zinc, platinum, tin, and rhenium. When present, the total weight of the third metal preferably is from 0.05 to 20 wt.%, e.g., from 0.1 to 10 wt.%, or from 0.1 to 7.5 wt.%. In one embodiment, the catalyst may comprise platinum, tin and cobalt.

[0051] In addition to one or more metals, in some embodiments of the present invention the catalysts further comprise a support or a modified support. As used herein, the term “modified support” refers to a support that includes a support material and a support modifier, which adjusts the acidity of the support material.

[0052] The total weight of the support or modified support, based on the total weight of the catalyst, preferably is from 75 to 99.9 wt.%, e.g., from 78 to 97 wt.%, or from 80 to 95 wt.%. Preferred supports include siliceous supports, such as silica, silica/alumina, a Group IIA silicate such as calcium metasilicate, pyrogenic silica, high purity silica, and mixtures thereof. Other supports may include, but are not limited to, iron oxide, alumina, titania, zirconia, magnesium oxide, carbon, graphite, high surface area graphitized carbon, activated carbons, and mixtures thereof.

[0053] The support may be a modified support and is present in an amount from 0.1 to 50 wt.%, e.g., from 0.2 to 25 wt.%, from 1 to 20 wt.%, or from 3 to 15 wt.%, based on the total weight of the catalyst.

[0054] In some embodiments, the support modifier may be an acidic modifier that increases the acidity of the catalyst. Suitable acidic support modifiers may be selected from the group consisting of: oxides of Group IVB metals, oxides of Group VB metals, oxides of Group VIB metals, oxides of Group VIIB metals, oxides of Group VIIIB metals, aluminum oxides, and mixtures thereof. Acidic support modifiers include those selected from the group consisting of TiO_2 , ZrO_2 , Nb_2O_5 , Ta_2O_5 , Al_2O_3 , B_2O_3 , P_2O_5 , Sb_2O_3 , WO_3 , MoO_3 , Fe_2O_3 , Cr_2O_3 , V_2O_5 , MnO_2 , CuO , Co_2O_3 , and Bi_2O_3 . Preferred support modifiers include oxides of tungsten, molybdenum, and vanadium.

[0055] In another embodiment, the support modifier may be a basic modifier that has a low volatility or no volatility. Such basic modifiers, for example, may be selected from the group consisting of: (i) alkaline earth metal oxides, (ii) alkali metal oxides, (iii) alkaline earth metal metasilicates, (iv) alkali metal metasilicates, (v) Group IIB metal oxides, (vi) Group IIB metal metasilicates, (vii) Group IIIB metal oxides, (viii) Group IIIB metal metasilicates, and mixtures thereof. The basic support modifier may be selected from the group consisting of oxides and metasilicates of any of sodium, potassium, magnesium, calcium, scandium, yttrium, and zinc, as well as mixtures of any of the foregoing. In one embodiment, the basic support modifier is a calcium silicate, such as calcium metasilicate (CaSiO_3). The calcium metasilicate may be crystalline or amorphous.

[0056] Catalysts on a modified support may include one or more metals selected from the group consisting of platinum, palladium, cobalt, tin, and rhenium on a silica support, optionally modified by one or more modifiers selected from the group consisting of calcium metasilicate, and one or more oxides of tungsten, molybdenum, and/or vanadium.

[0057] The catalyst compositions suitable for use with the present invention preferably are formed through metal impregnation of the modified support, although other processes such as chemical vapor deposition may also be employed. Such impregnation techniques are described in U.S. Pat. Nos. 7,608,744 and 7,863,489 and U.S. Pub. No. 2010/0197485 referred to above, the entireties of which are incorporated herein by reference.

[0058] After the washing, drying and calcining of the catalyst is completed, the catalyst may be reduced in order to activate it. Reduction is carried out in the presence of a reducing gas, preferably hydrogen. The reducing gas is continuously passed over the catalyst at an initial ambient temperature that is increased up to 400°C . In one embodiment, the reduction is

preferably carried out after the catalyst has been loaded into the reaction vessel where the hydrogenation will be carried out.

[0059] In particular, the hydrogenation of acetic acid may achieve favorable conversion of acetic acid and favorable selectivity and productivity to ethanol in the reactor. For purposes of the present invention, the term “conversion” refers to the amount of acetic acid in the feed that is converted to a compound other than acetic acid. Conversion is expressed as a percentage based on acetic acid in the feed. The conversion may be at least 40%, e.g., at least 50%, at least 60%, at least 70% or at least 80%. Although catalysts that have high conversions are desirable, such as at least 80% or at least 90%, in some embodiments a low conversion may be acceptable at high selectivity for ethanol.

[0060] Selectivity is expressed as a mole percent based on converted acetic acid. It should be understood that each compound converted from acetic acid has an independent selectivity and that selectivity is independent from conversion. For example, if 60 mole % of the converted acetic acid is converted to ethanol, we refer to the ethanol selectivity as 60%. Preferably, the catalyst selectivity to ethanol is at least 60%, e.g., at least 70%, or at least 80%. Preferred embodiments of the hydrogenation process also have low selectivity to undesirable products, such as methane, ethane, and carbon dioxide. The selectivity to these undesirable products preferably is less than 4%, e.g., less than 2% or less than 1%.

[0061] The term “productivity,” as used herein, refers to the grams of a specified product, e.g., ethanol, formed during the hydrogenation based on the kilograms of catalyst used per hour. The productivity may range from 100 to 3,000 grams of ethanol per kilogram of catalyst per hour.

[0062] In various embodiments of the present invention, the crude ethanol product produced by the reactor, before any subsequent processing, such as purification and separation, will typically comprise unreacted acetic acid, ethanol and water. Exemplary compositional ranges for the crude ethanol product are provided in Table 1, excluding hydrogen. The “others” identified in Table 1 may include, for example, esters, ethers, aldehydes, ketones, alkanes, and carbon dioxide.

TABLE 1
CRUDE ETHANOL PRODUCT COMPOSITIONS

Component	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
Ethanol	5 to 72	15 to 72	15 to 70	25 to 65
Acetic Acid	0 to 90	0 to 50	0 to 35	0 to 15
Water	5 to 40	5 to 30	10 to 30	10 to 26
Ethyl Acetate	0 to 30	1 to 25	3 to 20	5 to 18
Acetaldehyde	0 to 10	0 to 3	0.1 to 3	0.2 to 2
Others	0.1 to 10	0.1 to 6	0.1 to 4	--

[0063] In one embodiment, the crude ethanol product of Table 1 may have low concentrations of acetic acid with higher conversion, and the acetic acid concentration may range from 0.01 wt.% to 20 wt.%, e.g., 0.05 wt.% to 15 wt.%, from 0.1 wt.% to 10 wt.% or from 1 wt.% to 5 wt.%. In embodiments having lower amounts of acetic acid, the conversion of acetic acid is preferably greater than 75%, e.g., greater than 85% or greater than 90%. In addition, the selectivity to ethanol may also be preferably high, and is preferably greater than 75%, e.g., greater than 85% or greater than 90%.

[0064] FIGS. 1 and 2 show a hydrogenation system 100 suitable for the hydrogenation of acetic acid and separating ethanol from the crude reaction mixture according to one embodiment of the invention. System 100 comprises reaction zone 101 and distillation zone 102. Reaction zone 101 comprises reactor 103, hydrogen feed line 104 and acetic acid feed line 105. In FIG. 1, distillation zone 102 comprises first column 134, water separation unit 140, and second column 138. An ion exchange reactor bed 128 is also provided. The ion exchange resin reactor bed 128 preferably is a gel or marco-reticular bed. One or more of the derivative streams may be fed to the ion exchange resin reactor bed 128 and the outflow of the reactor bed 128 may be directly or indirectly returned to the distillation zone 102 or reaction zone 101.

[0065] FIG. 1 illustrates one exemplary separation system. The reaction zone 101 of FIG. 1 produces a liquid stream 109, e.g., crude ethanol product, for further separation. In one preferred embodiment, the reaction zone 101 of FIG. 1 operates at above 80% acetic acid conversion, e.g., above 90% conversion or above 99% conversion. Thus, the acetic acid concentration in the liquid stream 109 may be low.

[0066] The crude ethanol product may be condensed and fed to a separator 110, which, in turn, forms a vapor stream 111 and a liquid stream 112. In some embodiments, separator 110 may comprise a flasher or a knockout pot. Separator 110 may operate at a temperature from 20°C to 350°C, e.g., from 30°C to 325°C or from 60°C to 250°C. The pressure of separator 110 may be from 100 kPa to 3000 kPa, e.g., from 125 kPa to 2500 kPa or from 150 kPa to 2200 kPa.

Optionally, the crude ethanol product in line 112 may pass through one or more membranes to separate hydrogen and/or other non-condensable gases.

[0067] Vapor stream 111 exiting separator 110 may comprise hydrogen and hydrocarbons, and may be purged and/or returned to reaction zone 101. As shown, vapor stream 111 is combined with the hydrogen feed 104 and co-fed to vaporizer 106. In some embodiments, the returned vapor stream 112 may be compressed before being combined with hydrogen feed 104.

[0068] Liquid stream 112 from separator 110 is withdrawn and directed as a feed composition to the side of first distillation column 134. Liquid stream 112 may be heated from ambient temperature to a temperature of up to 70°C, e.g., up to 50°C, or up to 40°C. The additional energy required to pre-heat liquid stream 112 above 70°C does not achieve the desired energy efficiency in first column 134 with respect to reboiler duties. In another embodiment, liquid stream 112 is not separately preheated, but is withdrawn from separator 110, and cooled if needed, at a temperature of less than 70°C, e.g., less than 50°C, or less than 40°C, and directly fed to first column 134. In one embodiment, the contents of liquid stream 112 are substantially similar to the crude ethanol product obtained from the reactor, except that the composition has been depleted of hydrogen, carbon dioxide, methane or ethane, which have been removed by separator 110. Accordingly, liquid stream 112 may also be referred to as a crude ethanol product. Exemplary components of liquid stream 112 are provided in Table 1A. It should be understood that liquid stream 112 may contain other components, not listed in Table 1A.

TABLE 1A
FEED COMPOSITION TO COLUMN 134
(Liquid Stream 112)

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
Ethanol	5 to 72	10 to 70	15 to 65
Acetic Acid	< 90	5 to 80	0 to 35
Water	5 to 40	5 to 30	10 to 26
Ethyl Acetate	< 30	1 to 25	3 to 20

Acetaldehyde	< 10	0.001 to 3	0.1 to 3
Acetal	< 5	0.01 to 5	0.01 to 3
Acetone	< 5	0.0005 to 0.05	0.001 to 0.03

[0069] The amounts indicated as less than (<) in the tables throughout the present specification are preferably not present and if present may be present in amounts greater than 0.0001 wt.%.

[0070] In one embodiment, the ethyl acetate concentration in the liquid stream 112 may affect the first column reboiler duty and size. Decreasing ethyl acetate concentrations may allow for reduced reboiler duty and size. In one embodiment, to reduce the ethyl acetate concentration (a) the catalyst in reactor may convert ethyl acetate in addition to acetic acid; (b) the catalyst may be less selective for ethyl acetate, and/or (c) the feed to reactor, including recycles, may contain less ethyl acetate.

[0071] Liquid stream 112 is introduced in the middle or lower portion of first column 134, also referred to as acid-water column. In one embodiment, no entrainers are added to first column 134. In FIG. 1, first column 134, water and unreacted acetic acid, along with any other heavy components, if present, are removed from liquid stream 112 and are withdrawn, preferably continuously, as a first residue in line 136. Preferably, a substantial portion of the water in the crude ethanol product that is fed to first column 134 may be removed in the first residue, for example, up to about 75% or to about 90% of the water from the crude ethanol product. First column 134 also forms a first distillate, which is withdrawn in line 135.

[0072] When column 134 is operated under about 170 kPa, the temperature of the residue exiting in line 136 preferably is from 90°C to 130°C, e.g., from 95°C to 120°C or from 100°C to 115°C. The temperature of the distillate exiting in line 135 preferably is from 60°C to 90°C, e.g., from 65°C to 85°C or from 70°C to 80°C. In some embodiments, the pressure of first column 134 may range from 0.1 kPa to 510 kPa, e.g., from 1 kPa to 475 kPa or from 1 kPa to 375 kPa.

[0073] The first distillate in line 135 comprises water, in addition to ethanol and other organics. In terms of ranges, the concentration of water in the first distillate in line 135 preferably is from 4 wt.% to 38 wt.%, e.g., from 7 wt.% to 32 wt.%, or from 7 to 25 wt.%. A portion of first distillate in line 137 may be condensed and refluxed, for example, at a ratio of from 10:1 to 1:10, e.g., from 3:1 to 1:3 or from 1:2 to 2:1. It is understood that reflux ratios may vary with the number of stages, feed locations, column efficiency and/or feed composition. Operating with a

reflux ratio of greater than 3:1 may be less preferred because more energy may be required to operate the first column 134. The condensed portion of the first distillate may also be fed to a second column 138.

[0074] The remaining portion of the first distillate in 139 is fed to a water separation unit 140. Water separation unit 140 may be an adsorption unit, membrane, molecular sieves, extractive column distillation, or a combination thereof. A membrane or an array of membranes may also be employed to separate water from the distillate. The membrane or array of membranes may be selected from any suitable membrane that is capable of removing a permeate water stream from a stream that also comprises ethanol and ethyl acetate.

[0075] In a preferred embodiment, water separator 140 is a pressure swing adsorption (PSA) unit. The PSA unit is optionally operated at a temperature from 30°C to 160°C, e.g., from 80°C to 140°C, and a pressure of from 0.01 kPa to 550 kPa, e.g., from 1 kPa to 150 kPa. The PSA unit may comprise two to five beds. Water separator 140 may remove at least 95% of the water from the portion of first distillate in line 139, and more preferably from 95% to 99% of the water from the first distillate, in a water stream 141. All or a portion of water stream 141 may be returned to column 134 in line 142, where the water preferably is ultimately recovered from column 134 in the first residue in line 136. Additionally or alternatively, all or a portion of water stream 141 may be purged via line 143. The remaining portion of first distillate exits the water separator 140 as ethanol mixture stream 144. Ethanol mixture stream 144 may have a low concentration of water of less than 10 wt.%, e.g., less than 6 wt.% or less than 2 wt.%. Exemplary components of ethanol mixture stream 144 and first residue in line 136 are provided in Table 2 below. It should also be understood that these streams may also contain other components, not listed, such as components derived from the feed.

TABLE 2
FIRST COLUMN 134 WITH PSA (FIG. 1)

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Ethanol Mixture Stream</u>			
Ethanol	20 to 95	30 to 95	40 to 95
Water	< 10	0.01 to 6	0.1 to 2
Acetic Acid	< 2	0.001 to 0.5	0.01 to 0.2
Ethyl Acetate	< 60	1 to 55	5 to 55
Acetaldehyde	< 10	0.001 to 5	0.01 to 4
Acetal	< 0.1	< 0.1	< 0.05
Acetone	< 0.05	0.001 to 0.03	0.01 to 0.025
<u>Residue</u>			
Acetic Acid	< 90	1 to 50	2 to 35
Water	30 to 100	45 to 95	60 to 90
Ethanol	< 1	< 0.9	< 0.3

[0076] Preferably, ethanol mixture stream 144 is not returned or refluxed to first column 134. The condensed portion of the first distillate in line 137 may be combined with ethanol mixture stream 144 to control the water concentration fed to the second column 138. For example, in some embodiments the first distillate may be split into equal portions, while in other embodiments, all of the first distillate may be condensed or all of the first distillate may be processed in the water separation unit. In FIG. 1, the condensed portion in line 137 and ethanol mixture stream 144 are co-fed to second column 138. In other embodiments, the condensed portion in line 137 and ethanol mixture stream 144 may be separately fed to second column 138. The combined distillate and ethanol mixture has a total water concentration of greater than 0.5 wt.%, e.g., greater than 2 wt.% or greater than 5 wt.%. In terms of ranges, the total water concentration of the combined distillate and ethanol mixture may be from 0.5 to 15 wt.%, e.g., from 2 to 12 wt.%, or from 5 to 10 wt.%.

[0077] The second column 138 in FIG. 1, also referred to as the “light ends column,” removes ethyl acetate and acetaldehyde from the first distillate in line 137 and/or ethanol mixture stream 144. Ethyl acetate and acetaldehyde are removed as a second distillate in line 145 and ethanol is removed as the second residue in line 146. Second column 138 may be a tray column or packed column. In one embodiment, second column 138 is a tray column having from 5 to 70 trays, e.g., from 15 to 50 trays or from 20 to 45 trays.

[0078] Second column 138 operates at a pressure ranging from 0.1 kPa to 510 kPa, e.g., from 10 kPa to 450 kPa or from 50 kPa to 350 kPa. Although the temperature of second column 138 may vary, when at about 20 kPa to 70 kPa, the temperature of the second residue exiting in line 146 preferably is from 30°C to 75°C, e.g., from 35°C to 70°C or from 40°C to 65°C. The temperature of the second distillate exiting in line 145 preferably is from 20°C to 55°C, e.g., from 25°C to 50°C or from 30°C to 45°C.

[0079] The total concentration of water fed to second column 138 preferably is less than 10 wt.%, as discussed above. When first distillate in line 137 and/or ethanol mixture stream comprises minor amounts of water, e.g., less than 1 wt.% or less than 0.5 wt.%, additional water may be fed to the second column 138 as an extractive agent in the upper portion of the column. A sufficient amount of water is preferably added via the extractive agent such that the total concentration of water fed to second column 138 is from 1 to 10 wt.% water, e.g., from 2 to 6 wt.%, based on the total weight of all components fed to second column 138. If the extractive agent comprises water, the water may be obtained from an external source or from an internal return/recycle line from one or more of the other columns or water separators.

[0080] Suitable extractive agents may also include, for example, dimethylsulfoxide, glycerine, diethylene glycol, 1-naphthol, hydroquinone, N,N'-dimethylformamide, 1,4-butanediol; ethylene glycol-1,5-pentanediol; propylene glycol-tetraethylene glycol-polyethylene glycol; glycerine-propylene glycol-tetraethylene glycol-1,4-butanediol, ethyl ether, methyl formate, cyclohexane, N,N'-dimethyl-1,3-propanediamine, N,N'-dimethylethylenediamine, diethylene triamine, hexamethylene diamine and 1,3-diaminopentane, an alkylated thiopene, dodecane, tridecane, tetradecane, chlorinated paraffins, or a combination thereof. When extractive agents are used, a suitable recovery system, such as a further distillation column, may be used to recycle the extractive agent.

[0081] Exemplary components for the second distillate and second residue compositions for the second column 138 are provided in Table 3, below. It should be understood that the distillate and residue may also contain other components, not listed in Table 3.

TABLE 3
SECOND COLUMN 138 (FIG. 1)

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Second Distillate</u>			
Ethyl Acetate	5 to 90	10 to 80	15 to 75
Acetaldehyde	< 60	1 to 40	1 to 35
Ethanol	< 45	0.001 to 40	0.01 to 35
Water	< 20	0.01 to 10	0.1 to 5
<u>Second Residue</u>			
Ethanol	80 to 99.5	85 to 97	60 to 95
Water	< 20	0.001 to 15	0.01 to 10
Ethyl Acetate	< 1	0.001 to 2	0.001 to 0.5
Acetic Acid	< 0.5	< 0.01	0.001 to 0.01

[0082] The second residue in FIG. 1 comprises one or more impurities selected from the group consisting of ethyl acetate, acetic acid, acetaldehyde, and diethyl acetal. The second residue may comprise at least 100 wppm of these impurities, e.g., at least 250 wppm or at least 500 wppm. In some embodiments, the second residue may contain substantially no ethyl acetate or acetaldehyde.

[0083] The second distillate in line 145, which comprises ethyl acetate and/or acetaldehyde, preferably is refluxed as shown in FIG. 1, for example, at a reflux ratio of from 1:30 to 30:1, e.g., from 1:10 to 10:1 or from 1:3 to 3:1. In some embodiments, higher reflux ratios may be used. In one aspect, not shown, a portion of the second distillate 145 may be directly returned to reactor 103. The ethyl acetate and/or acetaldehyde in the second distillate may be further reacted in hydrogenation reactor 103.

[0084] In one optional embodiment, water separator 140 may be after second column 138. The first distillate in line 137 may be fed to second column, and second residue in line 146 may be fed to water separator 140.

[0085] In one embodiment, all or a portion of the second distillate in line 145 is directed to ion exchange reactor bed 128. In another embodiment, all or a portion of the second distillate in line 145 may feed a reactive distillation column (not shown) to hydrolyze the ethyl acetate. This portion of the distillate is hydrolyzed to form a hydrolyzed stream, and the outflow stream of the ion exchange reactor bed 128 can be directly or indirectly returned to reactor 103. Exemplary indirect return methods may include storing or further treating the hydrolyzed stream in one or

more additional columns to remove impurities prior to being sent to reaction zone 101. The outflow in line 131 comprises acetic acid and ethanol, and preferably comprises less ethyl acetate than present in line 145. Preferably, the outflow in line 131 has at least 2% less ethyl acetate than line 145, e.g., at least 10% less or at least 20% less. In terms of ranges the amount of ethyl acetate in line 131 is less than line 145 by 2% to 25%, e.g., from 5 to 22% or from 7 to 20%. Preferably, the outflow in line 131 has at least 0.5% more ethanol than line 145, e.g., at least 2% more or at least 4% more. In terms of ranges the amount of ethanol in line 131 is more than line 145 by 0.5% to 20%, e.g., from 2 to 20% or from 4 to 20%. In addition, the outflow in line 131 may also comprise less water than is present in line 145.

[0086] In one embodiment, the second distillate in line 145 and/or a refined second distillate, or a portion of either or both streams, may be further separated to produce an acetaldehyde-containing stream and an ethyl acetate-containing stream. This may allow a portion of the resulting ethyl acetate-containing stream to be recycled to reactor 103 (either directly or after passing through the ion exchange reactor bed 128) while purging the acetaldehyde-containing stream. The purge stream may be valuable as a source of acetaldehyde.

[0087] FIG. 2 illustrates another exemplary separation system. Reaction zone 101 and separator 110 of FIG. 2 are similar to FIG. 1 and produce a liquid stream 112, e.g., crude ethanol product, for further separation (see above, including Table 1A). It should be understood that although FIG. 2 uses first and second columns that these columns are different, and operate differently, than those described above for FIG. 1. Preferably, separation zone 102 of FIG. 2 removes a majority of the ethanol, acetic acid, and water from the crude ethanol product into the first residue in line 114. In addition, the first residue may also comprise ethyl acetate.

[0088] In the exemplary embodiment shown in FIG. 2, liquid stream 112 is introduced in the upper part of first column 107, e.g., upper half or upper third. For purposes of convenience, the columns in each exemplary separation process, may be referred as the first, second, third, etc., columns, but it is understood that first column 107 in FIG. 2 operates differently than the first column 134 of FIG. 1. Optionally, an extractive agent, such as water, may be introduced into first column above the liquid stream 112. When used, the extractive agent may be obtained from a portion of the second residue in line 117.

[0089] In one embodiment, first column 107 is a tray column having from 5 to 90 theoretical trays, e.g. from 10 to 60 theoretical trays or from 15 to 50 theoretical trays. The number of

actual trays for each column may vary depending on the tray efficiency, which is typically from 0.5 to 0.7 depending on the type of tray. The trays may be sieve trays, fixed valve trays, movable valve trays, or any other suitable design known in the art. In other embodiments, a packed column having structured packing or random packing may be employed.

[0090] When first column 107 is operated under 50 kPa, the temperature of the residue exiting in line 114 preferably is from 20°C to 100°C, e.g., from 30°C to 90°C or from 40°C to 80°C. The base of column 107 may be maintained at a relatively low temperature by withdrawing a residue stream comprising ethanol, ethyl acetate, water, and acetic acid, thereby providing an energy efficiency advantage. The temperature of the distillate exiting in line 115 from column 107 preferably at 50 kPa is from 10°C to 80°C, e.g., from 20°C to 70°C or from 30°C to 60°C. The pressure of first column 107 may range from 0.1 kPa to 510 kPa, e.g., from 1 kPa to 475 kPa or from 1 kPa to 375 kPa. In some embodiments, first column 107 may operate under a vacuum of less than 70 kPa, e.g., less than 50 kPa, or less than 20 kPa. Operating under a vacuum may decrease the reboiler duty and reflux ratio of first column 107. However, a decrease in operating pressure for first column 107 does not substantially affect column diameter.

[0091] In first column 107, a weight majority of the ethanol, water, acetic acid, and other heavy components, if present, are removed from the feed and are withdrawn, preferably continuously, as residue in line 114. Concentrating the ethanol in the residue reduces the amount of ethanol that is recycled to reactor 103 and in turn reduces the size of reactor 103. Preferably, at least 50% of the ethanol in the crude ethanol product is recovered in the first residue in line 114. Preferably less than 10% of the ethanol from the feed, e.g., less than 5% or less than 1% of the ethanol, is returned to reactor 103 from first column 107. In addition, concentrating the ethanol also will concentrate the water and/or acetic acid in the residue. In one embodiment, at least 90% of the ethanol from the organic feed is withdrawn in the residue, and more preferably at least 95%. In addition, ethyl acetate may also be present in the first residue in line 114. The reboiler duty may decrease with an ethyl acetate concentration increase in the first residue in line 114. Recovering a majority of the ethyl acetate provides for low concentrations of ethyl acetate in the residue from the initial column, e.g., less than 5 wt.%, less than 3 wt.% or less than 1 wt.%.

[0092] First column 107 also forms an distillate, which is withdrawn in line 115, and which may be condensed and refluxed, for example, at a ratio of from 30:1 to 1:30, e.g., from 10:1 to

1:10 or from 5:1 to 1:5. Higher mass flow ratios of water to organic feed may allow first column 107 to operate with a reduced reflux ratio.

[0093] First distillate in line 115 preferably comprises a weight majority of the acetaldehyde and ethyl acetate from liquid stream 112. In one embodiment, the first distillate in line 115 comprises a concentration of ethyl acetate that is less than the ethyl acetate concentration for the azeotrope of ethyl acetate and water, and more preferably less than 75 wt.%.

[0094] In some embodiments, first distillate in line 115 also comprises ethanol. In one embodiment, first distillate 115 is fed to an extraction column (not shown) to recover ethanol and reduce the ethanol concentration recycled to the reactor.

[0095] Exemplary components of the distillate and residue compositions for first column 107 are provided in Table 4 below. It should also be understood that the distillate and residue may also contain other components, not listed in Table 4.

[0096] For convenience, the distillate and residue of the first column may also be referred to as the “first distillate” or “first residue.” The distillates or residues of the other columns may also be referred to with similar numeric modifiers (second, third, etc.) in order to distinguish them from one another, but such modifiers should not be construed as requiring any particular separation order.

TABLE 4
FIRST COLUMN 107 (FIG. 2)

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Distillate</u>			
Ethyl Acetate	35 to 95	35 to 80	35 to 60
Acetaldehyde	<35	0.1 to 30	5 to 30
Acetal	<35	0.1 to 30	5 to 30
Acetone	< 0.05	0.001 to 0.03	0.01 to 0.025
Ethanol	<50	0.1 to 15	0.5 to 10
Water	1 to 30	2 to 25	4 to 15
Acetic Acid	<0.2	<0.01	not detectable
<u>Residue</u>			
Acetic Acid	0.1 to 50	0.5 to 40	1 to 30
Water	5 to 60	5 to 55	10 to 40
Ethanol	10 to 80	15 to 60	15 to 45
Ethyl Acetate	<5.0	<3.0	<1.0

[0097] In one embodiment of the present invention, firstcolumn 107 may be operated at a

temperature where most of the water, ethanol, and acetic acid are removed from the residue stream and only a small amount of ethanol and water is collected in the distillate stream due to the formation of binary and tertiary azeotropes. The weight ratio of water in the residue in line 114 to water in the distillate in line 115 may be greater than 1:1, e.g., greater than 2:1. Higher water concentrations may be possible in the first residue in line 114 when an water extractive agent is used, e.g. up to 85 wt.%. The weight ratio of ethanol in the residue to ethanol in the distillate may be greater than 1:1, e.g., greater than 2:1.

[0098] The amount of acetic acid in the first residue may vary depending primarily on the conversion in reactor 103. In one embodiment, when the conversion is high, e.g., greater than 90%, the amount of acetic acid in the first residue may be less than 10 wt.%, e.g., less than 5 wt.% or less than 2 wt.%. In other embodiments, when the conversion is lower, e.g., less than 90%, the amount of acetic acid in the first residue may be greater than 10 wt.%.

[0099] The first distillate in line 115 preferably is substantially free of acetic acid, e.g., comprising less than 1000 wppm, less than 500 wppm or less than 100 wppm acetic acid.

[0100] In one embodiment, all or a portion of the first distillate in line 115 is directed to ion exchange reactor bed 128. In another embodiment, all or a portion of the first distillate in line 115 may feed a reactive distillation column (not shown) to hydrolyze the ethyl acetate. This portion of the distillate is hydrolyzed to form a hydrolyzed stream, and the outflow stream of the ion exchange reactor bed 128 can be directly or indirectly returned to the reaction zone 101 via line 116. Exemplary indirect return methods may include storing or further treating the hydrolyzed stream in one or more additional columns to remove impurities prior to being sent to reaction zone 101. The outflow in line 116 comprises acetic acid and ethanol, and preferably comprises less ethyl acetate than present in line 115. Preferably, the outflow in line 116 has at least 2% less ethyl acetate than line 115, e.g., at least 10% less or at least 20% less. In terms of ranges the amount of ethyl acetate in line 116 is less than line 115 by 2% to 25%, e.g., from 5 to 22% or from 7 to 20%. Preferably, the outflow in line 116 has at least 0.5% more ethanol than line 115, e.g., at least 2% more or at least 4% more. In terms of ranges the amount of ethanol in line 116 is more than line 115 by 0.5% to 20%, e.g., from 2 to 20% or from 4 to 20%. In addition, the outflow in line 116 may also comprise less water than is present in line 115.

[0101] In some embodiments, the first distillate in line 115 may be further separated, e.g., in a distillation column (not shown), into an acetaldehyde stream and an ethyl acetate stream. Either

of these streams may be returned to the reactor 103 (either directly or through ion exchange reaction bed 128) or separated from system 100 as a separate product.

[0102] Some species, such as acetals, may decompose in first column 107 such that very low amounts, or even no detectable amounts, of acetals remain in the distillate or residue.

[0103] To recover ethanol, the residue in line 114 may be further separated in a second column 108, also referred to as an “acid separation column.” An acid separation column may be used when the acetic acid concentration in the first residue is greater than 1 wt.%, e.g., greater than 5 wt.%. Second column 108 yields a second residue in line 117 comprising acetic acid and water, and a second distillate in line 118 comprising ethanol and ethyl acetate. In one embodiment, a weight majority of the water and/or acetic acid fed to second column 108 is removed in the second residue in line 117, e.g., at least 60% of the water and/or acetic acid is removed in the second residue in line 117 or more preferably at least 80% of the water and/or acetic acid. An acid column may be favorable when the acetic acid concentration in the first residue is greater 50 wppm, e.g., greater than 0.1 wt.%, 1 wt.%, e.g., greater than 5 wt.%.

[0104] In one embodiment first residue in line 114 may be preheated prior to being introduced into second column 108. The first residue in line 114 may be heat integrated with either the residue of the second column 108 or vapor overhead of second column 108. In some embodiments, esterification may be carried out in the vapor phase that results in preheating a portion of first residue in line 114 to form an intermediate vapor feed (not shown). Esterifying the acetic acid in first residue in line 114 increases the ethyl acetate concentration which leads to increases in the size of second column 108 as well increases in reboiler duty. Thus, the conversion of acetic acid may be controlled depending on the initial ethyl acetate concentration withdrawn from first column. To maintain an efficient separation the ethyl acetate concentration of the first residue in line 118 feed to second column is preferably less than 1000 wppm, e.g., less than 800 wppm or less than 600 wppm.

[0105] Second column 108 operates in a manner to concentrate the ethanol from first residue such that a majority of the ethanol is carried overhead. Thus, the residue of second column 108 may have a low ethanol concentration of less than 5 wt.%, e.g. less than 1 wt.% or less than 0.5 wt.%. Lower ethanol concentrations may be achieved without significant increases in reboiler duty or column size. Thus, in some embodiments it is efficient to reduce the ethanol concentration in the residue to less than 50 wppm, or more preferably less than 25 wppm. As

described herein, the residue of second column 108 may be treated and lower concentrations of ethanol allow the residue to be treated without generating further impurities.

[0106] The first residue in line 114 is introduced to second column 108 preferably in the top part of column 108, e.g., top half or top third. Feeding first residue in line 114 in a lower portion of second column 108 may unnecessarily increase the energy requirements of second column. Feeding first residue in line 114 in a lower portion of second column 108 may unnecessarily increase the energy requirements of second column. Acid column 108 may be a tray column or packed column. Second column 108 may be a tray column having from 10 to 110 theoretical trays, e.g. from 15 to 95 theoretical trays or from 20 to 75 theoretical trays. Additional trays may be used if necessary to further reduce the ethanol concentration in the residue. In one embodiment, the reboiler duty and column size may be reduced by increasing the number of trays. Although the temperature and pressure of second column 108 may vary, when at atmospheric pressure the temperature of the second residue in line 117 preferably is from 95°C to 160°C, e.g., from 100°C to 150°C or from 110°C to 145°C. In one embodiment, when first residue in line 118 is preheated to a temperature that is within 20°C of the temperature of second residue in line 131, e.g., within 15°C or within 10°C. The temperature of the second distillate exiting in line 118 preferably is from 50°C to 120°C, e.g., from 75°C to 118°C or from 80°C to 115°C. The temperature gradient may be sharper in the base of second column 108.

[0107] The pressure of second column 108 may range from 0.1 kPa to 510 kPa, e.g., from 1 kPa to 475 kPa or from 1 kPa to 375 kPa. In one embodiment, second column 130 operates above atmospheric pressure, e.g., above 170 kPa or above 375 kPa. Second column 130 may be constructed of a material such as 316L SS, Allot 2205 or Hastelloy C, depending on the operating pressure. The reboiler duty and column size for second column remain relatively constant until the ethanol concentration in the second distillate in line 118 is greater than 90 wt.%.

[0108] Second column 108 also forms an overhead, which is withdrawn in line 118, and which may be condensed and refluxed, for example, at a ratio from 12:1 to 1:12, e.g., from 10:1 to 1:10 or from 8:1 to 1:8. The overhead in line 118 preferably comprises 85 to 92 wt.% ethanol, e.g., about 87 to 90 wt.% ethanol, with the remaining balance being water and ethyl acetate.

[0109] In one embodiment, water may be removed prior to recovering the ethanol product. In one embodiment, the overhead in line 118 may comprise less than 15 wt.% water, e.g., less than

10 wt.% water or less than 8 wt.% water. In embodiments, overhead vapor 118 may be fed to a water separator (not shown), which may be an adsorption unit, membrane, molecular sieves, extractive column distillation, or a combination thereof. For example, in optional embodiments, when ethyl acetate is in the feed to reactor 103, second residue in line 131 exemplified in Table 5 may also comprise high boiling point components.

[0110] Exemplary components for the distillate and residue compositions for second column 108 are provided in Table 5 below. It should be understood that the distillate and residue may also contain other components, not listed in Table 5.

TABLE 5
SECOND COLUMN 108 (FIG. 2)

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Second Distillate</u>			
Ethanol	80 to 96	85 to 92	87 to 90
Ethyl Acetate	< 30	0.001 to 15	0.005 to 4
Acetaldehyde	< 20	0.001 to 15	0.005 to 4
Water	< 20	0.001 to 10	0.01 to 8
Acetal	< 2	0.001 to 1	0.005 to 0.5
<u>Second Residue</u>			
Acetic Acid	0.1 to 45	0.2 to 40	0.5 to 35
Water	45 to 100	55 to 99.8	65 to 99.5
Ethyl Acetate	<2	<1	<0.5
Ethanol	<5	0.001 to 5	<2

[0111] The weight ratio of ethanol in the second distillate in line 118 to ethanol in the second residue in line 117 preferably is at least 35:1. Preferably, the second distillate in line 118 is substantially free of acetic acid and may only contain, if any, trace amounts of acetic acid. Preferably, the second distillate in line 118 contains substantially no ethyl acetate.

[0112] In one embodiment, ethyl acetate fed to second column 108 may concentrate in the vapor overhead and pass through in second distillate in line 118. Thus, preferably no ethyl acetate is withdrawn in the second residue in line 117. Advantageously this allows most of the ethyl acetate to be subsequently recovered without having to further process the second residue in line 117.

[0113] In one embodiment, water may be removed from the second distillate in line 118 using a water removal unit as described above in FIG. 1. The water removal unit is selected from the

group consisting of adsorption unit, membrane, molecular sieves, extractive column distillation, and combinations thereof.

[0114] In optional embodiments, the feed to reactor 103 may comprise acetic acid and/or ethyl acetate. When ethyl acetate is used alone as a feed, the crude ethanol product may comprise substantially no water and/or acetic acid. There may be high boiling point components, such as alcohols having more than 2 carbon atoms, e.g., n-propanol, isopropanol, n-butanol, 2-butanol, and mixtures thereof. High boiling point components refer to compounds having a boiling point that is greater than ethanol. The high boiling point components may be removed in second column 108 in the second residue in line 117 described herein.

[0115] The remaining water from the second distillate in line 118 may be removed in further embodiments of the present invention. Depending on the water concentration, the ethanol product may be derived from the second distillate in line 118. Some applications, such as industrial ethanol applications, may tolerate water in the ethanol product, while other applications, such as fuel applications, may require an anhydrous ethanol. The amount of water in the second distillate in line 118 may be closer to the azeotropic amount of water, e.g., at least 4 wt.%, preferably less than 20 wt.%, e.g., less than 12 wt.% or less than 7.5 wt.%. Water may be removed from the second distillate in line 118 using several different separation techniques as described herein. Particularly preferred techniques include the use of distillation column, membranes, adsorption units, and combinations thereof.

[0116] In some embodiments, where the second distillate comprises some ethyl acetate, primarily due to the equilibrium reaction with acetic acid, a further distillation column may be used to separate ethyl acetate and ethanol as shown in FIG. 2. FIG. 2, shows a third column 125, referred to as a secondary light ends column, for removing ethyl acetate from the second distillate in line 118 into a third distillate in line 126.

[0117] Light ends column 125 may be a tray column or packed column. In FIG. 2, third column 125 may be a tray column having from 5 to 90 theoretical trays, e.g. from 10 to 60 theoretical trays or from 15 to 50 theoretical trays.

[0118] The feed location of second distillate stream 118 may vary depending on ethyl acetate concentration and it is preferred to feed second distillate stream 118 to the upper portion of third column 125. Higher concentrations of ethyl acetate may be fed at a higher location in third column 125. The feed location should avoid the very top trays, near the reflux, to avoid excess

reboiler duty requirements for the column and an increase in column size. For example, in a column having 45 actual trays, the feed location should be between 10 to 15 trays from the top. Feeding at a point above this may increase the reboiler duty and size of light ends column 125.

[0119] Second distillate stream 118 may be fed to third column 125 at a temperature of up to 70°C, e.g., up to 50°C, or up to 40°C. In some embodiments it is not necessary to preheat second distillate stream 118.

[0120] Ethyl acetate may be concentrated in the third distillate in line 126. Due to the relatively lower amounts of ethyl acetate fed to third column 125, third distillate in line 126 also comprises substantial amounts of ethanol. To recover the ethanol, third distillate in line 126 may be fed to first column as an ethyl acetate recycle stream. Because this increased the demands on the first and second columns, it is preferred that the concentration of ethanol in third distillate in line 126 be from 70 to 90 wt.%, e.g., from 72 to 88 wt.%, or from 75 to 85 wt.%.

[0121] In other embodiments, a portion of third distillate in line 126 may be purged from the system as a separate product, such as an ethyl acetate solvent.

[0122] In some embodiments to recover the ethanol without sending third distillate in line 126 back to first column 107, the ethanol may be recovered using an extractive column (not shown).

[0123] In an optional embodiment, the third residue may be further processed to recover ethanol with a desired amount of water, for example, using a further distillation column, adsorption unit, membrane or combination thereof, may be used to further remove water from third residue in line 127 as necessary. In some embodiments, the water is removed prior to third column 125 using a water separator and thus further drying of the ethanol is not required.

[0124] Third column 125 is preferably a tray column as described above and preferably operates at atmospheric pressure. The temperature of the third residue in line 127 exiting from third column 125 preferably is from 65°C to 110°C, e.g., from 70°C to 100°C or from 75°C to 80°C. The temperature of the third distillate in line 126 exiting from third column 125 preferably is from 30°C to 70°C, e.g., from 40°C to 65°C or from 50°C to 65°C.

[0125] The pressure of third column 125 may range from 0.1 kPa to 510 kPa, e.g., from 1 kPa to 475 kPa or from 1 kPa to 375 kPa. In some embodiments, third column 125 may operate under a vacuum of less than 70 kPa, e.g., less than 50 kPa, or less than 20 kPa. Decreasing in operating pressure substantially decreases column diameter and reboiler duty for third column 125.

[0126] Exemplary components for ethanol mixture stream and residue compositions for third column 125 are provided in Table 6 below. It should be understood that the distillate and residue may also contain other components, not listed in Table 6.

TABLE 6
LIGHT ENDS COLUMN

	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
<u>Third Distillate</u>			
Ethanol	70 to 90	72 to 88	75 to 85
Ethyl Acetate	1 to 30	1 to 25	1 to 15
Acetaldehyde	< 15	0.001 to 10	0.1 to 5
Water	< 10	0.001 to 2	0.01 to 1
Acetal	< 2	0.001 to 1	0.01 to 0.5
<u>Third Residue</u>			
Ethanol	80 to 99.5	85 to 97	90 to 95
Water	< 3	0.001 to 2	0.01 to 1
Ethyl Acetate	< 1.5	0.0001 to 1	0.001 to 0.5
Acetic Acid	< 0.5	< 0.01	0.0001 to 0.01

[0127] When first residue in line 114 comprise low amounts of acetic acid and/or there is no esterification of first residue, such that the ethyl acetate concentration is less than 50 wppm, third column 125 may be optional and removed. Thus, second distillate 118 (possibly after a water separation) may be the ethanol product and there is no ethyl acetate recycle stream.

[0128] As mentioned, all or a portion of the third distillate 126 can be purged from the system or returned to the first column 107. Before returning to the first column 107, all or a portion of the third distillate in line 126 can be hydrolyzed in ion exchange reactor bed 129. Additionally, all or a portion of the third distillate in line 126 can also be directed to ion exchange reactor bed 128 (along with all or a portion of the first distillate 115). In another embodiment, all or a portion of the third distillate in line 126 (along with all or a portion of the first distillate 115) may feed a reactive distillation column (not shown) to hydrolyze the ethyl acetate. This portion of the third distillate (and/or the first distillate) is hydrolyzed to form a hydrolyzed stream, and the outflow stream 116 of the ion exchange reactor bed 128 can be directly or indirectly recycled in whole or part to reactor 103. The third residue in line 127 from third column 125 may comprise ethanol and optionally water. The third residue may be further processed to recover ethanol with a desired amount of water, for example, using an ethanol product column. An ethanol product

column, adsorption unit, membrane or combination thereof, may be used to further remove water from third residue in line 127 as necessary.

[0129] Some of the residues withdrawn from the separation zone 102 comprise acetic acid and water. Depending on the amount of water and acetic acid contained in the residue of first column, e.g., 134 in FIG. 1, 107 in FIG. 2, the residue may be treated in one or more of the following processes. The following are exemplary processes for further treating the residue and it should be understood that any of the following may be used regardless of acetic acid concentration. A suitable weak acid recovery system is described in US Pub. No. 2012/0010446, the entire contents and disclosure of which is hereby incorporated by reference. When the residue comprises a majority of acetic acid, e.g., greater than 70 wt.%, the residue may be recycled to the reactor without any separation of the water. In one embodiment, the residue may be separated into an acetic acid stream and a water stream when the residue comprises a majority of acetic acid, e.g., greater than 50 wt.%. Acetic acid may also be recovered in some embodiments from the residue having a lower acetic acid concentration. The residue may be separated into the acetic acid and water streams by a distillation column or one or more membranes. If a membrane or an array of membranes is employed to separate the acetic acid from the water, the membrane or array of membranes may be selected from any suitable acid resistant membrane that is capable of removing a permeate water stream. The resulting acetic acid stream optionally is returned to the reactor 103. The resulting water stream may be used as an extractive agent or to hydrolyze an ester-containing stream in a hydrolysis unit.

[0130] In other embodiments, for example, where the residue comprises less than 50 wt.% acetic acid, possible options include one or more of: (i) returning a portion of the residue to reactor 103, (ii) neutralizing the acetic acid, (iii) reacting the acetic acid with an alcohol, or (iv) disposing of the residue in a waste water treatment facility. It also may be possible to separate a residue comprising less than 50 wt.% acetic acid using a weak acid recovery distillation column to which a solvent (optionally acting as an azeotroping agent) may be added. Exemplary solvents that may be suitable for this purpose include ethyl acetate, propyl acetate, isopropyl acetate, butyl acetate, vinyl acetate, diisopropyl ether, carbon disulfide, tetrahydrofuran, isopropanol, ethanol, and C₃-C₁₂ alkanes. When neutralizing the acetic acid, it is preferred that the residue comprises less than 10 wt.% acetic acid. Acetic acid may be neutralized with any suitable alkali or alkaline earth metal base, such as sodium hydroxide or potassium hydroxide.

When reacting acetic acid with an alcohol, it is preferred that the residue comprises less than 50 wt.% acetic acid. The alcohol may be any suitable alcohol, such as methanol, ethanol, propanol, butanol, or mixtures thereof. The reaction forms an ester that may be integrated with other systems, such as carbonylation production or an ester production process. Preferably, the alcohol comprises ethanol and the resulting ester comprises ethyl acetate. Optionally, the resulting ester may be fed to the hydrogenation reactor.

[0131] In some embodiments, when the residue in line 131 comprises very minor amounts of acetic acid, e.g., less than 5 wt.% or less than 1 wt.%, the residue may be neutralized and/or diluted before being disposed of to a waste water treatment facility. The organic content, e.g., acetic acid content, of the residue beneficially may be suitable to feed microorganisms used in a waste water treatment facility.

[0132] The associated condensers and liquid separation vessels that may be employed with each of the distillation columns may be of any conventional design and are simplified in the figures. Heat may be supplied to the base of each column or to a circulating bottom stream through a heat exchanger or reboiler. Other types of reboilers, such as internal reboilers, may also be used. The heat that is provided to the reboilers may be derived from any heat generated during the process that is integrated with the reboilers or from an external source such as another heat generating chemical process or a boiler. Although one reactor and one flasher are shown in the figures, additional reactors, flashers, condensers, heating elements, and other components may be used in various embodiments of the present invention. As will be recognized by those skilled in the art, various condensers, pumps, compressors, reboilers, drums, valves, connectors, separation vessels, etc., normally employed in carrying out chemical processes may also be combined and employed in the processes of the present invention.

[0133] The temperatures and pressures employed in the columns may vary. Temperatures within the various zones will normally range between the boiling points of the composition removed as the distillate and the composition removed as the residue. As will be recognized by those skilled in the art, the temperature at a given location in an operating distillation column is dependent on the composition of the material at that location and the pressure of column. In addition, feed rates may vary depending on the size of the production process and, if described, may be generically referred to in terms of feed weight ratios.

[0134] The ethanol product produced by the process of the present invention may be an industrial grade ethanol or fuel grade ethanol. Exemplary finished ethanol compositional ranges are provided below in Table 7.

TABLE 7
FINISHED ETHANOL COMPOSITIONS

Component	Conc. (wt.%)	Conc. (wt.%)	Conc. (wt.%)
Ethanol	85 to 99.9	90 to 99.5	92 to 99.5
Water	< 12	0.1 to 9	0.5 to 8
Acetic Acid	< 1	< 0.1	< 0.01
Ethyl Acetate	< 2	< 0.5	< 0.05
Acetal	< 0.05	< 0.01	< 0.005
Acetone	< 0.05	< 0.01	< 0.005
Isopropanol	< 0.5	< 0.1	< 0.05
n-propanol	< 0.5	< 0.1	< 0.05

[0135] The finished ethanol composition of the present invention preferably contains very low amounts, e.g., less than 0.5 wt.%, of other alcohols, such as methanol, butanol, isobutanol, isoamyl alcohol and other C4-C20 alcohols. In one embodiment, the amount of isopropanol in the finished ethanol composition is from 80 to 1,000 wppm, e.g., from 95 to 1,000 wppm, from 100 to 700 wppm, or from 150 to 500 wppm. In one embodiment, the finished ethanol composition is substantially free of acetaldehyde, optionally comprising less than 8 wppm acetaldehyde, e.g., less than 5 wppm or less than 1 wppm.

[0136] The finished ethanol composition produced by the embodiments of the present invention may be used in a variety of applications including applications as fuels, solvents, chemical feedstocks, pharmaceutical products, cleansers, sanitizers, hydrogen transport or consumption. In fuel applications, the finished ethanol composition may be blended with gasoline for motor vehicles such as automobiles, boats and small piston engine aircraft. In non-fuel applications, the finished ethanol composition may be used as a solvent for toiletry and cosmetic preparations, detergents, disinfectants, coatings, inks, and pharmaceuticals. The finished ethanol composition may also be used as a processing solvent in manufacturing processes for medicinal products, food preparations, dyes, photochemicals and latex processing.

[0137] The finished ethanol composition may also be used as a chemical feedstock to make other chemicals such as vinegar, ethyl acrylate, ethyl acetate, ethylene, glycol ethers, ethylamines, aldehydes, and higher alcohols, especially butanol. In the production of ethyl acetate, the finished ethanol composition may be esterified with acetic acid. In another application, the finished ethanol composition may be dehydrated to produce ethylene.

[0138] In order that the invention disclosed herein may be more efficiently understood, examples are provided below. The following examples describe the conversion of ethyl acetate in the recycle streams.

Examples

[0139] Simulated mixtures of ethyl acetate, water, ethanol, and small amounts of acetic acid corresponding to the recycle streams of an acetic acid hydrogenation and crude ethanol purification process of certain embodiments of the present invention are shown in Table 7 as initial compositions (wt %). An equilibrium for the mixtures after the hydrolysis of ethyl acetate was calculated with the equilibrium compositions (wt %) for the given initial composition shown in Table 7 as well, along with the calculated ethyl acetate conversion in going from the the initial mixture composition to the equilibrium composition. Such conversions are calculated without the use of an ion exchange resin reactor bed, as is used in certain embodiments of the present invention to hydrolyze ethyl acetate.

TABLE 7

RECYCLE STREAM ETHYL ACETATE HYDROLYSIS

	Ethyl Acetate (wt.%)	Water (wt.%)	Ethanol (wt.%)	Acetic Acid (wt.%)	Ethyl Acetate Conv. (%)
Initial Comp. #1	60	5	35	0.001	
Equilibrium Comp. #1	56.0	4.2	37.1	2.8	-6.7
Initial Comp. #2	56	1	43	0.001	
Equilibrium Comp. #2	55.3	0.9	43.4	0.5	-1.3
Initial Comp. #3	53	5	42	0.001	
Equilibrium Comp. #3	49.8	4.4	43.7	2.2	-6.0
Initial Comp. #4	51	10	39	0.001	
Equilibrium Comp. #4	45.0	8.8	42.1	4.1	-11.7
Initial Comp. #5	48.5	15	36.5	0.001	
Equilibrium Comp. #5	40.1	13.3	40.9	5.7	-17.2

[0140] While the invention has been described in detail, modifications within the spirit and scope of the invention will be readily apparent to those of skill in the art. In view of the foregoing discussion, relevant knowledge in the art and references discussed above in connection with the Background and Detailed Description, the disclosures of which are all incorporated herein by reference. In addition, it should be understood that aspects of the invention and portions of various embodiments and various features recited below and/or in the appended claims may be combined or interchanged either in whole or in part. In the foregoing descriptions of the various embodiments, those embodiments which refer to another embodiment may be appropriately combined with other embodiments as will be appreciated by one of skill in the art. Furthermore, those of ordinary skill in the art will appreciate that the foregoing description is by way of example only, and is not intended to limit the invention.

We claim:

1. A process for purifying a crude ethanol product, comprising the steps:
 - hydrogenating an acetic acid and ethyl acetate stream in a reactor in the presence of a catalyst to form a crude ethanol product;
 - separating a portion of the crude ethanol product in a first distillation column to yield a first distillate comprising ethyl acetate and acetaldehyde, and a first residue comprising ethanol, ethyl acetate, acetic acid and water, wherein the first residue comprises a majority of the ethanol, acetic acid, and water from the crude ethanol product;
 - separating a portion of the first residue in a second distillation column to yield a second residue comprising acetic acid and water and a second distillate comprising ethanol and ethyl acetate;
 - separating a portion of the second distillate in a third distillation column to yield a third residue comprising ethanol and a third distillate comprising ethyl acetate; and
 - hydrolyzing at least a portion of the first distillate or third distillate to form a hydrolyzed stream.
2. The process of claim 1, wherein the step of hydrolyzing is conducted under liquid phase conditions.
3. The process of any of the preceding claims, wherein the at least a portion of the first distillate or third distillate is hydrolyzed to form the hydrolyzed stream comprising acetic acid and ethanol.
4. The process of any of the preceding claims, wherein at least a portion of the hydrolyzed stream is directly or indirectly fed to the first column or reactor.
5. The process of any of the preceding claims, wherein a portion of the first distillate and a portion of the third distillate are hydrolyzed to form the hydrolyzed stream.

6. The process of any of the preceding claims, wherein the at least a portion of one of the first distillate, or the third distillate, that is hydrolyzed has a molar ratio of water to ethyl acetate of at least 1:10.
7. The process of any of the preceding claims, wherein the at least a portion of one of the first distillate or the third distillate is hydrolyzed in the presence of a strongly acidic heterogeneous or homogenous catalyst.
8. The process of any of the preceding claims, wherein the at least a portion of one of the first distillate or the third distillate is hydrolyzed in an ion exchange reactor bed, and preferably the ion exchange reactor bed is located externally from the first column, second column and third column.
9. The process of any of the preceding claims, wherein the first column comprises a hydrolyzing section.
10. The process of any of the preceding claims, wherein the first column comprises an internal ion exchange reactor bed resin.
11. The process of any of the preceding claims, wherein the first column is a reactive distillation column.
12. The process of any of the preceding claims, wherein the first column comprises a strongly acidic heterogeneous or homogenous catalyst.
13. The process of any of the preceding claims, wherein the hydrolyzed steam comprises at least 2% less ethyl acetate than the at least a portion of the first distillate, the third distillate, or mixtures thereof prior to being hydrolyzed.

14. The process of any of the preceding claims, wherein the hydrolyzed steam comprises at least 10% less ethyl acetate than the at least a portion of the first distillate, the third distillate, or mixtures thereof prior to being hydrolyzed.

15. The process of any of the preceding claims, wherein the hydrolyzed steam comprises at least 0.5 % more ethanol than the at least a portion of the first distillate, the third distillate, or mixtures thereof prior to being hydrolyzed.

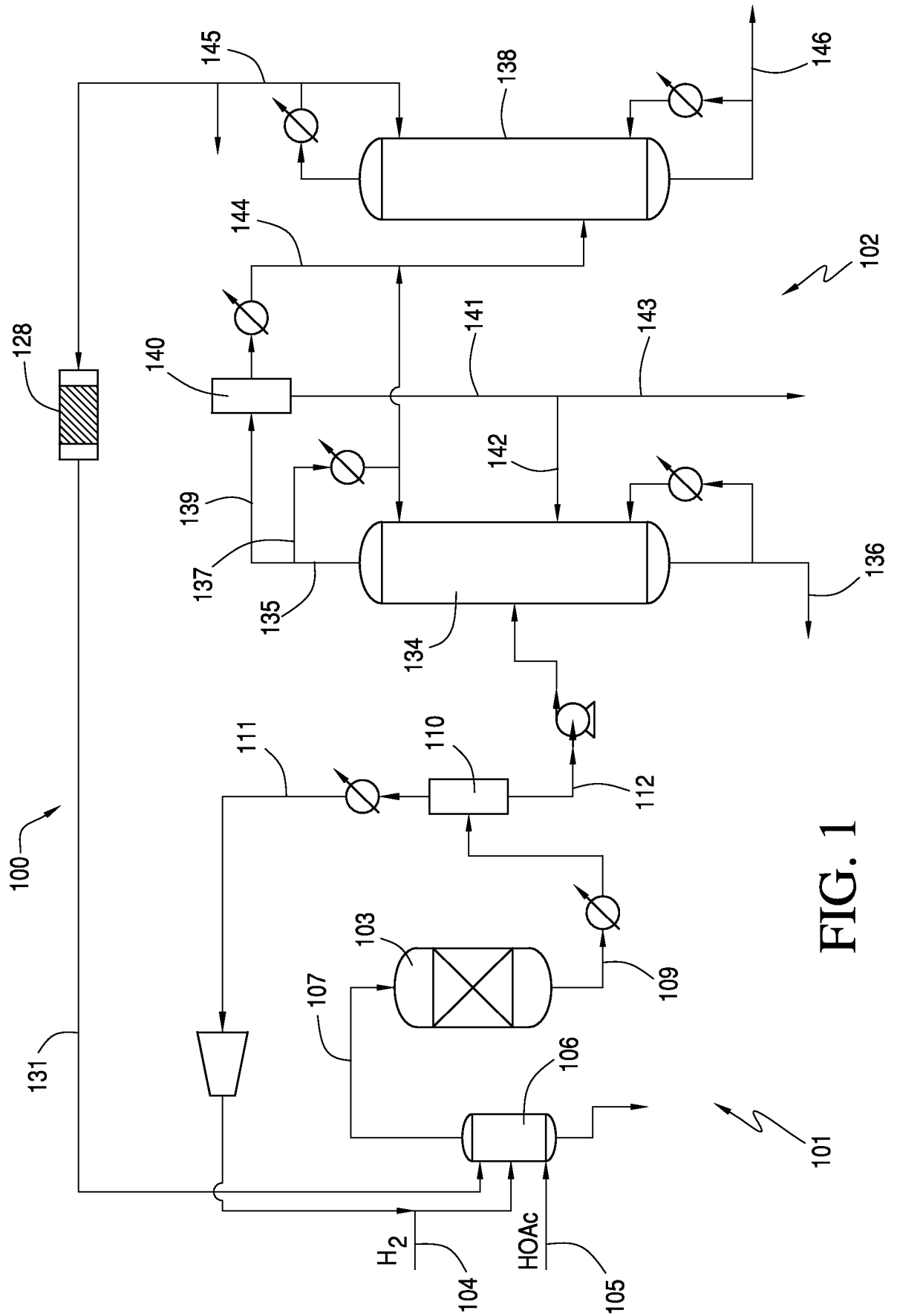


FIG. 1

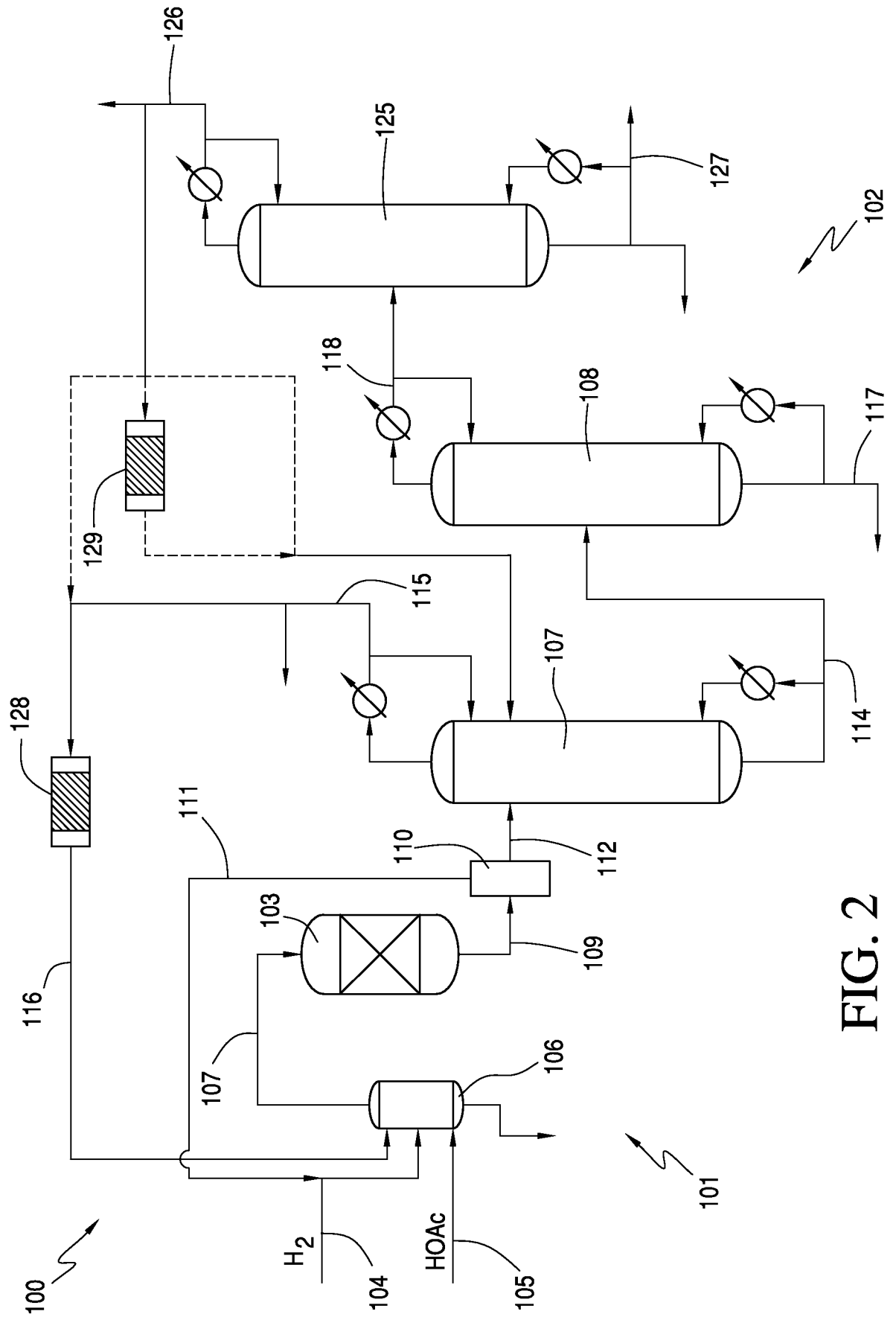


FIG. 2

INTERNATIONAL SEARCH REPORT

International application No PCT/US2012/035189

A. CLASSIFICATION OF SUBJECT MATTER INV. C07C29/149 C07C31/08 C07C29/88 ADD.				
According to International Patent Classification (IPC) or to both national classification and IPC				
B. FIELDS SEARCHED				
Minimum documentation searched (classification system followed by classification symbols) C07C				
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched				
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, CHEM ABS Data, WPI Data				
C. DOCUMENTS CONSIDERED TO BE RELEVANT				
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.		
A	US 2010/197959 A1 (JOHNSTON VICTOR J [US] ET AL) 5 August 2010 (2010-08-05) paragraphs [0070], [0095] -----	1-15		
A	EP 2 060 553 A1 (BP PLC [GB]) 20 May 2009 (2009-05-20) cited in the application paragraph [0086]; figure 1 -----	1-15		
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INTERNATIONAL SEARCH REPORT

International application No PCT/US2012/035189

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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