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(54) **SYSTEM AND METHODS FOR CONTINUOUS BIOMASS PROCESSING**

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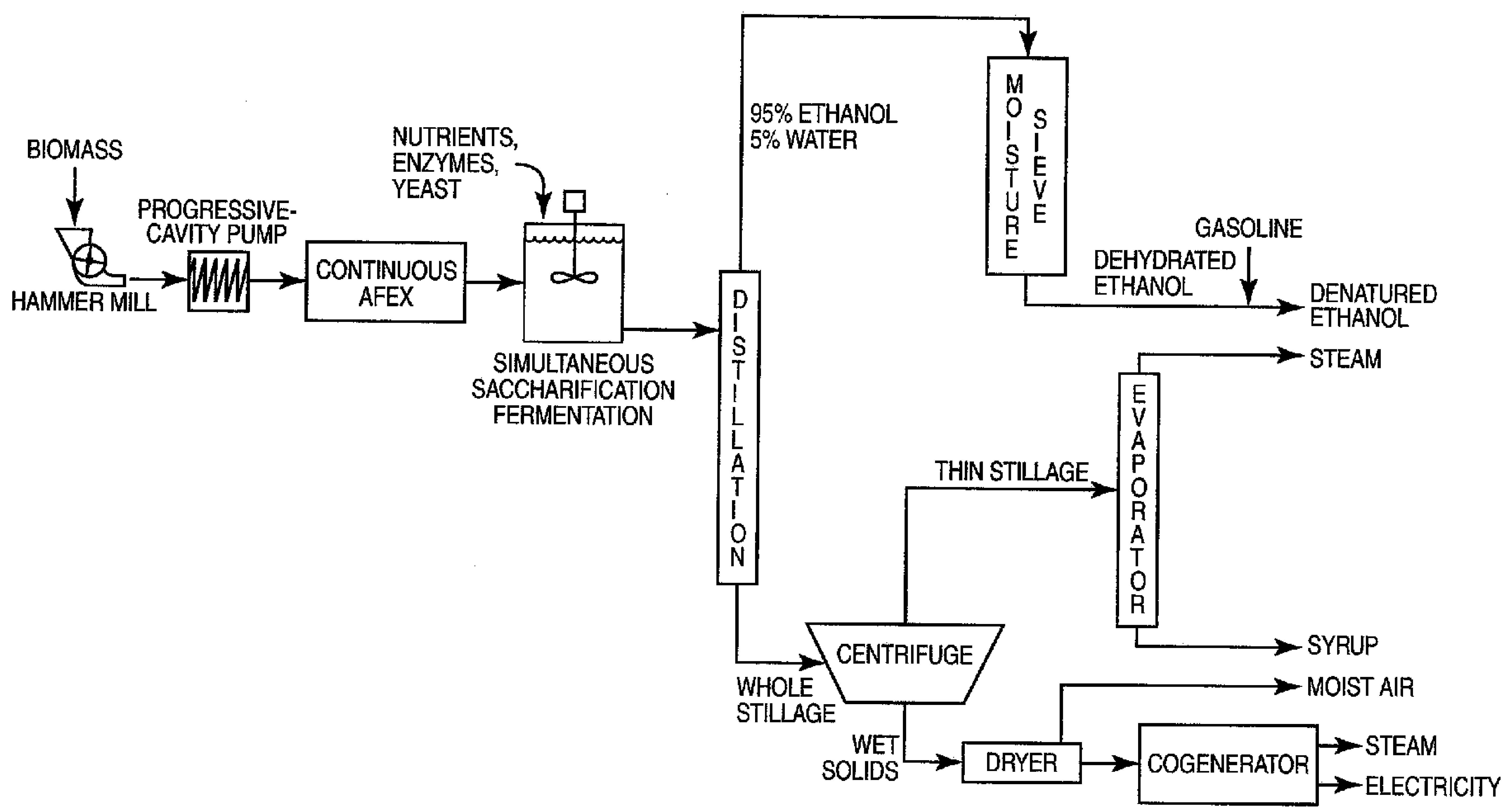
C10L 1/02 (2006.01)

(52) **U.S. Cl.** **44/605**

(57) **ABSTRACT**

This invention is directed to biomass processing. In one embodiment, the biomass is processed by contacting the biomass with a swelling agent as the biomass and swelling agent are transported through a reactor system. In another embodiment, the processed biomass is fermented. Steam is also applied in the biomass processing. The steam can be applied before, during or after the biomass is first contacted with the swelling agent.



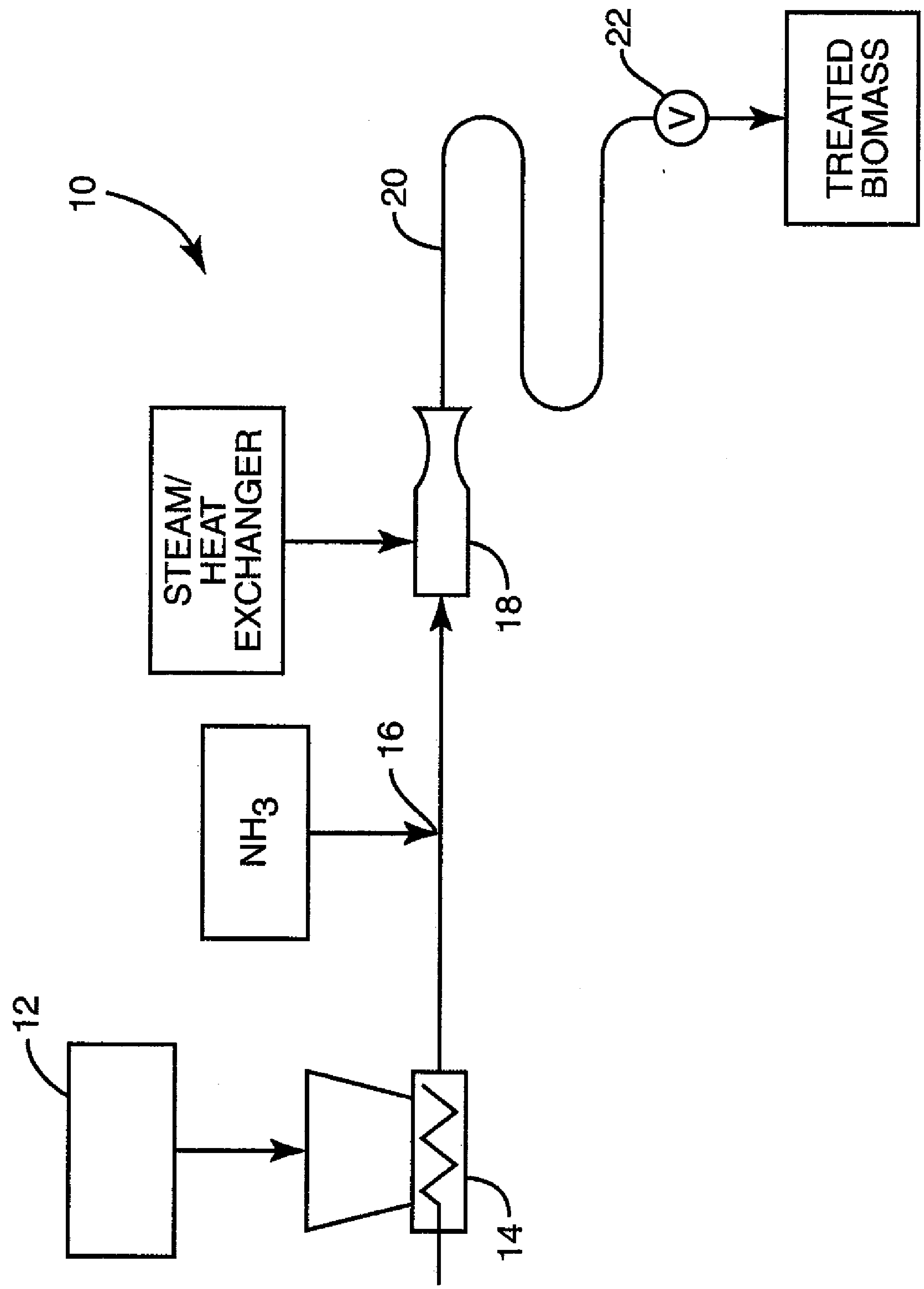

10
12
14
NH_3
16
STEAM/
HEAT
EXCHANGER
18
20
22
V
TREATED
BIOMASS

FIG. 1

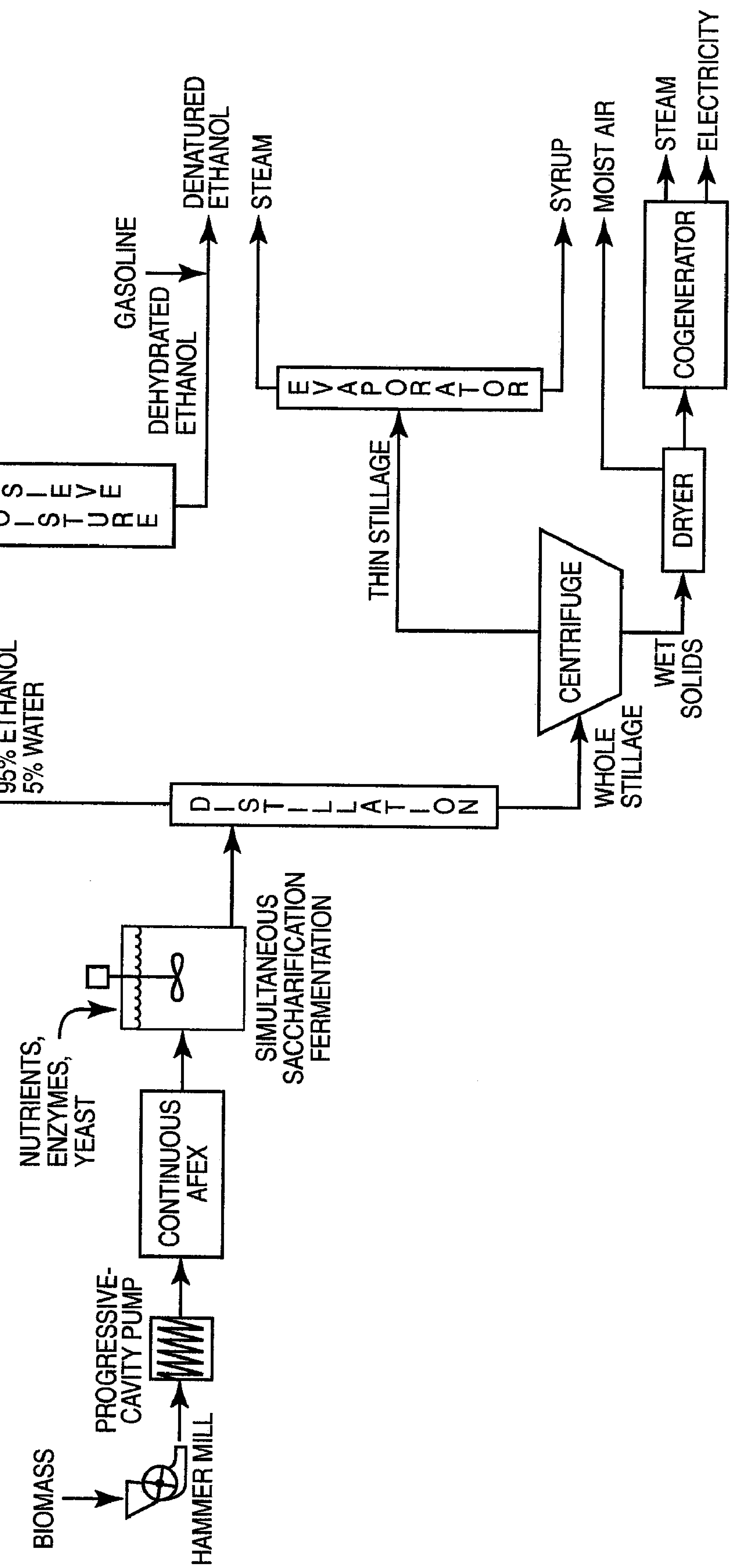

BIOMASS
HAMMER MILL
PROGRESSIVE-CAVITY PUMP
CONTINUOUS AFEX
NUTRIENTS, ENZYMES, YEAST
SIMULTANEOUS SACCHARIFICATION FERMENTATION
DISTILLATION
95% ETHANOL 5% WATER
MOLSIEVE
DEHYDRATED ETHANOL
GASOLINE
DENATURED ETHANOL
WHOLE STILLAGE
CENTRIFUGE
THIN STILLAGE
WET SOLIDS
EVAPORATOR
STEAM
SYRUP
DRYER
MOIST AIR
COGENERATOR
STEAM
ELECTRICITY

FIG. 2

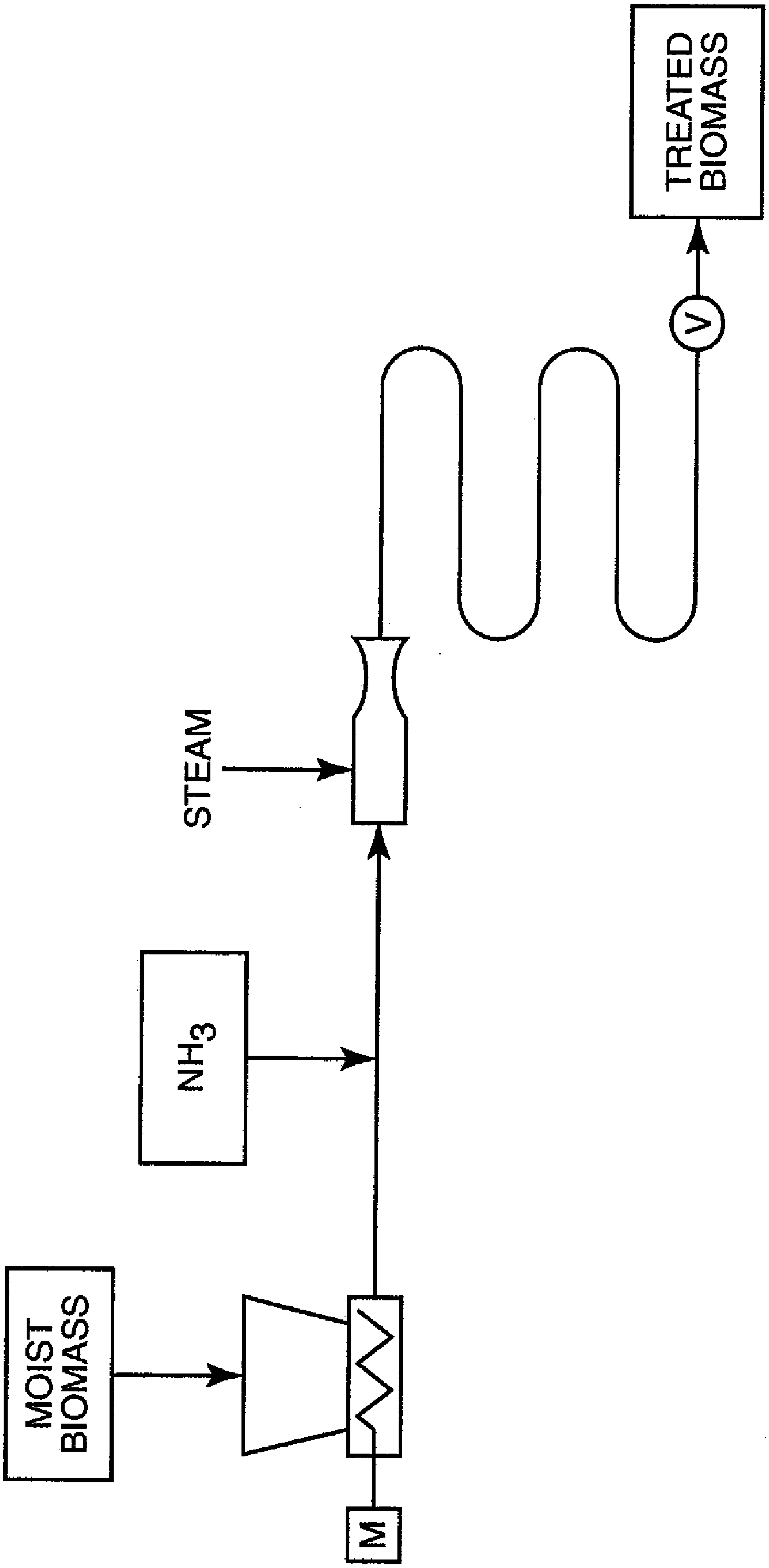


FIG. 3

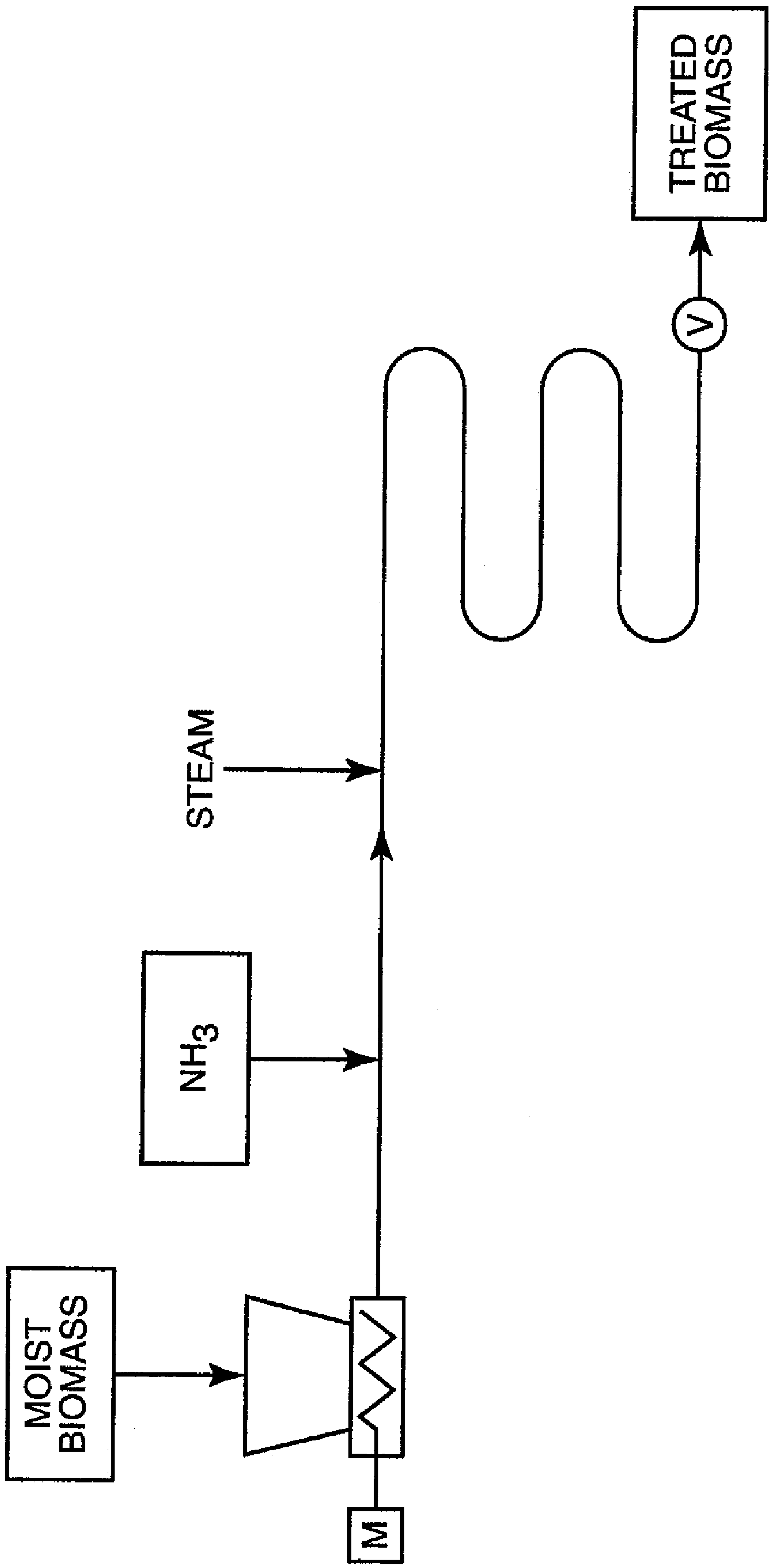


FIG. 4

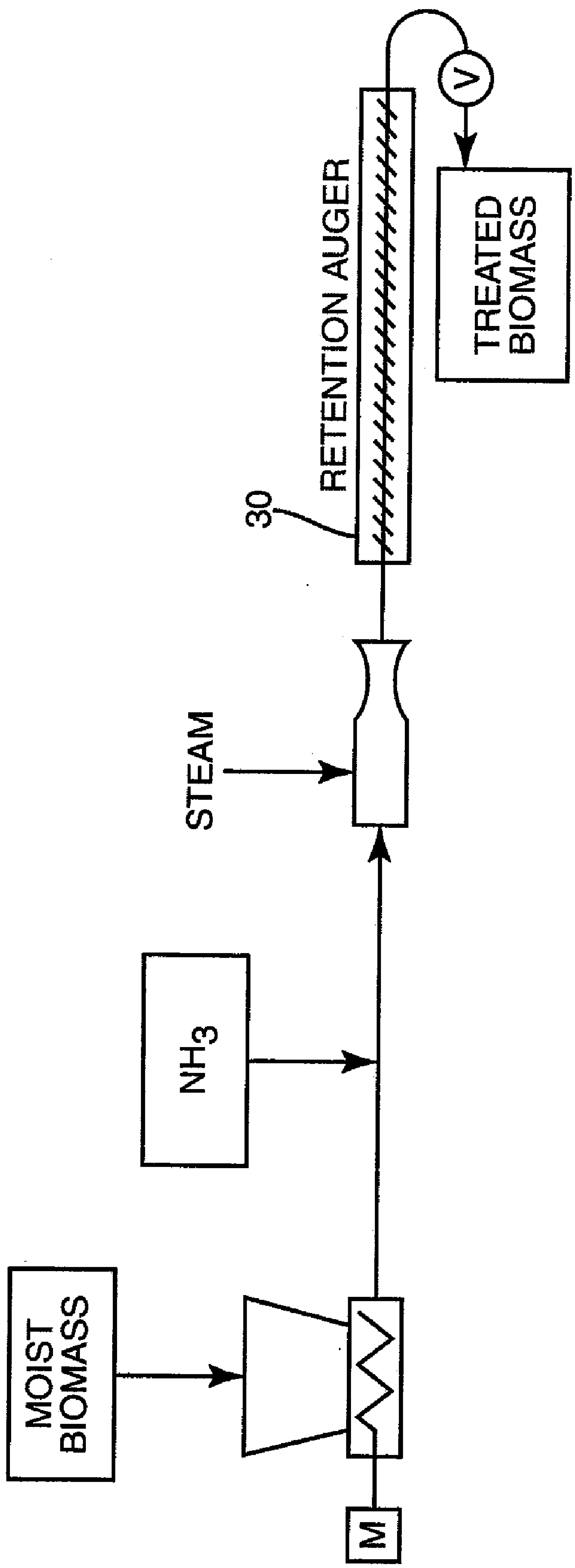

MOIST BIOMASS
M
NH_3
STEAM
30
RETENTION AUGER
V
TREATED BIOMASS

FIG. 5

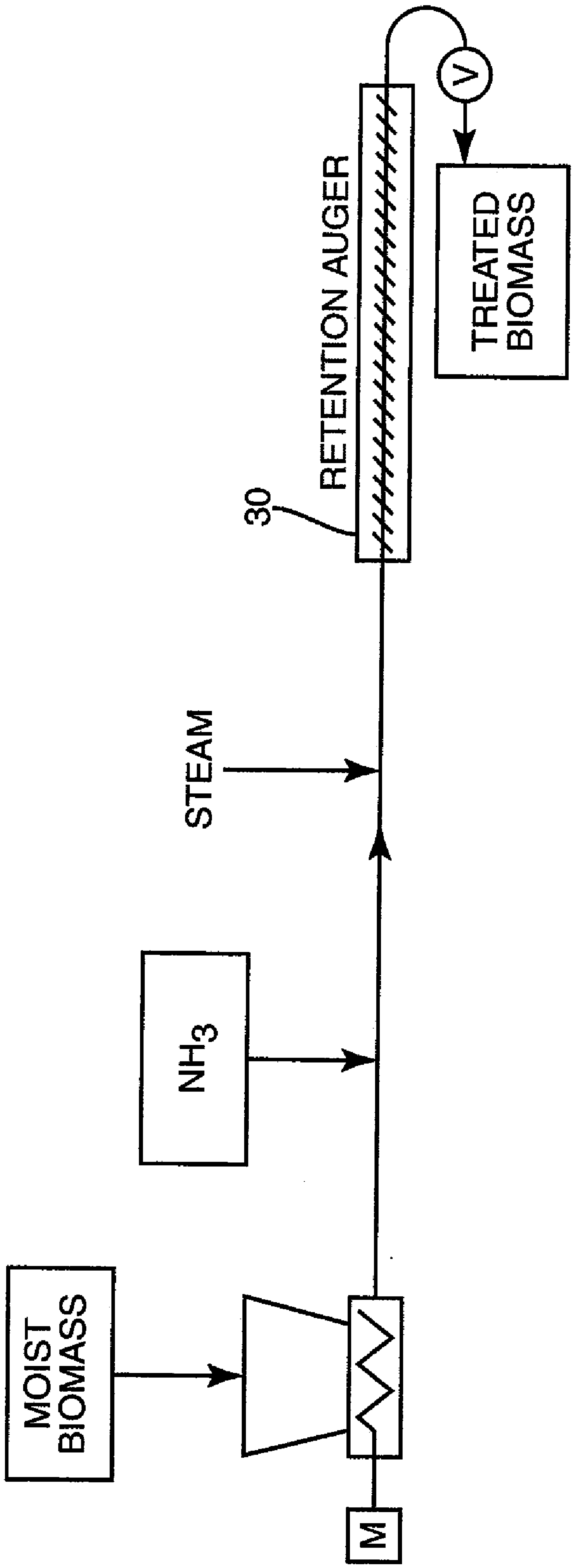

MOIST BIOMASS
M
NH_3
STEAM
30
RETENTION AUGER
V
TREATED BIOMASS

FIG. 6

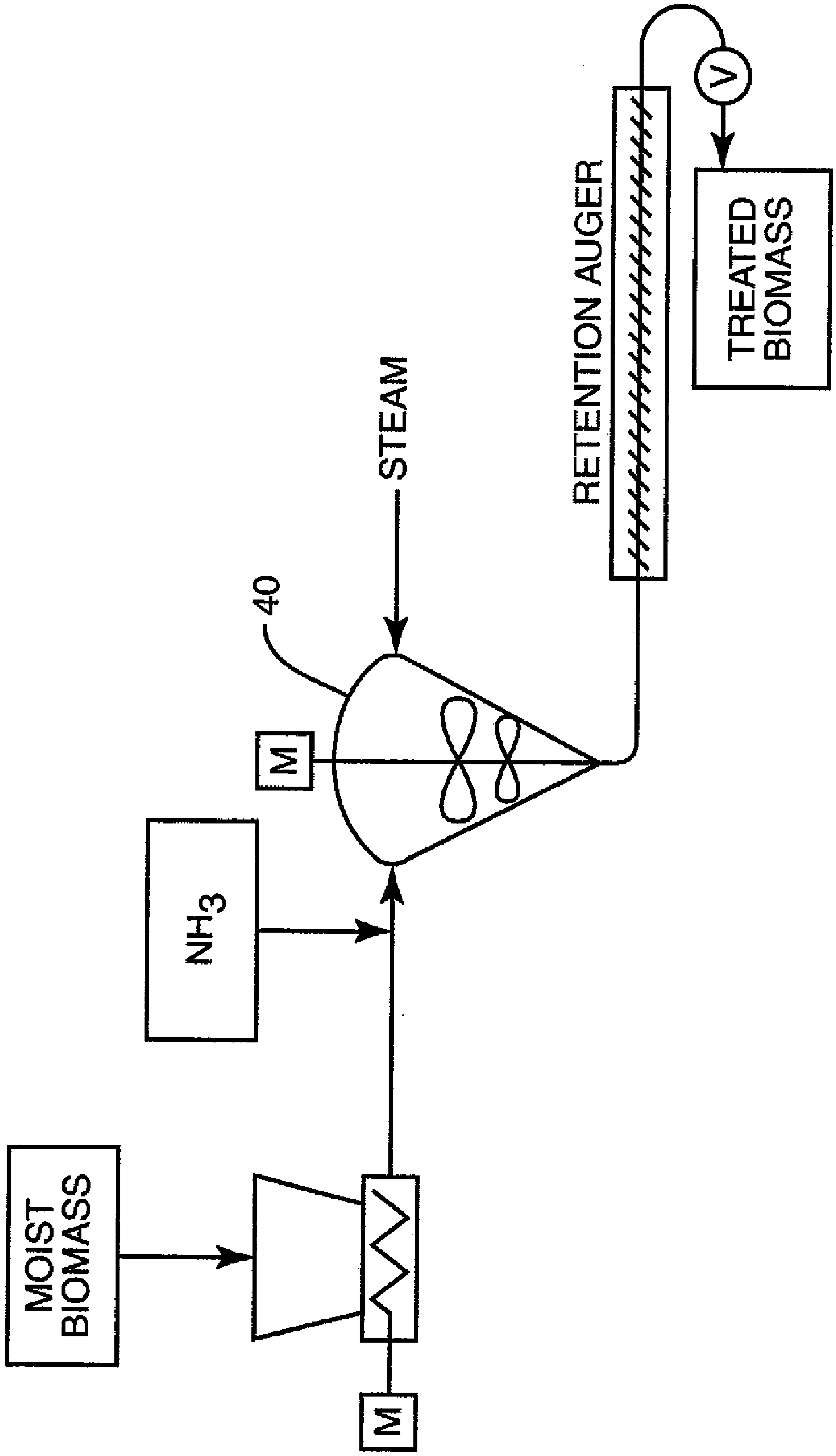

MOIST BIOMASS
M
NH_3
M
40
STEAM
RETENTION AUGER
V
TREATED BIOMASS

FIG. 7

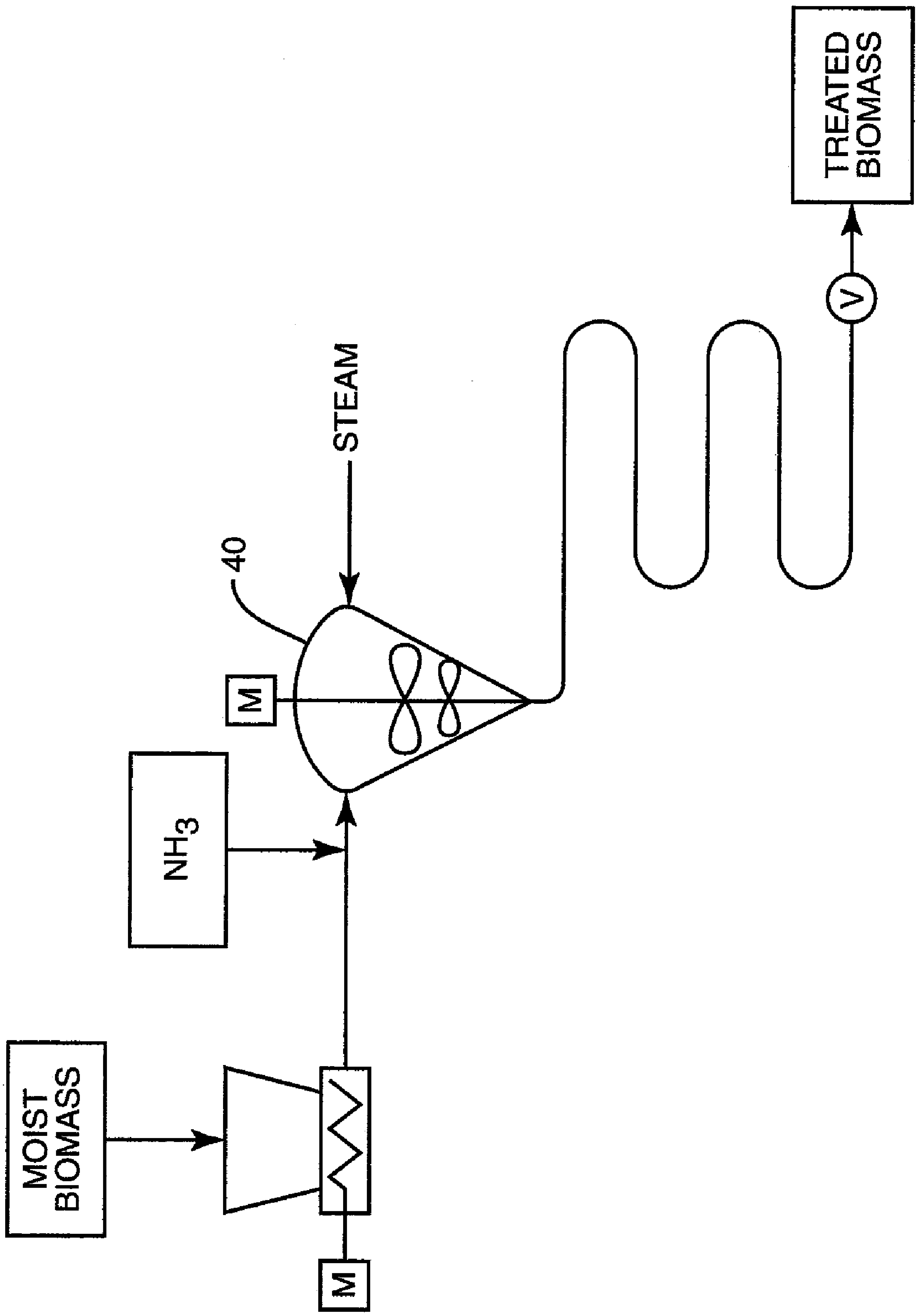


FIG. 8

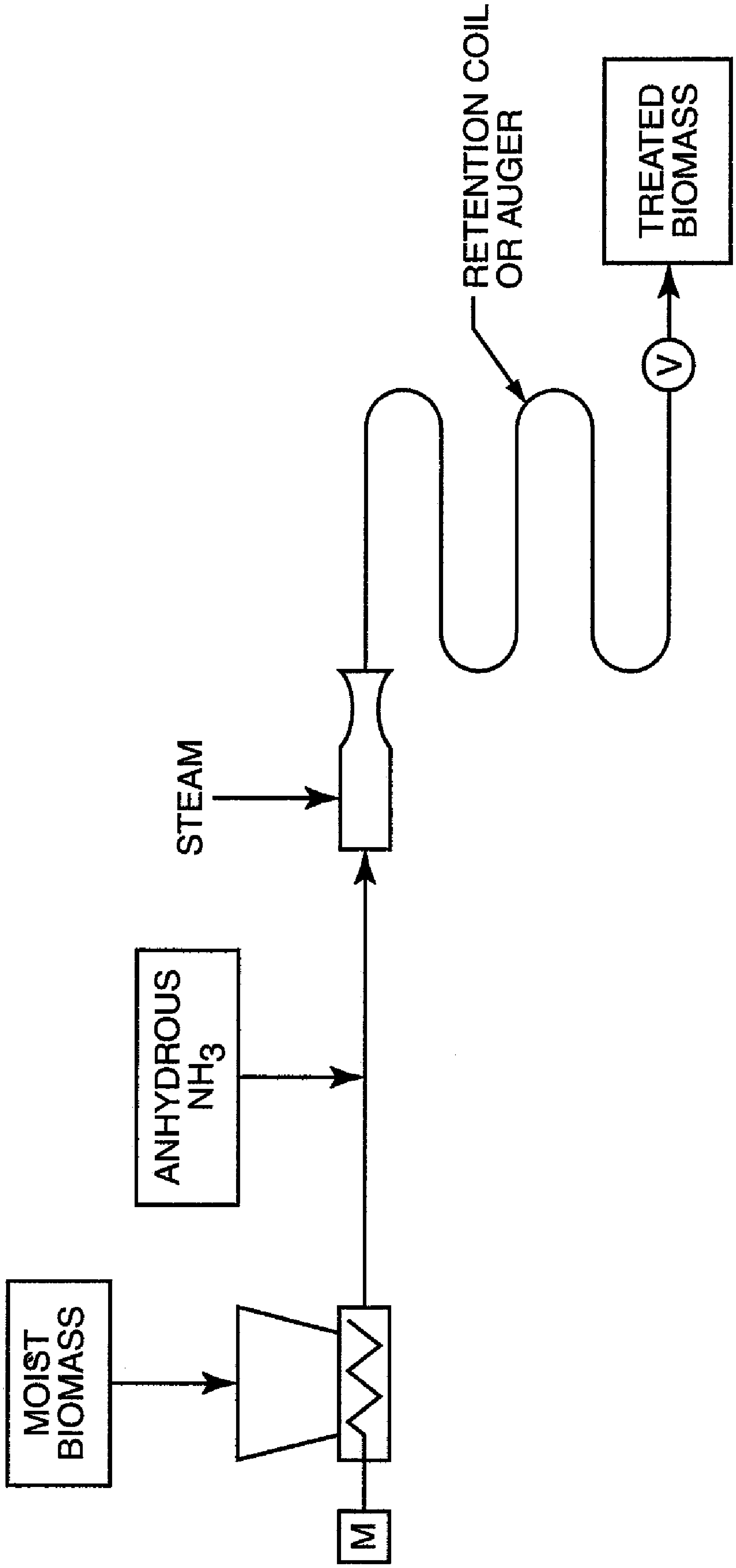

MOIST BIOMASS
M
ANHYDROUS NH_3
STEAM
RETENTION COIL OR AUGER
V
TREATED BIOMASS

FIG. 9

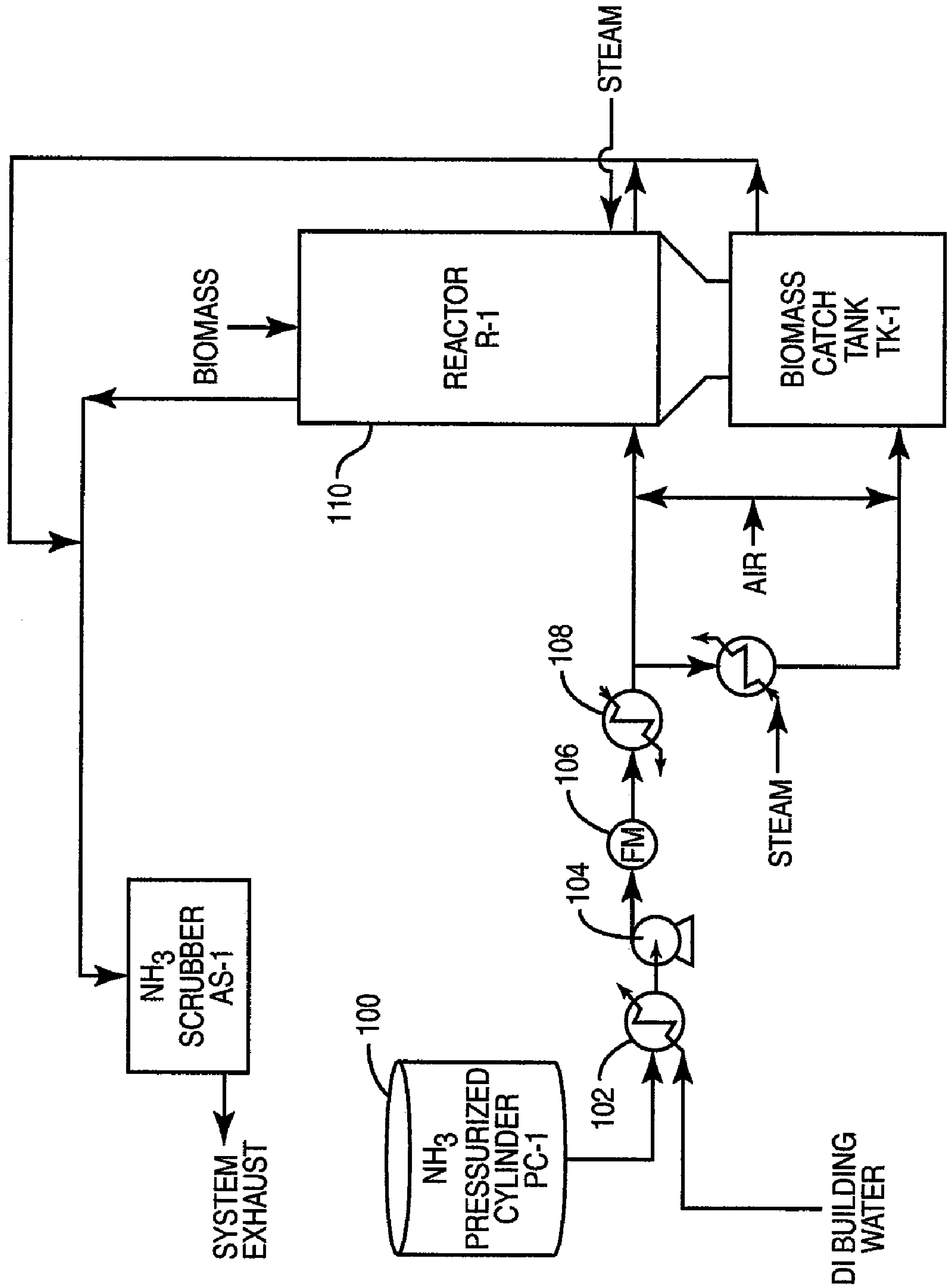

STEAM
BIOMASS
REACTOR
R-1
BIOMASS
CATCH
TANK
TK-1
110
AIR
108
106
104
FM
STEAM
NH_3
SCRUBBER
AS-1
100
NH_3
PRESSURIZED
CYLINDER
PC-1
102
SYSTEM
EXHAUST
DI BUILDING
WATER

FIG. 10

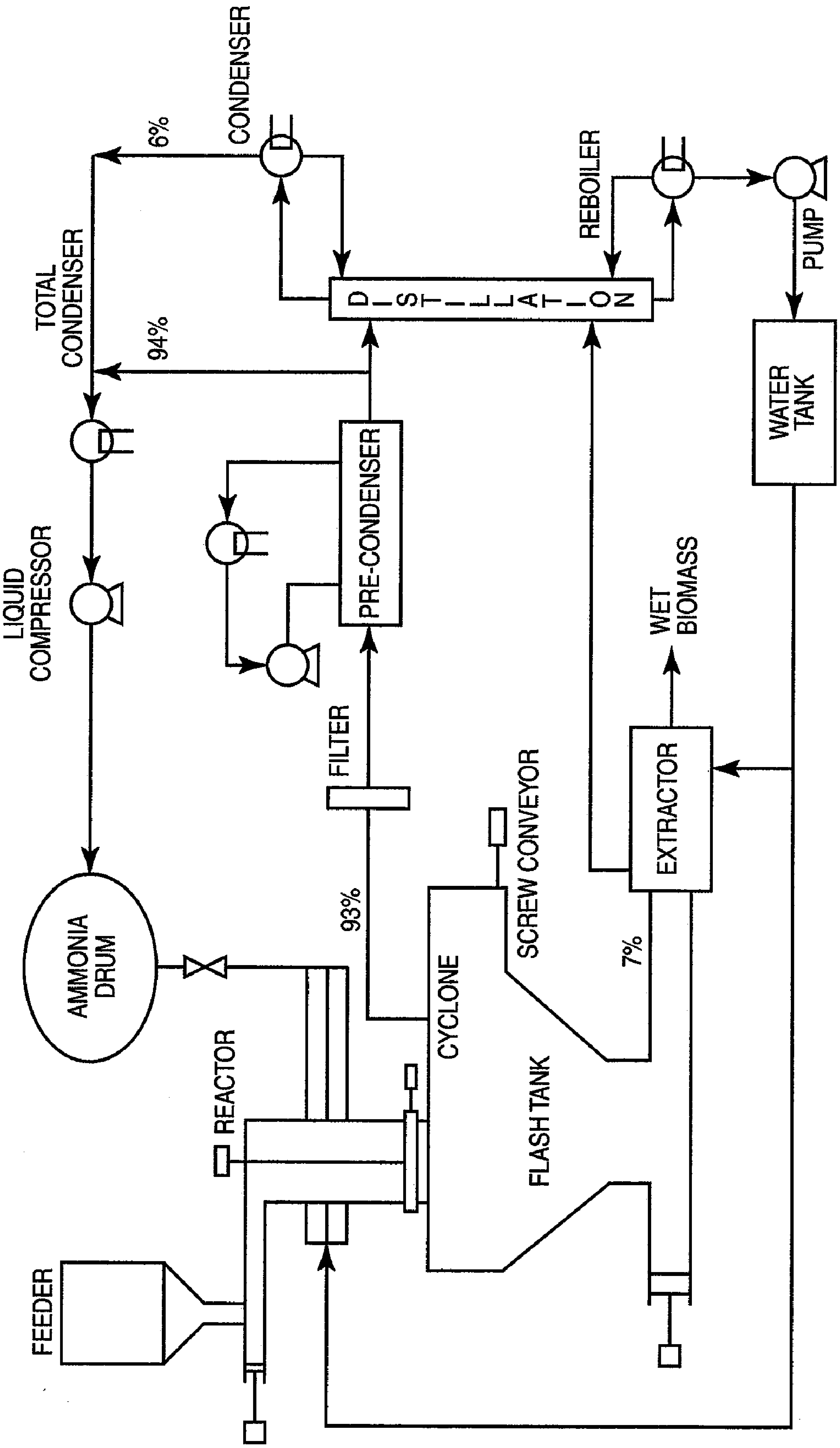

CONDENSER
6%
TOTAL CONDENSER
94%
DISTILLATION
REBOILER
PUMP
WATER TANK
LIQUID COMPRESSOR
PRE-CONDENSER
WET BIOMASS
FILTER
EXTRACTOR
SCREW CONVEYOR
93%
7%
AMMONIA DRUM
CYCLONE
REACTOR
FLASH TANK
FEEDER

FIG. 11

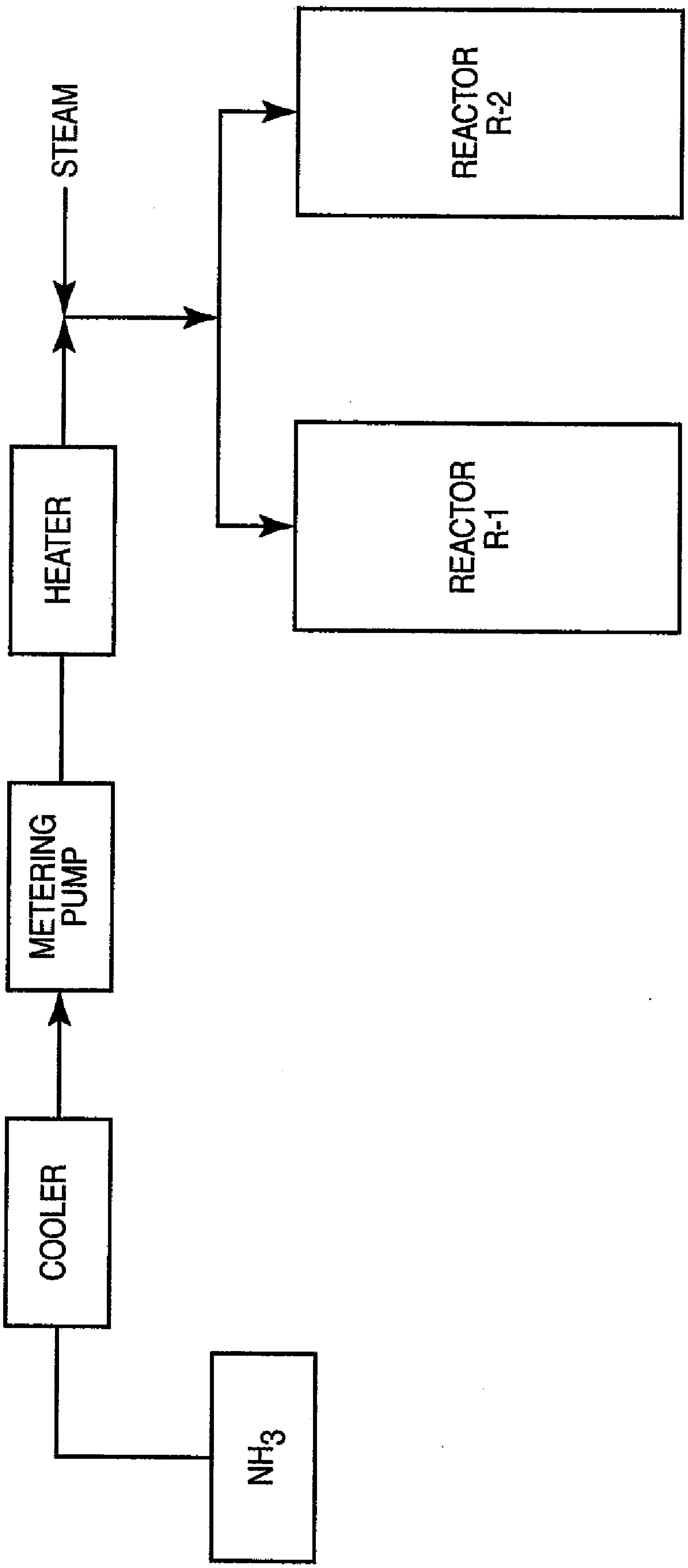

STEAM
REACTOR R-2
REACTOR R-1
HEATER
METERING PUMP
COOLER
NH_3

FIG. 12

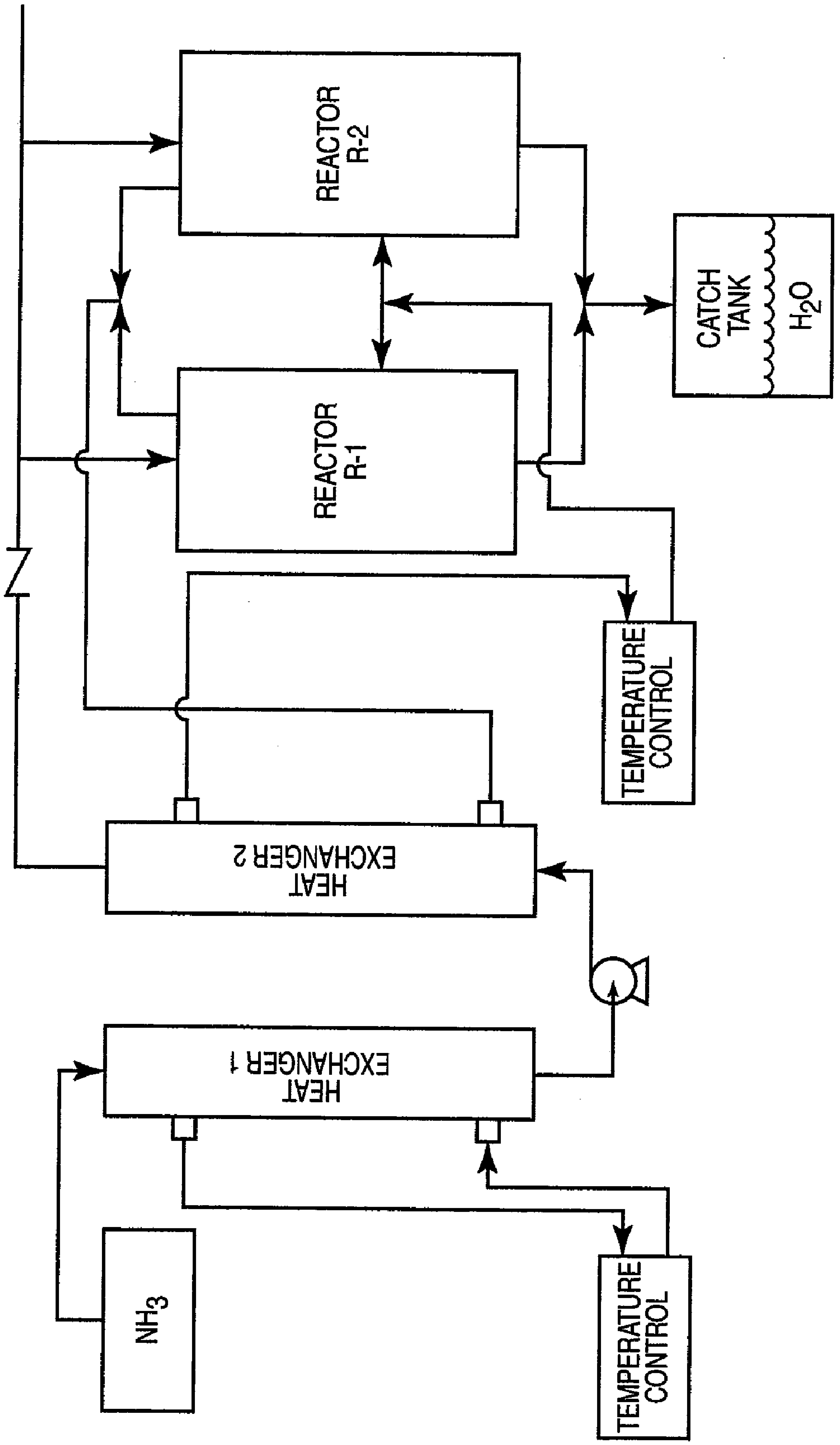

REACTOR R-2
REACTOR R-1
CATCH TANK
H_2O
TEMPERATURE CONTROL
HEAT EXCHANGER 2
HEAT EXCHANGER 1
NH_3
TEMPERATURE CONTROL

FIG. 13

SYSTEM AND METHODS FOR CONTINUOUS BIOMASS PROCESSING

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Ser. No. 60/895,673, filed Mar. 19, 2007, which is fully incorporated herein by reference.

FIELD OF INVENTION

[0002] This invention relates to biomass processing. In particular, this invention is to a process for treating or swelling cellulosic biomass using a swelling agent to swell at least a portion of the biomass.

BACKGROUND OF THE INVENTION

[0003] It is desirable to develop fuels that are cheap, clean, non-petroleum-based, and renewable. It follows that fuels derived from plant materials are becoming more popular. Plant-derived lignocellulosic biomass materials (cellulose) are known in the art to be useful for fermentation processes to produce, for example, ethanol. Brazil has demonstrated the feasibility of producing ethanol and the use of ethanol as a primary automotive fuel for more than 20 years. Similarly, the United States produces a significant amount of fuel ethanol each year. See, generally, U.S. Pat. No. 7,026,152 to Ingram, et al. Ethanol production, fueled by increasing demand, is expected to rise sharply.

[0004] Utilization of cellulose in fermentation has traditionally been hindered by its relatively un-reactive nature. The crystalline structure of cellulose and the physical protection provided by hemicellulose and lignin prevent efficient hydrolysis of these materials. To improve the lignocellulosic hydrolysis, pretreating the biomass to make the cellulose fraction more accessible to a cellulase enzyme has been applied. These processes, developed to increase the chemical and biological reactivity of cellulose, can be physical treatments (such as milling) or chemical treatments (such as use of cellulose swelling and dissolving agents). See generally, U.S. Pat. No. 4,600,590 to Dale, U.S. Pat. No. 5,171,592 to Holtzapple et al., and WO 2006/055362.

[0005] Specifically, chemical pretreatment processes have been developed to reduce the recalcitrance of cellulosic material to hydrolysis and fermentation. The ammonia fiber expansion (AFEX) process has been recognized as one of the most effective processes among the biomass pretreatment; (Mosier, N., Wyman, C., Dale, B., Elander, R., Lee, Y. Y., Holtzapple, M., Ladish, M. (2005), Bioresource Technology. 96, pp. 673-686.). The AFEX process treats biomass with ammonia at moderate temperature under pressure followed by explosive pressure release to rupture the biomass and enhance the conversion of structural carbohydrate (cellulose and hemicellulose) to fermentable sugar. The AFEX treatment effectuates a physico/chemical alteration in the biomass micro and macro structure. AFEX increase the digestibility of the biomass by de-crystallization of cellulose (Laureano-Perez, L., Teymouri, F., Alizadeh, H., Dale, B. (2005), Applied Biochemistry and Biotechnology. 121-124, pp 1081-1099; Gollapalli, L., Dale, B., Rivers, D. (2002), Applied Biochemistry and Biotechnology. 98-100, pp 23-35.), partial depolymerization of hemicellulose and lignin, cleavage of hydrogen bonds that holding cellulose and hemicellulose together, deacetylation of acetyl groups (O'Connor, J. (1972), Tappi 55:353), cleavage of lignin-carbohydrate complex linkages, lignin C—O—C bond cleavage, and increase in accessible surface area due to structural disruption (Turner, N., McDonough, C., Byers, F., Holtzapple M., Dale, B., Jun, J., Greene, L. (1990), Proceeding Western Section, American Society of Animal Science Vol. 41.).

[0006] The applicability of AFEX process for treatment of several different lignocellulosic biomasses such as corn stover (Teymouri, F., Laureano-Perez, L., Alizadeh, H., Dale, B. (2004), Applied Biochemistry and Biotechnology. 113-116, pp., 951-963), switchgrass (Alizadeh, H., Teymouri, F., Gilbert, Th., Dale, B. (2005) Applied Biochemistry and Biotechnology. 121-124, pp., 1133-1142), corn fiber (Hanchar, R., Teymouri, F., Nielson, Ch., McCalla, D., Stowers, M. (2007), Applied Biochemistry and Biotechnology. In press), distiller's dried grains with solubles (DDGS) (Bals, B., Dale, B., Balan, V., (2006) Energy & Fuels, 20, pp., 2,732-2,736), and bagasse have been evaluated and shown that this pretreatment helps increase enzymatic digestibility several fold over the untreated biomass.

[0007] There is an obvious desire in the art to optimize the AFEX pretreatment process towards making commercially viable ethanol. The major AFEX operating parameter variations include: temperature (70-110° C.), moisture content (20-80 wt %), ammonia loading (0.5-2.5 g ammonia per gram of dry biomass), residence time (5-30 min). The most effective conditions are chosen based on the highest glucose and xylose yield from enzymatic hydrolysis of the treated biomass.

[0008] It is more economically and commercially desirable in the art to create a scalable AFEX process. Such processes have been attempted using extrusion reactors (Dale, B., Weaver, J., Byers, F. (1999), Applied Biochemistry and Biotechnology, 77-79, pp., 35-45) or in a Staketech process (commercially available by Stake Technology Ltd., 208 Wyecroft Road, Oakville, Ontario, Canada, L6K 3T8).

[0009] To meet the ever increasing demand for ethanol production, there is a demand and a desire in the art to develop biomass pretreatment systems and methods capable of improving AFEX process conditions in a simple and scalable design.

SUMMARY OF THE INVENTION

[0010] Accordingly, the present invention provides a biomass pretreatment system and fermentation processes incorporating a biomass or cellulose treatment system in a simple and scalable design.

[0011] The invention may be practiced using a plug flow reactor capable of accomplishing several of the desired functions simultaneously while meeting desired or predetermined process conditions.

[0012] An advantage of the present invention is the ability to continuously provide required residence time and expansion. In one embodiment, residence time is provided by continuous flow of the ammonia/moistened biomass. In a particular embodiment, the process incorporates a retention coil or auger and ammonia expansion occurs across a pressure reduction device (valve, orifice, or other mechanical devices).

[0013] According to one aspect of the invention, there is provided a process for swelling biomass. The process includes contacting the biomass with a swelling agent as the biomass and swelling agent are transported through a reactor system. In one embodiment, the reactor system is at a pressure sufficient to maintain the swelling agent predominantly in the liquid phase, and the contact is for a time sufficient to allow the swelling agent to swell at least a portion of the biomass.

[0014] According to another aspect of the invention, there is provided a fermentation process. The fermentation process includes a pretreatment system in which biomass is contacted with a swelling agent as the biomass and swelling agent are transported through a reactor system. In one embodiment, the reactor system is at a pressure sufficient to maintain the swelling agent predominantly in the liquid phase, and the contact is for a time sufficient to allow the swelling agent to swell at least a portion of the biomass. At least a portion of the biomass that has been contacted with the swelling agent is then fermented.

[0015] In one embodiment of the invention, steam is applied to the biomass to achieve a total moisture content of from 20 wt % to 90 wt % as the steam mixes with the biomass. In another embodiment, steam is applied to the biomass to achieve a temperature of from 60° C. to 200° C. as the swelling agent mixes with the biomass.

[0016] In another embodiment, the steam is applied to the biomass prior to contacting with the swelling agent. In yet another, the steam is applied to the biomass after contacting with the swelling agent. In still another, the steam is applied to the biomass during contacting with the swelling agent, which means that at or near concurrent application of steam and swelling agent with biomass can also be utilized.

[0017] In a preferred embodiment, the biomass is contacted with the swelling agent at a ratio of swelling agent to biomass of from 0.1:1 to 2.5:1 dry weight basis (dwb). The steam can be applied by way of a mixing device to mix the steam with the biomass or by way of a transport device to transport the biomass. Preferably, the steam is applied by way of a mixing and transport device to mix and transport the biomass.

[0018] In one embodiment, the biomass is contacted with the swelling agent for at least one minute to swell the biomass. Preferably, the swelled biomass is dried to provide a vapor stream and a dried biomass stream such that the vapor stream contains at least a portion of the swelling agent and moisture from the biomass.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The foregoing features, as well as other features, will become apparent with reference to the description and figures below, in which like numerals represent elements, and in which:

[0020] FIG. **1** is a schematic diagram depicting a system for continuous biomass processing in accordance with an embodiment of the present invention;

[0021] FIG. **2** is a schematic diagram depicting an overall system for continuous biomass processing in accordance with an embodiment of the present invention;

[0022] FIGS. **3-9** are schematic diagrams depicting alternate embodiments of a system for continuous biomass processing in accordance with an embodiment of the present invention;

[0023] FIG. **10** is a schematic diagram depicting components that could be used for a system for continuous biomass processing in accordance with an embodiment of the present invention using a heating heat exchanger to heat ammonia to, at or near reaction temperature; and

[0024] FIGS. **11-13** are schematic diagrams depicting components and system variations that could be used for a system for continuous or semi-continuous biomass processing in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

[0025] The present invention relates to the use of a process for treatment of cellulosic biomass using a swelling agent to swell the biomass. The swelling of the biomass increases the chemical and biological reactivity of biomass for subsequent processing. In one embodiment, the invention incorporates the use of the pretreatment system in fermentation processes.

[0026] The present invention is capable of providing a variety of functions desired for treatment of biomass with swelling agent. These functions include: 1) pressurizing the biomass and swelling agent, 2) mixing and generating a homogeneous mixture of swelling agent and biomass, 3) heating the biomass and swelling agent, 4) providing adequate residence time, 5) releasing the pressure quickly. One embodiment of the present invention is providing for a reactor system that uses a plug flow reactor while meeting desired process conditions.

[0027] Several types of reactors can be utilized with the systems and methods of the present invention. In one basic form illustrated in FIG. **10**, an ammonia addition system works by running pressurized ammonia, from a pressurized ammonia tank **100**, through a cooling heat exchanger **102**, then through a metering pump **104**, followed by a flow meter **106**, then through a heating heat exchanger **108** to add in heat, then proceeding into a reactor **110**. The cooling heat exchanger is configured to cool the ammonia below a vaporization point, therefore keeping it predominantly in liquid form through the metering pump. This allows for accurate measurement of the ammonia. The heat exchanger is configured to heat the measured ammonia flowing through the system to at or near reaction temperature prior to flowing through the reactor. Other components and process schematics are shown at FIGS. **11-13**. In FIG. **11** a continuous or semi-continuous reactor is illustrated. FIG. **12** illustrates another variation of a schematic for a process that uses a heat exchanger to bring ammonia to at or near reaction temperature. It is noted that the given components in line in this process may also involve various other combinations including heating exchangers and/or including steam to increase the biomass to reaction temperature. All possible heating heat exchange combinations are contemplated to fall within the design and scope of the present invention.

[0028] In one embodiment of the present invention, the pressurization and transport of the biomass utilizes a positive displacement pump. Possible mixing devices can include mechanically powered inline mixers, annular jet pumps, externally and internally modulated steam injection heaters. Annular jet pumps and steam injection heaters may also serve multiple functions in the continuous reactor. For example, these devices can act as one or more of a heating device, a transport device and a mixing device. Residence time is preferably provided by a retention pipe or auger.

[0029] According to one aspect of the invention, biomass is contacted with a swelling agent, and this mix of biomass and swelling agent are continuously transported through a reactor system. By continuous, it is meant that the mix does not need to be collected in a vessel. Rather, the biomass and swelling agent are flowed at a relatively constant rate through the reaction system. The reaction system can include a vessel, but the flow of the mixture is relatively uninterrupted as at least a portion of the biomass is swelled during the flow.

[0030] Biomass refers to living and recently dead biological material that can be used as fuel or for industrial production. Generally, biomass refers to plant matter grown for use as biofuel, but it also includes plant or animal matter that can be used for production of fibers, chemicals or heat. Biomass may also include biodegradable wastes that can be burned as fuel. It excludes organic material which has been transformed by geological processes into substances such as coal or petroleum.

[0031] Particularly suitable biomass includes such plant matter containing a relatively high content of cellulose. Examples of such biomass or plant matter include miscanthus, switchgrass, hemp, corn (e.g., stover or cob), poplar, willow, sugarcane and oil palm (palm oil). Even municipal wastes such as newspaper can all be used as suitable biomass material.

[0032] Other examples of biomass include stems, leaves, hulls, husks, wood, wood chips, wood pulp, and sawdust. Particular examples of paper waste include discard photocopy paper, computer printer paper, notebook paper, notepad paper, typewriter paper, newspapers, magazines, cardboard, and paper-based packaging materials.

[0033] In one embodiment, the biomass is predominantly one or more C_4 grasses. C_4 grasses are classified by their pathway of carbon dioxide metabolism, which involves intermediates with 4 carbon atoms. This is described in *Biology of Plants*, by Raven, Evert, and Curtis, Worth Publishing Co., second edition, 1976, pages 116-117, incorporated herein by reference. Particularly preferred C_4 grasses are C_4 perennial grasses. Perennial grasses do not require yearly planting and fertilization and are therefore more suitable for fermentation and ethanol production than annual grasses. Particularly preferred C_4 perennial grasses include switchgrass, miscanthus, cord grass, and rye grass. These grasses are particularly fast growing. Cord grass is classified as a C_4 grass even though a portion of its growth cycle uses C_3 metabolism.

[0034] In this invention, the pressure of the reaction system (i.e., the portion of the system in which there is contact of the biomass and swelling agent and swelling of at least a portion of the biomass occurs) is at a pressure sufficient to prevent substantial vaporization of the swelling agent. This means that the swelling agent should remain predominantly in the liquid phase while contacting the biomass, and while swelling of at least a portion of the biomass occurs. Of course, it is not intended that there will be no vapor space within the reaction system, but that the conditions of the system are such that the swelling agent will be considered to be maintained predominantly in the liquid phase.

[0035] It is also understood that the pressure condition of the reaction system will depend upon the type of swelling agent. For example, when the swelling agent is ammonia, the pressure condition will be that at which ammonia is predominantly in the liquid phase. Other examples of swelling agents include: 1) water soluble amines having the structure NRR^1R^2 where R, R^1 and R^2 are either the same or different and are selected from the group consist of H or hydrocarbons containing 1~60 carbons, optionally substituted with oxygen, nitrogen, sulfur or phosphorous, or where two or more of the R groups are attached to form a cyclic group. Preferred examples of swelling agents include ammonia, methyl amine, dimethylamine, N-methyl, ethylamine, tripropylamine, and morpholine; 2) water soluble ammonium ions having the structure $+NRR^1R^2R^3$ where R, R^1, R^2 and R^3 are either the same or different and are selected from the group consisting of H or hydrocarbons containing 1~60 carbons, optionally substituted with oxygen, nitrogen, sulfur or phosphorous, or where two or more of the R groups are attached to form a cyclic group. Preferred examples include, ammonium hydroxide, ammonium chloride, and trimethylammonium chloride; 3) hydroxides, carbonates, and bicarbonates of lithium, sodium, potassium, magnesium, and calcium, such as sodium hydroxide, magnesium carbonate, and calcium carbonate (lime); 4) water soluble mono, or poly carboxylic acids containing 1~20 carbons such as carbonic, acetic, trifloroacetic, succinic and citric; 5) inorganic acids such as sulfuric, sulfurous, nitric, nitrous, phosphoric, and hydrochloric, including agents that form inorganic acids when dissolved in water such as sulfur dioxide, which forms sulfurous acid when dissolved in water.

[0036] In one embodiment of the invention, the reactor system is at a pressure of from 50 psig to 600 psig. Preferably, the reaction system is at a pressure of from 100 psig to 450 psig.

[0037] The contact of the biomass with the swelling agent is also for a period of time sufficient to swell at least a portion of the biomass. Preferably, the swelling agent contacts the biomass for at least one minute, more preferably for at least two minutes, and most preferably for at least five minutes.

[0038] According to the invention, steam is applied to the biomass. The steam can be applied before, during or after the biomass is first contacted with the swelling agent. The steam is preferably saturated steam.

[0039] In one embodiment, the steam is applied to the biomass to maintain the appropriate moisture content as the steam mixes with the biomass. The presence of moisture in the biomass allows faster and more even distribution of the swelling agent in the biomass. The moisture in the biomass particularly affects hydrolysis of hemicellulose in the biomass, and thereby enhances the overall effect of the pretreatment. However, too high of a moisture content will dilute the overall swelling agent content in the process and also pose an unnecessary burden on any recovery of the swelling agent and on any drying of the biomass that has been contacted with the swelling agent and steam. Preferably, steam is applied to maintain a moisture content of from 20 wt % to 90 wt % on a total weight basis as the steam mixes with the biomass. More preferably, steam is applied to maintain a moisture content of from 60 wt % to 90 wt %, and most preferably from 70 wt % to 85 wt % on a total weight basis as the steam mixes with the biomass.

[0040] In another embodiment, the steam is applied to the biomass to maintain the appropriate temperature as the swelling agent mixes with the biomass. Too low of a temperature will have little if any swelling effect on the biomass. Too high of a temperature can result in undesirable chemical reactions and generate potential inhibitory compounds that adversely affect downstream processes such as hydrolysis and fermentation. Preferably, steam is applied to achieve a temperature of from 60° C. to 200° C. as the steam mixes with the biomass. More preferably, steam is applied to achieve a temperature of from 80° C. to 120° C., and most preferably from 90° C. to 110° C. as the stream mixes with the biomass.

[0041] In another embodiment, the biomass is contacted with the swelling agent at a predetermined weight ratio of swelling agent to biomass. The weight ratio should be high enough to swell at least a significant portion of the biomass within an acceptable amount of time. The weight ratio need not be too high, however. Otherwise, excessive swelling can result such that the swelling agent can cause cellulose in the biomass to plasticize, thereby reducing chemical and biological reactivity of the biomass contacted with the swelling agent on downstream processes. Downstream processes that can be particularly impacted include hydrolysis and fermentation reaction processes. Preferably, the biomass is contacted with the swelling agent at a ratio of swelling agent to biomass of from 0.1:1 to 2.5:1 dwb. More preferably, the biomass is contacted with the swelling agent at a ratio of swelling agent to biomass of from 0.3:1 to 1.5:1 dwb, most preferably from 0.9:1 to 1.1:1 dwb.

[0042] The ruptured biomass is preferably dried to provide a vapor stream and a dried biomass stream. The vapor stream contains at least a portion of the swelling agent and moisture from the ruptured biomass. The vapor can be condensed or recycled or both in the process. Preferably, the swelling agent in the vapor is recovered and reused in the recycle stream.

[0043] The ruptured biomass, in dried or undried form, is a highly desirable feed for fermentation, as the ruptured biomass will have a significant amount of cellulose available for fermentation compared to the untreated or unruptured biomass. Fermentation can be anaerobic (deficient in oxygen) as well as aerobic (oxygenated). Under aerobic conditions, microorganisms such as yeast cells can break down sugars to end products such as CO_2 and H_2O. Under anaerobic conditions, yeast cells utilize an alternative pathway to produce CO_2 and ethanol. The fermentation reaction of the present invention is preferably anaerobic, i.e., partially or completely deficient in oxygen. Fermentation can also be used to refer to the bulk growth of microorganisms on a growth medium where no distinction is made between aerobic and anaerobic metabolism.

[0044] As a part of the fermentation process, the ruptured biomass is preferably contacted with one or more cellulase enzymes in an aqueous mixture. The cellulase can be provided as a purified enzyme or can be provided by a cellulase-producing microorganism in the aqueous mixture. Cellulase can include any enzyme that effects the hydrolysis or otherwise solubilizes cellulose (including insoluble cellulose and soluble products of cellulose). Suitable sources of cellulase include such commercial cellulase products as Spezyme™ CP, Cytolase™ M104, and Multifect™ CL (Genencor, South San Francisco, Calif.).

[0045] The conditions for cellulase hydrolysis are typically selected in consideration of the conditions suitable for the specific cellulase source, e.g, bacterial or fungal. For example, cellulase hydrolysis can be carried out at a temperature of from 30° C. to 60° C. and a pH of from 4.0 to 8.0. Preferably, cellulase hydrolysis is carried out at a temperature of from 30° C. to 48° C. and a pH between of from 4.0 to 6.0.

[0046] The aqueous mixture of biomass and enzyme can further advantageously comprise an ethanologenic microorganism for fermentation. Preferably, the microorganism in one that has the ability to convert a sugar or oligosaccharide to ethanol. Likewise, the hydrolysis product can be separated and then fermented with the microorganism.

[0047] Examples of ethanologenic microorganisms include ethanologenic bacteria and yeast. The microorganisms are ethanologenic by virtue of their ability to express one or more enzymes which, individually or together, convert a sugar to ethanol. For example, Saccharomyces (such as *S. cerevisiae*) can be employed in the conversion of glucose to ethanol. Other examples of microorganisms that convert sugars to ethanol include species of *Schizosaccharomyces* (such as *S. pombe*), *Zymomonas* (including *Z. mobilis*), *Pichia* (*P. stipitis*), *Candida* (*C. shehatae*) and *Pachysolen* (*P. tannophilus*). Preferred examples of ethanologenic microorganisms include ethanologenic microorganisms expressing alcohol dehydrogenase and pyruvate decarboxylase, such as can be obtained with or from *Zymomonas mobilis*.

[0048] In another embodiment, the ethanologenic microorganism can express xylose reductase and xylitol dehydrogenase, which convert xylose to xylulose. Xylose isomerase converts xylose to xylulose, as well. The ethanologenic microorganism can further express xylulokinase, which catalyzes the conversion of xylulose to xylulose-5-phosphate. Additional enzymes to complete the pathway can include transaldolase and transketolase. These enzymes can be obtained or derived from microorganisms such as *Escherichia coli*, *Klebsiella oxytoca* and *Erwinia* species.

[0049] In one embodiment, microorganisms capable of fermenting both pentoses and hexoses to ethanol are employed. Particularly preferred microorganisms include *Klebsiella oxytoca* P2 and *Escherichia coli* KO11.

[0050] Referring now to the figures, FIG. **1** illustrates a schematic diagram of a possible embodiment utilizing the objects of the present invention for a continuous biomass treatment system, and is generally shown at **10**.

[0051] In FIG. **1**, moistened biomass **12** may be pressurized in a positive displacement pump **14** or any other means to pressurize the biomass known in the art. Aqueous or anhydrous ammonia is added to moistened biomass upstream (such as at **16**) of an annular jet pump **18**. It is noted that when the term ammonia is used, it may also alternatively refer to anhydrous ammonia or other swelling agents known in the art. Steam may used as a transport, heating and/or moisturizing fluid. For example, steam can be injected by way of an annular jet pump **18** to heat the ammonia and biomass suspension, generate a homogeneous suspension, and aid in transporting the mixture through a retention pipe **20**. Retention pipe **20** is illustrated as curved, but may be straight in this and in all variations shown in the all the figures. It is noted that in addition to steam, other types of heat exchangers may be used to heat the ammonia to at or near reaction temperature. Once the suspension has passed through the retention pipe, the pressure is rapidly decreased such as across a pressure reduction valve **22**, orifice, or other mechanical device allowing for the vaporization of the ammonia and subsequent separation and recycle back into the process. It is also noted that in this Fig. and in all figures which use steam and ammonia, that the steam optionally may be introduced upstream of the introduction of the ammonia. Further, steam and ammonia may be introduced simultaneously.

[0052] FIG. **2** shows an example of incorporation of the biomass treatment process with an ethanol manufacturing facility. The treated biomass following enzyme hydrolysis is particularly suitable in any application that utilizes C5, C6 or a mixed C5/C6 sugar solution.

[0053] FIG. **3** is another schematic of the process illustrated in FIG. **1**.

[0054] FIG. **4** offers a slight variation of the schematic illustrated in FIGS. **1** and **3**. In FIG. **4** the annular jet pump is replaced by direct-contact steam injection for combined heating and mixing of the biomass/ammonia suspension. This could be accomplished by using spargers, mixing tees and internally modulated steam injection heaters as are known in the art. Steam may also drive the suspension as well as add pressure to the system.

[0055] FIGS. **5** and **6** differ from FIGS. **1** and **4** by using a retention auger **30** to replace a retention pipe. The auger would be configured to provide the required residence time for the biomass under pressure prior to depressurizing across a pressure reduction valve, orifice, or other mechanical device. Such configuration and schematic could be developed using methods well known in the art.

[0056] FIGS. **7** and **8** show replacement of the annular jet pump or direct-contact steam injectors with an inline mixer **40** or continuous stirred tank reactor (CSTR). In these examples the steam and/or ammonia could be added upstream or directly into the inline mixer or CSTR. In these cases the inline mixer and CSTR could provide mixing and all or some of the required mixing time.

[0057] FIG. **9** is a variation of FIG. **3** in that an auger may optionally be used.

[0058] Any of a variety of reactors are suitable for use with the systems and methods of the present invention. In one basic form illustrated in FIG. **10**, an ammonia addition system works by running pressurized ammonia, from a pressurized ammonia tank **100**, through a cooling heat exchanger **102**, then a metering pump **104**, followed by a flow meter **106**, then through a heating heat exchanger **108** to add in heat, then proceeding into a reactor **110**. The cooling heat exchanger is configured by means known in the art to cool the ammonia below a vaporization point, therefore keeping it predominantly in liquid form through the metering pump. This allows for accurate measurement of the ammonia. The heat exchanger is configured to heat the measured ammonia flowing through the system to at or near reaction temperature prior to flowing through the reactor. Other component and process schematics are shown at FIGS. **11-13**. In FIG. **11** a continuous or semi-continuous reactor system is illustrated. FIG. **12** illustrates another variation of a schematic for a process that uses a heat exchanger to bring the swelling agent to at or near reaction temperature. It is noted that the given components in line in this process may also involve various other combinations including heating exchangers and/or including steam to increase the biomass to reaction temperature. A wide variety of heating heat exchange combinations are contemplated to fall within the design and scope of the present invention.

[0059] The reactor system of this invention is energy efficient. In one embodiment of the present invention, mixing energy is provided by steam through a direct steam injection nozzle.

[0060] The invention is relatively easy to operate and maintain. In one embodiment, there are no moving parts in the reactor. In another embodiment, the reactor has no dynamic seals that could allow ammonia leakage into the work environment.

[0061] The description of the present invention herein is presented to enable any person skilled in the art to make and use the invention and is provided in the context of particular applications of the invention and their requirements. Various modifications to the disclosed embodiments will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments and applications without departing from the overall functions of the invention. Thus, the present invention is not intended to be literally limited to the embodiments as claimed.

What is claimed is:

1. A process for swelling biomass, comprising:

contacting the biomass with a swelling agent as the biomass and swelling agent are transported through a reactor system, wherein the reactor system is at a pressure sufficient to maintain the swelling agent predominantly in the liquid phase, and the contact is for a time sufficient to allow the swelling agent to swell at least a portion of the biomass; and

applying steam to the biomass to achieve a total moisture content of from 20 wt % to 90 wt % as the steam mixes with the biomass.

2. The process of claim **1**, wherein the steam is applied to the biomass prior to contacting with the swelling agent.

3. The process of claim **1**, wherein the steam is applied to the biomass after contacting with the swelling agent.

4. The process of claim **1**, wherein the steam is applied to the biomass during contacting with the swelling agent.

5. The process of claim **1**, wherein the steam is applied to achieve a temperature of from 60° C. to 200° C. as the steam mixes with the biomass.

6. The process of claim **1**, wherein the biomass is contacted with the swelling agent at a ratio of swelling agent to biomass of from 0.1:1 to 2.5:1 dwb.

7. The process of claim **1**, wherein the steam is applied by way of a mixing device to mix the steam with the biomass.

8. The process of claim **1**, wherein the steam is applied by way of a transport device to transport the biomass.

9. The process of claim **1**, wherein the steam is applied by way of a mixing and transport device to mix and transport the biomass.

10. The process of claim **1**, wherein the biomass is contacted with the swelling agent for at least one minute to swell the biomass.

11. The process of claim **1**, wherein the swelled biomass is dried to provide a vapor stream and a dried biomass stream such that the vapor stream contains at least a portion of the swelling agent and moisture from the biomass.

12. The process of claim **1**, further comprising fermenting at least a portion of the biomass that has been contacted with the swelling agent.

13. A process for swelling biomass, comprising:

contacting the biomass with a swelling agent as the biomass and swelling agent are transported through a reactor system, wherein the reactor system is at a pressure sufficient to maintain the swelling agent predominantly in the liquid phase, and the contact is for a time sufficient to allow the swelling agent to swell at least a portion of the biomass; and

applying steam to the biomass to achieve a temperature of from 60° C. to 200° C. as the swelling agent mixes with the biomass.

14. The process of claim **13**, wherein the steam is applied to the biomass prior to contacting with the swelling agent.

15. The process of claim **13**, wherein the steam is applied to the biomass after contacting with the swelling agent.

16. The process of claim **13**, wherein the steam is applied to the biomass during contacting with the swelling agent.

17. The process of claim **13**, wherein the steam is applied to achieve a total moisture content of from 20 wt % to 90 wt % as the steam mixes with the biomass.

18. The process of claim **13**, wherein the biomass is contacted with the swelling agent at a ratio of swelling agent to biomass of from 0.1:1 to 2.5:1 dwb.

19. The process of claim **13**, wherein the steam is applied by way of a mixing device to mix the steam with the biomass.

20. The process of claim **13**, wherein the steam is applied by way of a transport device to transport the biomass.

21. The process of claim **13**, wherein the steam is applied by way of a mixing and transport device to mix and transport the biomass.

22. The process of claim **13**, wherein the biomass is contacted with the swelling agent for at least one minute to swell the biomass.

23. The process of claim **13**, wherein the swelled biomass is dried to provide a vapor stream and a dried biomass stream such that the vapor stream contains at least a portion of the swelling agent and moisture from the biomass.

24. The process of claim **13**, further comprising fermenting at least a portion of the biomass that has been contacted with the swelling agent.

25. A fermentation process, comprising:

contacting biomass with a swelling agent as the biomass and swelling agent are transported through a reactor system, wherein the reactor system is at a pressure sufficient to maintain the swelling agent predominantly in the liquid phase, and the contact is for a time sufficient to allow the swelling agent to swell at least a portion of the biomass;

applying steam to the biomass to achieve a total moisture content of from 20 wt % to 90 wt % as the steam mixes with the biomass; and

fermenting at least a portion of the biomass that has been contacted with the swelling agent.

26. A fermentation process, comprising:

contacting biomass with a swelling agent as the biomass and swelling agent are transported through a reactor system, wherein the reactor system is at a pressure sufficient to maintain the swelling agent predominantly in the liquid phase, and the contact is for a time sufficient to allow the swelling agent to swell at least a portion of the biomass;

applying steam to the biomass to achieve a temperature of from 60° C. to 200° C. as the swelling agent mixes with the biomass; and

fermenting at least a portion of the biomass that has been contacted with the swelling agent.

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