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(54) **MICROWAVE-ENHANCED BIODIESEL METHOD AND APPARATUS**

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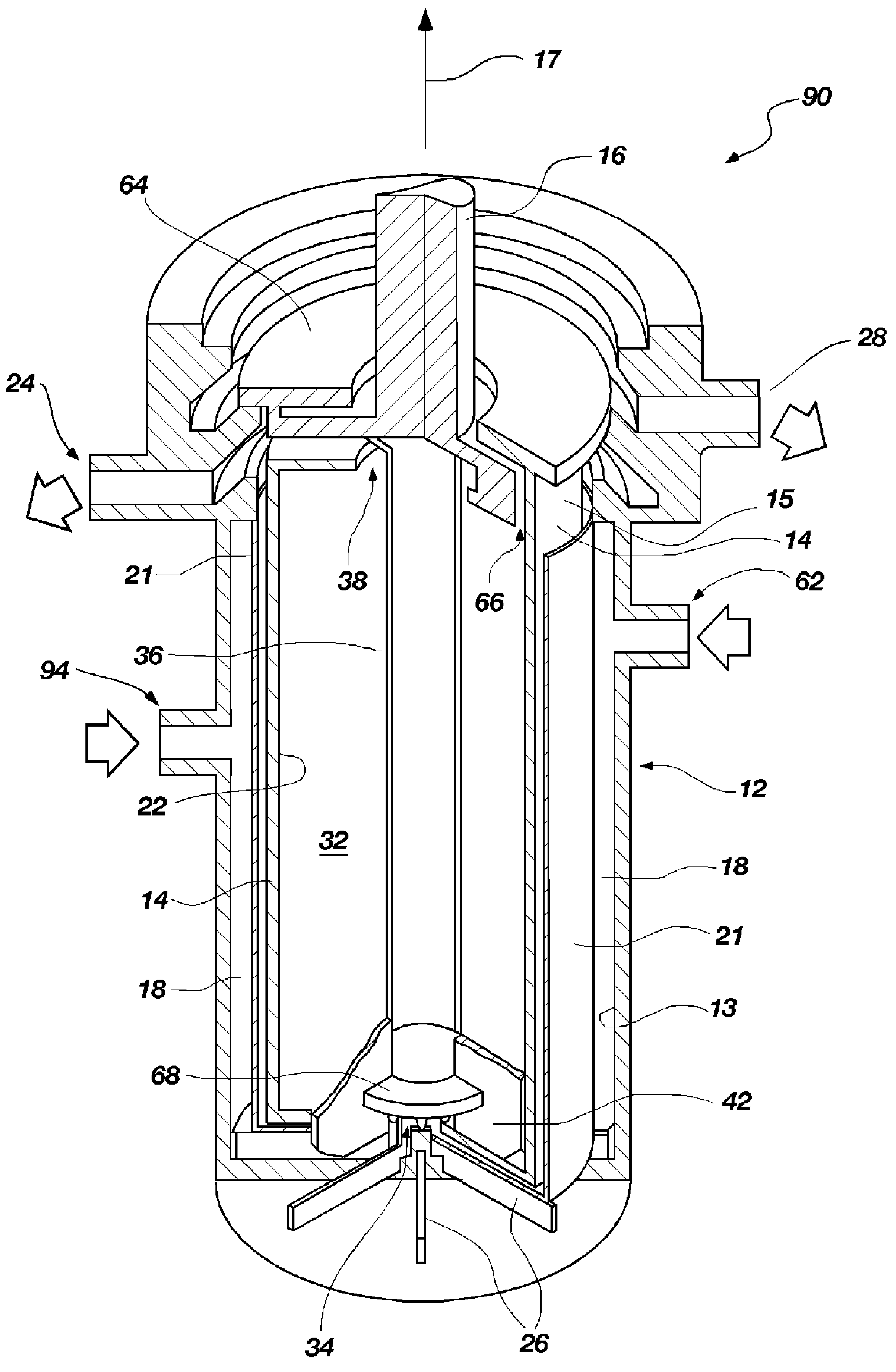
(57) **ABSTRACT**

A method and a device for the production of biodiesel are disclosed. A suitable bio-feedstock may be exposed to microwave energy during a mixing process, a separation process, and a wash process. A synergistic effect of the microwave energy and centrifugal separation may be used in a continuous process for producing biodiesel. The biodiesel may be produced from the feedstock in a continuous flow path. The microwave energy may enhance the reaction of the feedstock and catalyst to provide a mixture of an ester and glycerin, and the microwave energy may enhance the separation of the ester and the glycerin in a centrifuge. Finally, the microwave energy may enhance the wash process of the ester in a centrifuge to purify the ester to produce a usable biodiesel.



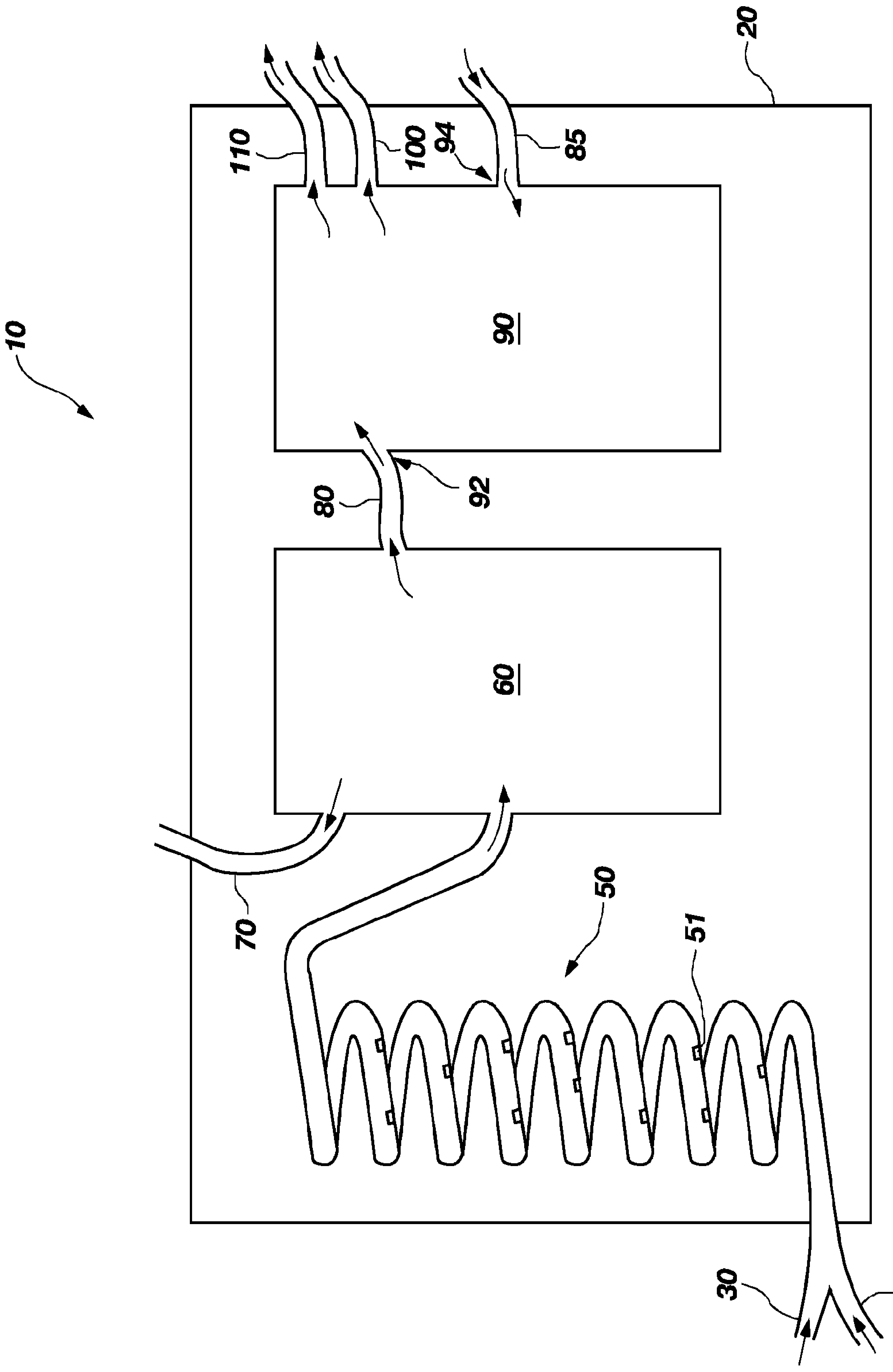


FIG. 1

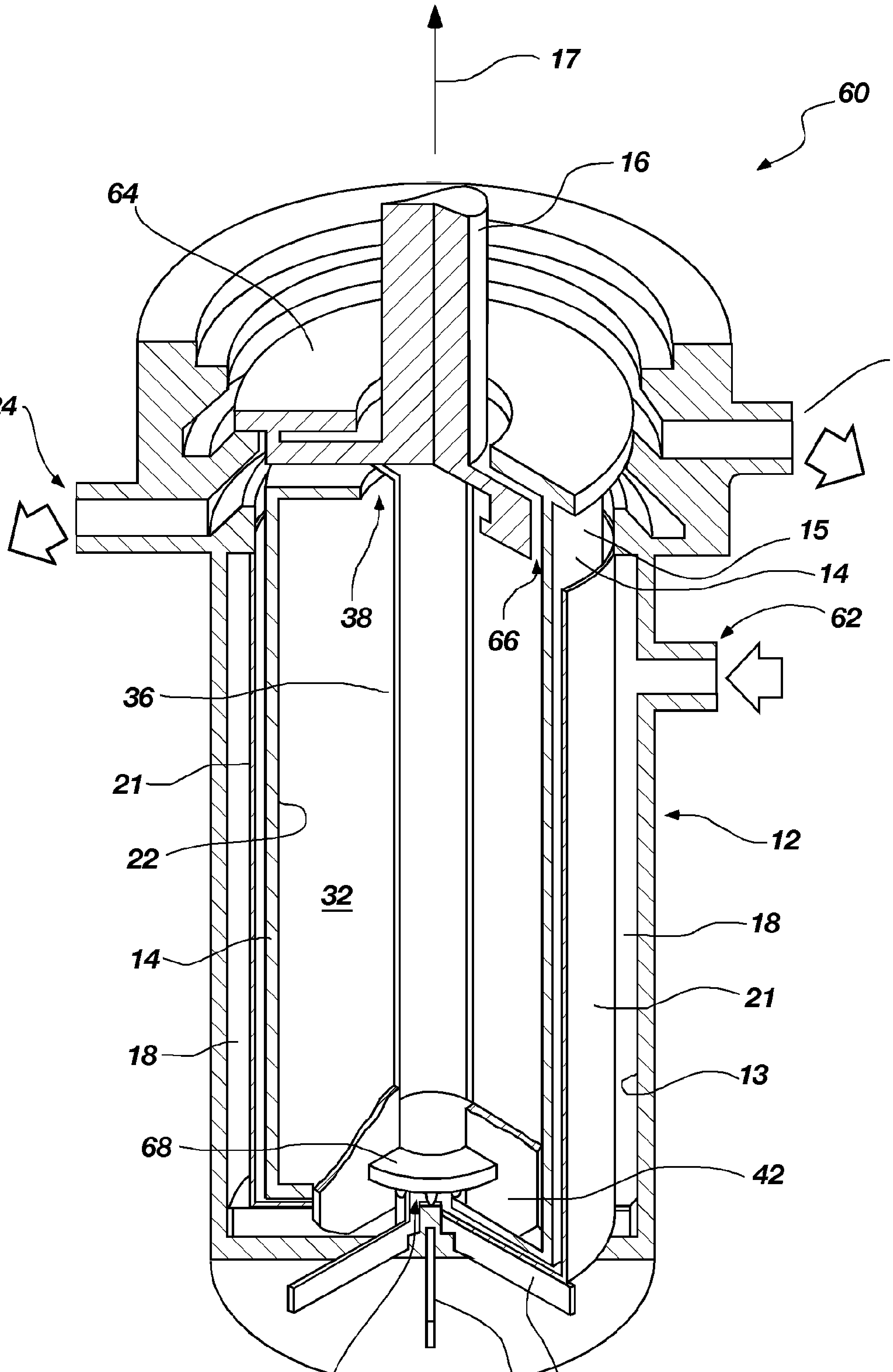

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FIG. 2

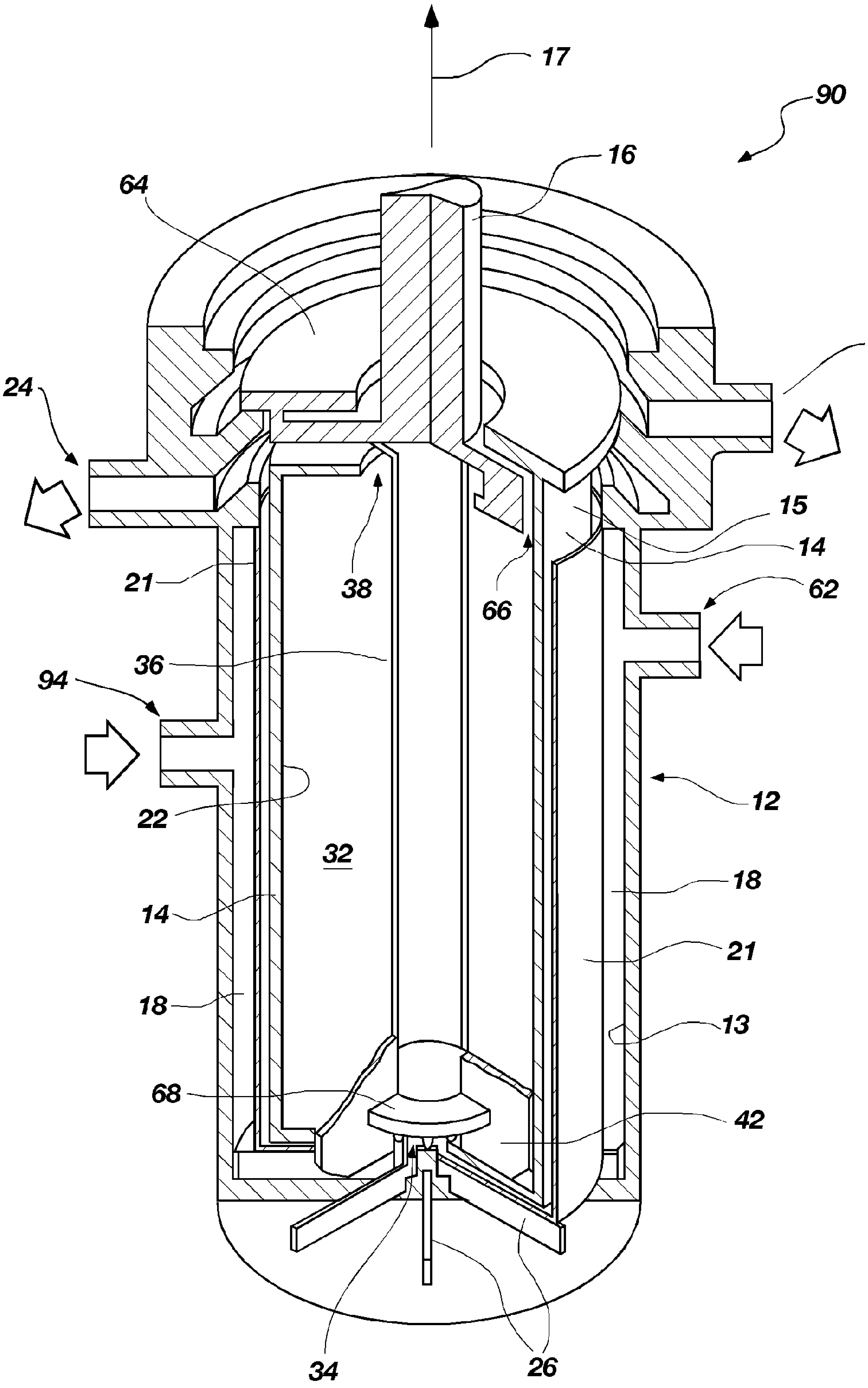
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FIG. 3

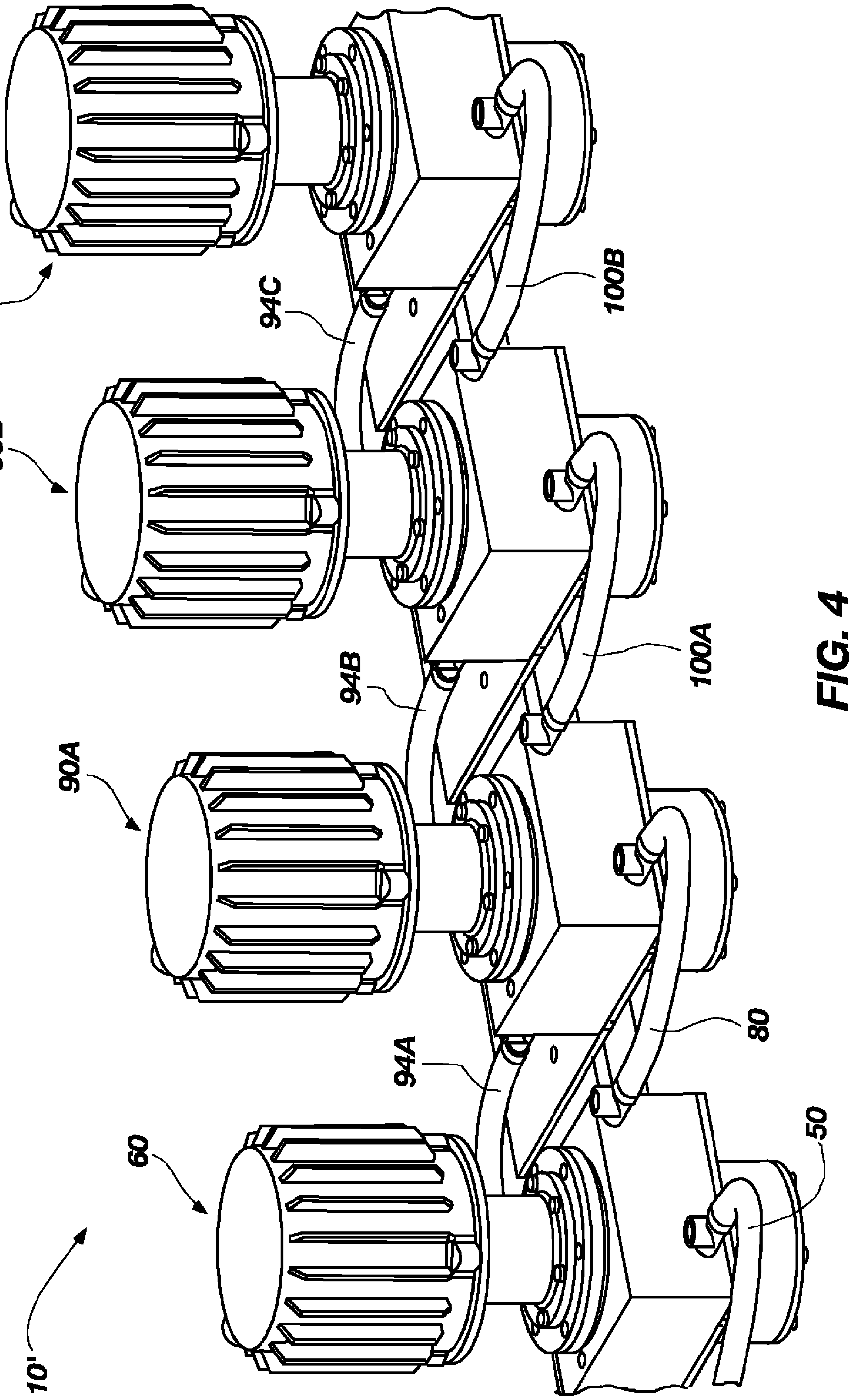

FIG. 4

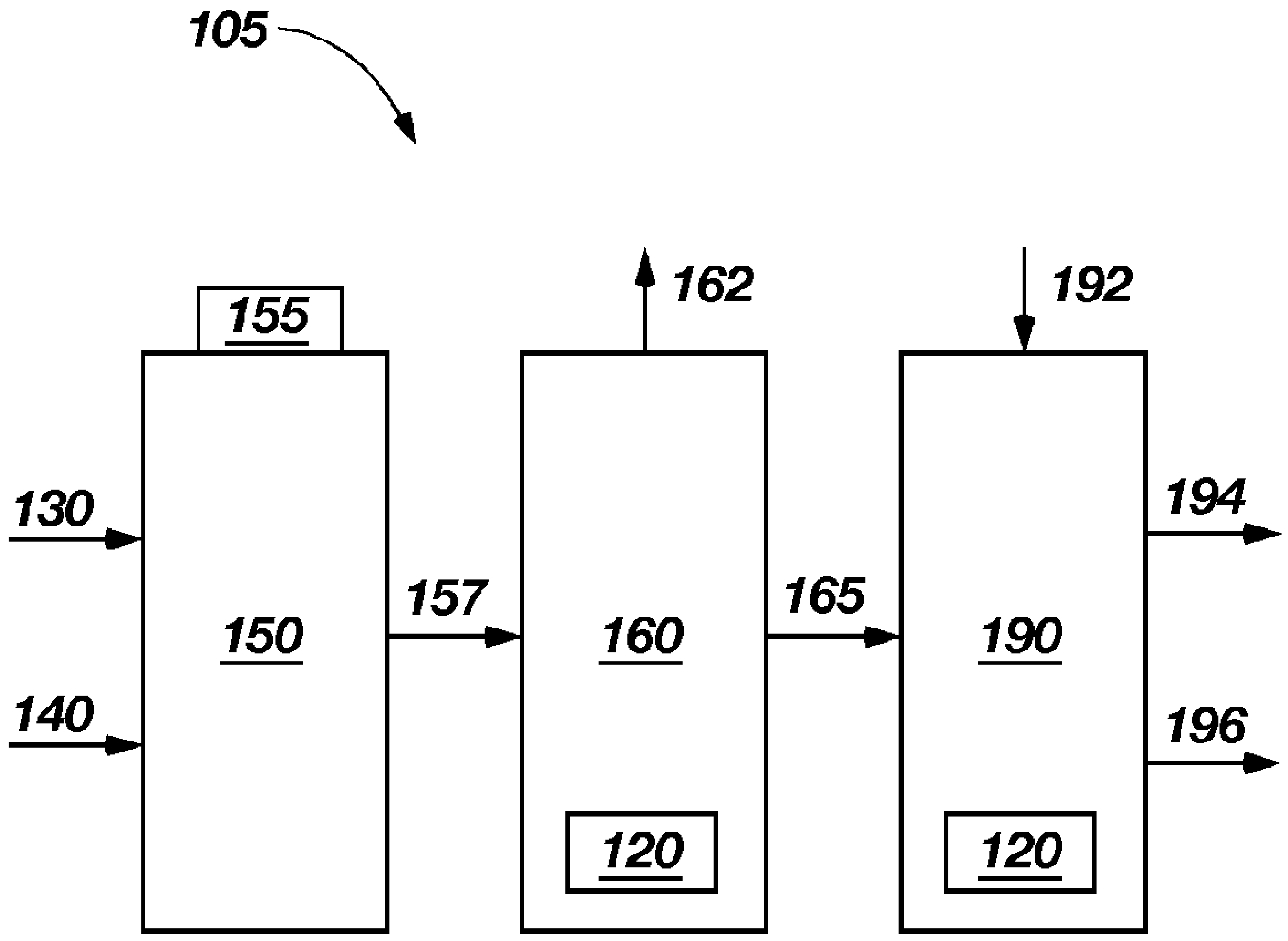
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FIG. 5

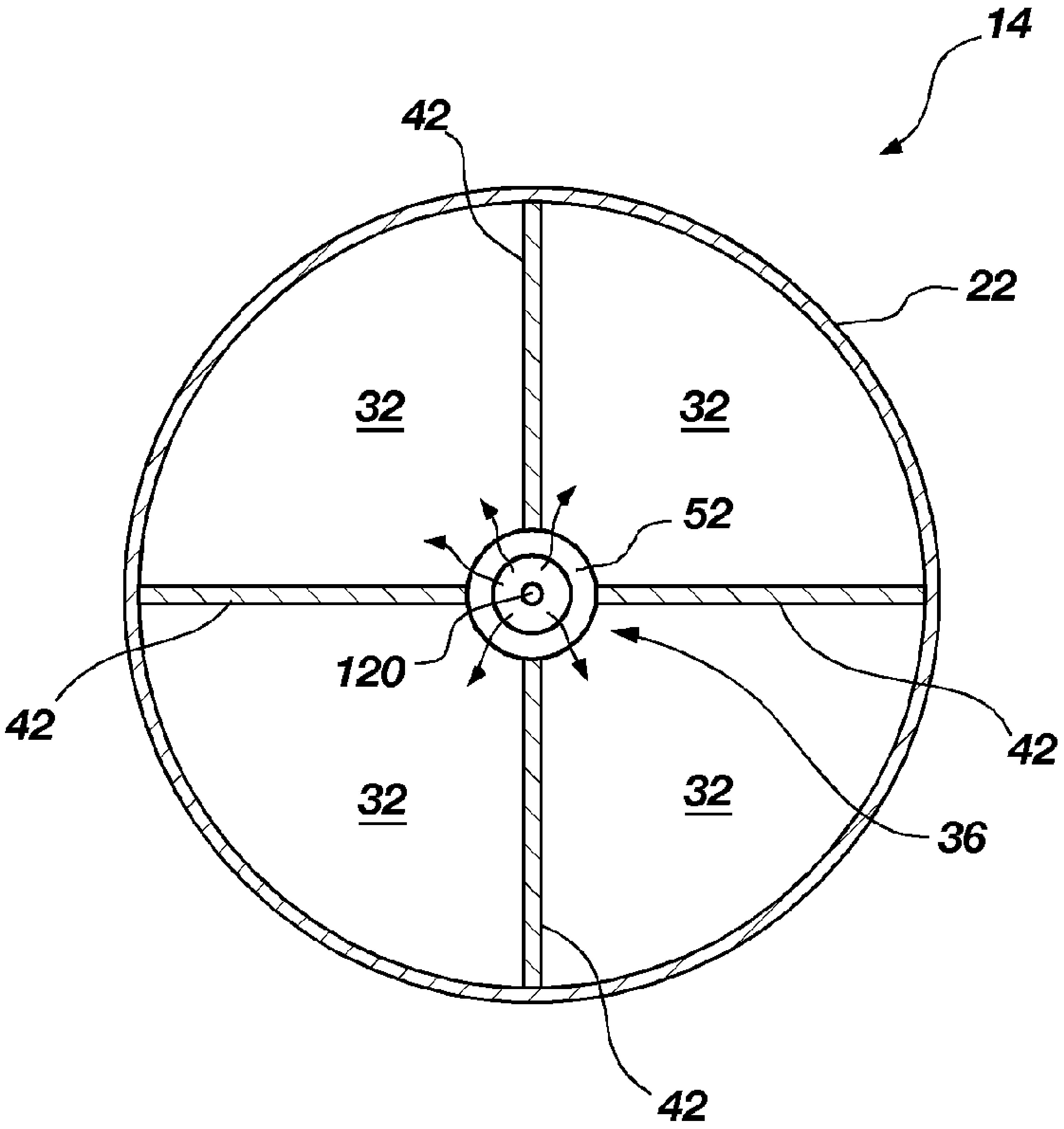
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FIG. 6

MICROWAVE-ENHANCED BIODIESEL METHOD AND APPARATUS

GOVERNMENT RIGHTS

[0001] The United States Government has certain rights in this invention pursuant to Contract No. DE-AC07-05-ID14517, between the United States Department of Energy and Battelle Energy Alliance, LLC.

FIELD OF THE INVENTION

[0002] Embodiments of the invention relate to devices for use in the preparation of biodiesel fuels and a microwave-enhanced continuous method of making biodiesel. More particularly, in various embodiments, the invention pertains to the application of microwave energy during a mixing process, a centrifuge separation process, and a centrifuge wash process.

BACKGROUND OF THE INVENTION

[0003] Biodiesel has been the subject of much investigation as an alternative for petroleum-based diesel fuel. As used herein, the term "biodiesel" refers to an ester-based fuel oxygenate that is derived from a biological source. The biodiesel is used as an alternative for, or as an additive to, petroleum diesel fuel in automobiles or other vehicles. The biodiesel is typically produced from a triglyceride starting material or a fatty acid starting material by a transesterification reaction or an esterification reaction, respectively. Generally, the triglyceride is reacted, or transesterified, with an alcohol to produce glycerol (also known as glycerin) and a corresponding alkyl ester of the triglyceride. Similarly, the fatty acid is reacted, or esterified, with an alcohol to produce a corresponding alkyl ester of the fatty acid. A reaction using methanol as the alcohol forms a methyl ester, and a reaction using ethanol produces an ethyl ester. All such reaction products are referred to commonly herein as an "ester"

[0004] Large amounts of the triglyceride and fatty acid starting materials, also referred to as a feed stock, are available from inexpensive sources, such as animal or plant-based fats or oils. Some of these sources are waste food oils. However, since these fats or oils are too viscous to use directly as the biodiesel fuel, the triglycerides or fatty acids are transesterified or esterified to produce the corresponding ester, which has a lower viscosity than that of the starting material. As such, the corresponding ester is suitable for use as the biodiesel fuel.

[0005] The transesterification of the triglyceride (or the esterification of the fatty acid) is conducted with an excess of the alcohol in the presence of a catalyst. As the transesterification reaction proceeds, two products are formed, the alkyl ester and the glycerol. One phase includes the alkyl ester and the other phase includes the glycerol. The liquid phases are allowed sufficient time to settle and separate before additional processing steps are conducted to purify the alkyl ester from the glycerol.

[0006] Several convention biodiesel production systems of different scale or size are available. Biodiesel may be conventionally produced in either small or large batches. In one conventional small batch method of producing biodiesel, the oil is heated, then mixed with methanol and stirred for two hours. The mixture is allowed to sit for eight hours or more. During this stage, the free fatty acids are esterfied. Sodium methoxide is then added to the mixture, and stirred for an hour. Triglycerids are transesterfied during this step. The final product is washed, and allowed to settle for days. Small batch systems are inefficient, and time-consuming. The process can be technically challenging to operate for the user, and may result in a non-usable product.

[0007] Another conventional biodiesel production system is a large scale batch or continuous system. One provider of such a system is Biodiesel Systems of Madison, Wis. These systems require a large capital investment, and require that the oils and fats be collected from remote locations and delivered to the biodiesel production site. Such operations also require dedicated operators or staff.

[0008] Therefore it would be desirable to provide a device and method which may be used at the location of the oils and fats, and produces biodiesel more rapidly than the multi-day period of a conventional small batch process and with less in-process feedstock and reagent inventory.

SUMMARY OF THE INVENTION

[0009] Embodiments of the invention relate to the production of biodiesel and, in particular, to microwave-enhanced methods and devices for the production of biodiesel.

[0010] According to one embodiment of the invention, a biodiesel production device comprises a microwave device configured to provide microwave energy to a chamber thereof; a reaction vessel positioned within the chamber; a first fluid separation apparatus in communication with the reaction vessel and positioned within the chamber; and a second fluid mixing and separation apparatus in communication with the first separation apparatus and positioned within the chamber. An embodiment of the biodiesel production device may be of less than 200 pounds weight and occupy a volume of no more than about nine cubic feet, making it highly portable.

[0011] According to another embodiment of the invention, a method of producing biodiesel comprises providing a chamber configured to provide microwave radiation therein; mixing a feedstock and a catalyst within a reaction vessel and subjecting the mixture to microwave energy to form an ester and glycerin mixture; centrifugally separating the ester and the glycerin while applying microwave energy; and washing the ester under the influence of centrifugal force while applying microwave energy.

[0012] In still another embodiment of the invention, a system and method of continuously producing biodiesel comprises mixing a feedstock and a catalyst within a reaction vessel having a microwave generation device associated therewith; forming an ester and glycerin mixture in the reaction vessel; separating the ester and the glycerin in a first centrifuge having a second microwave generation device associated therewith; and washing the ester in a second centrifuge having a third microwave generation device associated therewith.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] While the specification concludes with claims particularly pointing out and distinctly claiming that which is regarded as the present invention, this invention can be more readily understood and appreciated by one of ordinary skill in the art from the following description of the invention when read in conjunction with the accompanying drawings in which:

[0014] FIG. **1** illustrates a schematic drawing of one embodiment of a biodiesel production device of the present invention;

[0015] FIG. **2** illustrates a schematic cross-sectional view of one embodiment of a separation contactor of the present invention;

[0016] FIG. **3** illustrates a schematic cross-sectional view of one embodiment of a wash contactor of the present invention;

[0017] FIG. **4** illustrates portions of another embodiment of a biodiesel production device of the present invention;

[0018] FIG. **5** illustrates a schematic drawing of one embodiment of a continuous flow loop of the present invention; and

[0019] FIG. **6** shows a cross-sectional view of a rotor assembly of one embodiment of a contactor of the present invention.

DETAILED DESCRIPTION

[0020] Embodiments of the invention to biodiesel production devices and, in particular, to devices and methods incorporating microwave energy to esterfy or transesterfy oils and fats and both microwave energy and centrifugal action to rapidly separate and wash the product.

[0021] A first embodiment of a biodiesel production device **10** of the present invention is shown in FIG. **1**. The biodiesel production device **10** includes a microwave chamber **20**. The microwave chamber **20** is configured to provide microwave energy to a volume on the interior thereof. The microwave chamber **20** may comprise, for example, a commercially available microwave oven with some modification thereto, providing inlets and outlets for the materials used in the biodiesel production, and for the finished biodiesel. The microwave chamber **20** may be structured to provide microwave power in the range of 0 to about 5000 Watts. The power range may be adjusted as desired by an operator.

[0022] A triglyceride- or fatty acid-containing feedstock suitable for use in forming a biodiesel product may be a liquid, such as a fat, oil, or mixtures thereof. The fat or oil may include, but is not limited to, an animal fat, animal oil, vegetable fat, vegetable oil, or mixtures thereof, such as rapeseed oil, sesame oil, soybean oil, corn oil, sunflower oil, peanut oil, palm oil, palm kernel oil, coconut oil, safflower oil, olive oil, linseed oil, cotton seed oil, tung oil, castor oil, beef fat, pork fat, chicken fat, fish oil, rendered fat, or mixtures thereof. The triglyceride or fatty acid starting material may also be obtained from waste edible oils, such as restaurant grease, household grease, waste industrial frying oil, or mixtures thereof.

[0023] A first inlet conduit **30** to the microwave chamber **20** may be in communication with a source of the feedstock for delivery into the biodiesel production device **10**. A second inlet conduit **40** may be in communication with a source of catalyst, which may be an acid or base catalyst in alcohol, for delivery into the biodiesel production device **10**. For example, the catalyst may be sodium hydroxide, potassium hydroxide, sulphuric acid, or sodium methylate, and an alcohol such as methanol or ethanol. The first inlet conduit **30** and second inlet conduit **40** may join before entering the microwave chamber **20**, or within the microwave chamber **20** proximate a reaction vessel **50** disposed within microwave chamber **20**, or may feed into reaction vessel independently. The first inlet conduit **30** and the second inlet conduit **40** may be in fluid communication with the reaction vessel, and the catalyst and the feed stock may mix therein. The reaction vessel **50** is desirably transparent to microwave radiation, and microwave energy transmitted to the interior of reaction vessel **50** may be used enhance the reaction between the feed stock and the catalyst by heating. Heating to about 50° C. may be desirable. In addition, the microwave radiation may enhance the synthetic organic transformation and reduce the time needed for the esterfication or transesterification. For example, substantial conversion of the feedstock and the catalyst to an ester and glycerin may take place in about one minute of time in the reaction vessel **50**. Liquid transit time through the reaction vessel **50** may be between about 45 seconds and about ten minutes, and the in-process inventory of the reaction vessel may be between about one pint and about two gallons.

[0024] The reaction vessel **50** may comprise, for example, an elongated reaction loop of sufficient length for the feedstock and the catalyst to mix, and for the feed stock to be converted, or transesterfied or esterfied, into a corresponding ester. The reaction vessel **50** is desirably transparent to microwave radiation, and may be formed of, for example, a polymer, a plastic, a water-free ceramic, a quartz, a carbon fiber, or a glass.

[0025] Static mixers **51** may be included within the reaction vessel **50** to promote mixing of the feedstock and the catalyst. Static mixers **51** may comprise geometric mixing elements fixed within the pipe, which use the energy of the flow stream to mix the feedstock and the catalyst. The static mixers **51** may provide gentle mixing, and ensure a complete and efficient reaction between the feedstock and the catalyst.

[0026] The flow rate through the reaction vessel **50** may be modified to ensure adequate conversion. For example, substantial conversion of the feedstock and the catalyst to an ester and glycerin may take place in about one minute of time in the reaction vessel **50** with a flow rate of 1.6 gallons per hour under the application of microwave energy. The volume of the reaction vessel **50** (through adjustment of the length or cross-sectional area) may be predetermined for an adequate conversion at a desired flow rate. Alternatively, the respective rates of introduction of the feedstock and catalyst may be modified to adjust the flow rate for adequate conversion within a reaction vessel **50** having a fixed volume. The configuration of the reaction vessel **50** as a reaction loop enables the transesterfication or esterfication to take place in a continuous process, with the feedstock and the catalyst continuously entering the reaction vessel **50**, and a mixture of an ester and glycerin continuously exiting the reaction vessel **50**. Following a continuous separation process and wash process, as further described hereinbelow, continuous production of a finished biodiesel product is enabled.

[0027] As noted, the mixing and subsequent reaction of the feed stock and the catalyst may form an ester and glycerin combination. By way of example and not limitation, the ester may be a fatty acid alkyl ester, a triglyceride alkyl ester, a methyl ester, an ethyl ester, methyl oleate, or a combination thereof depending on the feedstock and catalyst used. The ester and glycerin combination may be introduced into a separator in the form of first centrifuge **60** and separated therein. The glycerin may be recaptured and recycled in other operations. For example, glycerin may be useful in the food, pharmaceutical or cosmetic industries. The ester may be washed, as described hereinbelow, to form a finished biodiesel product.

[0028] The first centrifuge **60** may comprise a liquid-liquid centrifuge for separating the ester and the glycerin. The first centrifuge **60** is desirably transparent to microwave radiation, and may be formed of, for example a polymer, a plastic, a water-free ceramic, a quartz, a carbon fiber, or a glass.

[0029] FIG. **2** depicts one embodiment of a first centrifuge **60** of the present invention. The first centrifuge **60** may comprise a centrifuge as disclosed in U.S. Pat. No. 7,150,836 to Meikrantz, entitled "Microwave-Emitting Rotor, Separator Apparatus Including Same, Methods of Operation and Design Thereof," the disclosure of which is incorporated in its entirety herein. Two commercially available centrifuges having suitable sizes and shapes are the model V02 centrifuge and the model V05 centrifuge, available from CINC Industries of Carson City, Nev. For example, the model V02 centrifuge may have a 2 inch diameter rotor, and the model V05 centrifuge may have a 5 inch diameter rotor.

[0030] The first centrifuge **60** may include a housing **12** which may be vertically oriented and may define a generally cylindrical volume which houses a vertically-oriented, substantially cylindrical rotor assembly **14** defined generally by rotor wall **22**. Rotor assembly **14** may also include drive shaft **16**, weir structure **64**, interior shaft **36**, walls **42**, diverter disk **68** and lower shaft extension **55**, each of which may be separable from one another, as known in the art. The drive shaft **16** may be operably coupled to and selectively rotated by a motor (not shown) positioned above the rotor assembly **14**, as known in the art. Of course, the rotor assembly **14** may include an upper bearing (not shown) and a lower bearing (not shown) configured for providing support and ease of rotation about a central axis **17** proximate the lower shaft extension **55** and drive shaft **16**, respectively.

[0031] The housing **12** may include an inlet **62** through which, during operation, the ester and glycerin combination may be introduced from the reaction vessel **50**. The combination or mixture may be introduced through an inlet **62** into an annular region **18** defined between the outer radial surface of the rotor sleeve **21** and the inner radial surface of the housing **12**. The rotor sleeve **21** may be configured to be stationary with respect to the inner surface **13** of the housing **12**. Such a configuration may reduce additional mixing of the constituents of the mixture as it flows within annular region **18**. Alternatively, the first centrifuge **60** may not include a rotor sleeve, and the outside surface **15** of the rotor assembly **14** may be in contact with the mixture to promote mixing within the annular region. If the reaction forming the ester is complete when the mixture enters the first centrifuge, no added mixing is desired and a rotor sleeve **21** will preferably be included. The flow of the mixture through the annular region **18** may proceed generally vertically downwardly from the inlet **62** and toward a plurality of radial vanes **26**.

[0032] The radial vanes **26** may be affixed to housing **12** and may be configured for directing the mixture toward a rotor inlet aperture **34**. The radial vanes **26** may extend substantially radially outwardly from the central axis **17** of the rotor assembly **14** toward the inner surface **13** of the housing **12** or, alternatively, may extend along an arcuate path in a generally radially outward fashion from the central axis **17** of the rotor assembly **14** toward the inner surface **13** of the housing **12**. Such a configuration may reduce turbulent mixing of the constituents of the mixture passing along the radial vanes **26**.

[0033] The mixture may continue past the radial vanes **26** and flow into the rotor inlet aperture **34** of the rotor assembly **14**. Since the rotor sleeve **21** may be stationary, while the adjacent rotor assembly **14** rotates, an annular seal (not shown) may be provided therebetween, as known in the art. Further, the mixture passing into the rotor inlet aperture **34** of the rotor assembly **14** may encounter a diverter disk **68**. Of course, one or more additional sealing elements (not shown), which may comprise dynamic sealing elements or static sealing elements, may be included within the first centrifuge **60** as known in the art. For instance, sealing elements may inhibit the mixture from contact with a motor (not shown), an upper bearing (not shown), or a lower bearing (not shown).

[0034] Generally, the rotor assembly **14** may define a generally annular volume which is defined between interior shaft **36** and the inner radial wall **22** of rotor assembly **14**. The annular volume may include one or more chambers **32**, which may be defined, at least in part, by one or more walls **42** in combination with rotor wall **22**, as described hereinbelow in greater detail. Such a configuration may provide increased surface area for interaction with the mixture passing through the rotor assembly **14**.

[0035] The one or more chambers **32** may comprise at least three chambers for distributing the weight of the mixture and its constituents passing therethrough substantially uniformly during rotation of the rotor assembly **14**. In addition, the walls **42** may be oriented substantially vertically or as otherwise desired for forming at least a portion of the one or more chambers **32**.

[0036] Once the mixture is admitted into the interior of the rotor assembly **14**, the centrifugal force of rotation thereof, at generally any desired rotation speed, may cause a constituent of the mixture having a higher density, the glycerin, to be forced outwardly against the inner radial wall **22** of the rotor assembly **14**. By way of example and not limitation, the rotor assembly **14** may be configured to rotate at speeds of up to 5000 revolutions per minute, between about 1700 and about 5000 revolutions per minute. A smaller rotor unit may rotate faster than a larger rotor unit to generate sufficient g-force for adequate separation. Thus, a constituent of the mixture having a lower density, the ester, may be displaced radially inwardly toward the interior shaft **36** by the higher density constituent, the glycerin. As may be appreciated, the separation of two liquids having different densities may be effected by operation of the first centrifuge **60** due to the forces developed by rotation of the rotor assembly **14**. The synergistic effect of the application of microwave energy and the rotation forces of the first centrifuge **60** may enhance the separation of the ester and the glycerin.

[0037] The constituent having a lesser density and the constituent having a greater density may be individually expelled from the housing **12** through exit ports **24** and **28**, respectively. More particularly, the ester, having a lesser density, may proceed through the weir structure **38**, which may be positioned generally proximate the interior shaft **36**, and through the exit port **24** to the outlet path **80** (FIG. **1**). The glycerin, having a greater density, may proceed through the weir structure **64** via underflow structure **66**, which may be positioned generally proximate to the rotor wall **22** of the rotor assembly **14**, and through the exit port **28** to the outlet path **70** (FIG. **1**).

[0038] The microwave radiation provided in the microwave chamber **20** may heat the mixture, causing the viscosity of the mixture to go down. The individual constituents, the ester and the glycerin may each coalesce more efficiently as the viscosity decreases. Therefore, the microwave radiation may speed the separation of the constituents. In addition, the microwave radiation is preferentially absorbed by the aqueous phase and thus vibrates the aqueous molecules within the mixture, disrupting the surface tension and promoting coalescence. Thus, there is a synergistic effect from the combination of the microwave heating, the application of microwave energy, and the rotational forces of the first centrifuge **60**. The separation may take place in as little as 5-30 seconds in the first centrifuge **60**. Liquid transit time through the first centrifuge **60** may be between about 10 seconds and about 30 seconds, and the in-process inventory within first centrifuge **60** may be between about 0.4 pints and about ½ gallon. A longer liquid transit time is also within the scope of the present invention. With a higher in-process inventory, the liquid transit time may be the same, but the flow rate will be correspondingly higher.

[0039] Turning back to FIG. **1**, the glycerin may exit the first centrifuge **60** and the microwave chamber **20** via an outlet path **70**. The ester may exit the first centrifuge **60** via outlet path **80** for subsequent introduction into a second mixer and separator in the form of centrifuge **90** for washing.

[0040] The second centrifuge **90** may have a first inlet **92** for receiving the ester from outlet path **80**. The ester may be washed in centrifuge **90** with a washing agent, for example, an acid or water, to remove traces of reactant, which may corrode an engine when the biodiesel is used. Remaining free glycerin and other impurities may also be removed from the ester. A second inlet **94** is provided to introduce the washing agent from a conduit **85** into the second centrifuge **90**. The wash waste may exit the second centrifuge **90** and the microwave chamber **20** via an outlet path **100**.

[0041] The second centrifuge **90** may comprise a "contactor" centrifuge for mixing and separating the washing agent and the ester. The second centrifuge **90** may be transparent to microwave radiation, and may be formed of, for example a polymer or plastic. FIG. **3** depicts one embodiment of a second centrifuge **90** of the present invention. The second centrifuge **90** may comprise a centrifuge similar to the first centrifuge **60**, depicted in FIG. **2**. Elements common to FIGS. **2** and **3** retain the same numerical designation. The housing **12** of the second centrifuge **90** includes a first inlet port **92** and a second inlet port **94**. The ester may be introduced through the first inlet port **92** and the washing agent may be introduced through the second inlet port **94**. The washing agent and the ester may mix in the annular region **18** defined between the outer radial surface of the rotor sleeve **21** and the inner radial surface of the housing **12**. The rotor sleeve **21** of the second centrifuge **90** may be employed to limit mixing in the annulus. Alternatively, the second centrifuge may not include a rotor sleeve **21**, and the outside surface **15** of the rotor assembly **14** may be in contact with the mixture to promote mixing within the annular region. The shear created in the two liquids trapped between the spinning rotor **14** and the stationary housing **12** enables full mixing. Remaining catalyst, free glycerin, aqueous by-products, reactant and other impurities will dissolve in the washing agent.

[0042] The phases of the mixture, that is, the purified ester and the washing agent with the dissolved impurities, may be separated in the interior of the rotor assembly **14**. The centrifugal force of rotation of the rotor assembly **14** may cause a constituent of the mixture having a higher density, the washing agent, to be forced outwardly against the inner radial wall **22** of rotor assembly **14**, and proceed through the weir structure **64** via underflow structure **66**, and through exit port **28** to outlet path **110** (FIG. **1**). The purified ester, having a lesser density, may proceed through weir structure **38**, which may be positioned generally proximate interior shaft **36**, and through exit port **24** to outlet path **100** (FIG. **1**).

[0043] The combination of the microwave energy and the g-force provided by the centrifuge may increase the output over a conventional washing apparatus by 20-400%. The microwave energy may cause the interface between the washing agent and the ester to resolve faster. The washing may take place in as little as 20-30 seconds in the second centrifuge **90**. Liquid transit time through the second centrifuge **90** may be between about 10 seconds and about 30 seconds, and the in-process inventory is about 0.4 pint to ½ gallon, depending on centrifuge size. A longer liquid transit time is also within the scope of the present invention.

[0044] Additional wash centrifuge contactors may be added to the cycle for additional purification. For example, as shown in FIG. **4**, a biodiesel production device **10'** may include a first centrifuge **60** configured for the separation phase, and three wash centrifuge contactors **90**A, **90**B, **90**C, in series. The centrifuge contactors **60**, **90**A, **90**B, and **90**C may all be positioned within a microwave chamber, along with a reaction vessel (not shown) as previously described. A feedstock and a catalyst may be mixed in the reaction vessel to form an ester and glycerin mixture, which may be separated in the first centrifuge **60**, as described hereinabove. The ester may exit the first centrifuge **60** and be introduced to the first wash centrifuge contactor **90**A via an outlet path **80**. The ester may be washed, as described herein above, within the first wash centrifuge contactor **90**A. The washing agent may be introduced via inlet path **94**A. The once-washed ester may be introduced into the second wash centrifuge contactor **90**B, and washed again with a fresh washing agent, introduced via inlet **94**B. The twice-washed ester may be introduced into the third wash centrifuge contactor **90**C, and washed again with a fresh washing agent, introduced via inlet **94**C. The outlets for the spent washing agent from the three wash centrifuge contactors **90**A, **90**B, **90**C are not shown. Each successive washing may be used to further purify the ester. Multiple wash stages may ensure that the biodiesel meets American Society for Testing and Materials (ASTM) and other specifications for biodiesel.

[0045] A biodiesel production device **10** or **10'** may have a liquid transit time through the between about one minute and about 30 minutes, and the in-process inventory within the device **10** or **10'** may be between about one gallon and about 10 gallons. The biodiesel production device **10** or **10'** may be transportable, and automated for ease of use. Thus, such a biodiesel production device may be employed at a location of waste oils, for example, at a fast food restaurant. Conversion efficiency with the application of microwave energy may exceed 95%. Thus, a small scale device requiring a low capital investment may be used by a non-technical operator to produce fuel from waste food oil. In one embodiment, the device may be less than nine cubic feet in volume, and weigh less than 200 pounds. For example, a biodiesel production device including first and second centrifuges **60**, **90** having two inch diameter rotors may weigh less than 200 pounds. The device **10** or **10'** including centrifuges with about two inch diameter rotors may be used to continuously produce biodiesel at a rate of between about 1 gallon per hour to about 12 gallons per hour, depending on the flow rate.

[0046] It is also within the scope of the present invention that the biodiesel production device be between about 200 and about 1000 pounds, and occupy a volume of about nine to about 150 cubic feet. For example, biodiesel production device including first and second centrifuges **60**, **90** having five inch diameter rotors may weigh about 1000 lbs, occupy 150 cubic feet. The rate of biodiesel production from such a device **10**, **10'** may be between 30 and 150 gallons per hour, depending on the flow rate. Thus, by way of example, a biodiesel device having a production rate of between about 1 gallon per hour to about 150 gallons per hour is within the scope of the present invention.

[0047] The microwave enhanced continuous process of the present invention may also be employed on a large scale. Turning to FIG. **5**, the microwave energy may be applied to individually to a reaction vessel **150**, and to a first and second separation apparatus such as a centrifuge **160**, **190**. The reaction vessel **150** may comprise a slab tank, enabling even heating. Microwave energy may be applied in the rotor assembly **14** of the first and second centrifuge **160**, **190**, as shown in FIG. **6**. The microwave energy (i.e., microwaves) may be communicated within one or more chambers **32** of the rotor assembly **14** of the first and second centrifuges **160**, **190**. Such a configuration may enhance or facilitate disengagement or disruption of the forces which form emulsions or dispersions. Accordingly, such a configuration may promote separation of the ester and the glycerin, or the ester and the washing agent. The presence of relatively high centrifugal forces in combination with microwave interaction may enhance the separation of the liquid-liquid mixture. That is, separation of dispersions, emulsions, or both may be promoted by exposure thereof to microwave radiation while under the influence of centrifugal force associated with the rotation of the rotor assembly **14**.

[0048] The rotor assembly **14** of the first and second centrifuges **160**, **190** of the present invention may include at least one microwave generation device for generating microwaves to be communicated therein. Microwave energy may be generated by a microwave generation device **120** positioned generally within the interior shaft **36** and configured for communication of microwave energy into a mixture or its constituents flowing through each of the chambers **32** of the rotor assembly **14**. The microwave generation device **120** may comprise any device capable of generating microwaves. For example, the microwave generation device **120** may comprise a maser, a klystron, or a magnetron tube.

[0049] Thus, microwave energy may be generated generally within the interior shaft **36**. The microwave generation device **120** may extend longitudinally within interior shaft **36**. The first and second centrifuges **160**, **190** may have rotors of 10 inch diameter or more, and may spin at about 1,000 to about 3,000 rpm.

[0050] Another embodiment of the microwave-enhanced diesel production method of the present invention is a continuous flow **105** including a reaction vessel **150** having a microwave generation device **155** associated therewith, a first separation apparatus such as the first centrifuge **160** having a microwave generation device **120** associated therewith, and at least a second mixing and separation apparatus such as the second centrifuge **190** having a microwave generation device **120** associated therewith. The first centrifuge **160** and the second centrifuge **190** may each include a rotor **14** and microwave generation device **120** as shown in FIG. **5**. A feedstock **130** and a catalyst **140** may be continuously introduced into the reaction vessel **150**, and may react therein to form a mixture of glycerin and an ester. The mixture **157** may be introduced into the first centrifuge **160**, and separated therein. The glycerin **162** may exit the system. The ester **165** may be introduced, along with a washing agent **192**, into the second centrifuge **190**. The ester **165** and the washing agent **192** may be mixed and then separated in the second centrifuge **190**, with the washing agent **194** containing impurities removed from the purified ester **196** exiting the system, and the purified ester exiting the system to be used as biodiesel. The reaction or separations may be enhanced by the application of microwave energy in the reaction vessel **150** and in each centrifuge **160**, **190**. Thus, a purified ester **196** may be continuously produced.

[0051] Although the foregoing description contains many specifics, these should not be construed as limiting the scope of the present invention, but merely as providing illustrations of some embodiments of the present invention. Similarly, other embodiments of the invention are contemplated and may be devised that do not depart from the spirit or scope of the present invention. Features from different embodiments may be employed in combination. The scope of the invention is, therefore, indicated and limited only by the appended claims and their legal equivalents, rather than by the foregoing description. All additions, deletions, and modifications to the invention, as disclosed herein, which fall within the meaning and scope of the claims, are to be embraced thereby.

What is claimed is:

1. A biodiesel production device, comprising:
a microwave device configured to provide microwave energy to a chamber thereof;
a reaction vessel positioned within the microwave chamber;
a first separation apparatus in communication with the reaction vessel and positioned within the chamber; and
at least one second mixing and separation apparatus in communication with the first separation apparatus and positioned within the chamber.

2. The biodiesel production device of claim **1**, wherein the reaction vessel includes static mixers.

3. The biodiesel production device of claim **1**, wherein the first separation apparatus comprises a first centrifuge configured for initial separation of an ester and glycerin.

4. The biodiesel production device of claim **3**, wherein the first centrifuge further comprises:
a first outlet for a first, denser material and configured to remove the first, denser material from the chamber; and
a second outlet in communication with the second mixing and separation apparatus.

5. The biodiesel production device of claim **1**, wherein the at least one second mixing and separation apparatus is a second centrifuge comprising:
an inlet in communication with an outlet of the first centrifuge;
an inlet for a washing agent;
a first outlet for a first, denser material and configured to remove the first, denser material from the second centrifuge and from the chamber; and
a second outlet.

6. The biodiesel production device of claim **1**, wherein the reaction vessel, the first separation apparatus, and the at least one second mixing and separation apparatus are substantially transparent to microwave energy.

7. The biodiesel production device of claim **1**, wherein the reaction vessel, the first separation apparatus, and the at least one second mixing and separation apparatus comprise at least one of a polymer, a plastic, a water-free ceramic, a quartz, a carbon fiber, and a glass.

8. The biodiesel production device of claim **1**, wherein the biodiesel production device weighs less than 200 pounds and occupies a volume of no more than about nine cubic feet.

9. The biodiesel production device of claim **1**, wherein the reaction vessel, the first separation apparatus, and the second mixing and separation apparatus are mutually configured in a continuous flow path therethrough.

10. The biodiesel production device of claim **9**, wherein the continuous flow path is configured to produce between about 1 gallon per hour to about 12 gallons per hour of biodiesel.

11. The biodiesel production device of claim **10**, wherein the continuous flow path is configured to accommodate an in-process inventory of between about one gallon and about five gallons.

12. The biodiesel production device of claim **1**, wherein the at least one second mixing and separation apparatus is a second centrifuge comprising:

a housing;

a rotor disposed within the housing;

an annular region defined by an inner wall of the housing and an outer wall of the rotor, and in communication with a first and a second inlet; and

a chamber disposed within the rotor and configured to separate a first material from a second, denser material.

13. The biodiesel production device of claim **1**, wherein the at least one second mixing and separation apparatus comprises at least two mixing and separation apparatuses configured in a series.

14. A method of producing biodiesel, comprising:

mixing a feedstock and a catalyst while applying microwave energy thereto to form an ester and glycerin mixture;

centrifugally separating the ester and the glycerin while applying microwave energy thereto; and

centrifugally mixing the ester with a washing agent and centrifugally separating a washed ester from the washing agent while applying microwave energy thereto.

15. The method of claim **14**, wherein the mixing the feedstock and the catalyst comprises introducing the feedstock and the catalyst into a reaction loop.

16. The method of claim **14**, wherein providing a feedstock comprises providing at least one animal- or plant-based fat feedstock or oil feedstock.

17. The method of claim **16**, wherein providing at least one animal-based or plant-based fat feedstock or oil feedstock comprises providing an animal fat, animal oil, vegetable fat, vegetable oil, restaurant grease, household grease, waste industrial frying oil, or mixtures thereof.

18. The method of claim **14**, wherein mixing the ester and the washing agent is effected in an annular region between a spinning rotor and a stationary housing of a centrifuge.

19. The method of claim **18**, wherein separating from the washing agent is effected within the spinning rotor of the centrifuge.

20. A method of producing biodiesel, comprising:

mixing a feedstock and a catalyst within a reaction vessel while applying microwave energy thereto from a microwave generation device associated therewith to form an ester and glycerin mixture in the reaction vessel;

separating the ester and the glycerin in a first centrifuge while applying microwave energy thereto from a second microwave generation device associated therewith; and

washing the ester in a second centrifuge while applying microwave energy thereto from a third microwave generation device associated therewith.

21. The method of claim **20**, wherein separating the ester and the glycerin in a first centrifuge while applying microwave energy thereto comprises applying the microwave energy from the second microwave generation device positioned within an interior shaft of the first centrifuge.

22. The method of claim **21**, further comprising providing the second microwave generation device selected from the group consisting of a maser, a klystron, and a magnetron.

23. The method of claim **20**, wherein washing the ester comprises mixing the ester and the washing agent in an annular region between a spinning rotor and a stationary housing of a centrifuge.

24. The method of claim **23**, wherein washing the ester further comprises separating the ester from the washing agent within the spinning rotor of the centrifuge.

25. A biodiesel production system, comprising:

a reaction vessel having a first microwave device configured to provide microwave energy to the reaction vessel;

a first separation apparatus in communication with the reaction vessel and having a second microwave device configured to provide microwave energy thereto; and

a second mixing and separation apparatus in communication with the first separation apparatus and having a third microwave device configured to provide microwave energy thereto.

26. The biodiesel production system of claim **25**, wherein the second microwave device is positioned is positioned within an interior shaft of the first separation apparatus.

27. The biodiesel production system of claim **25**, wherein the third microwave device is positioned is positioned within an interior shaft of the second mixing and separation apparatus.

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