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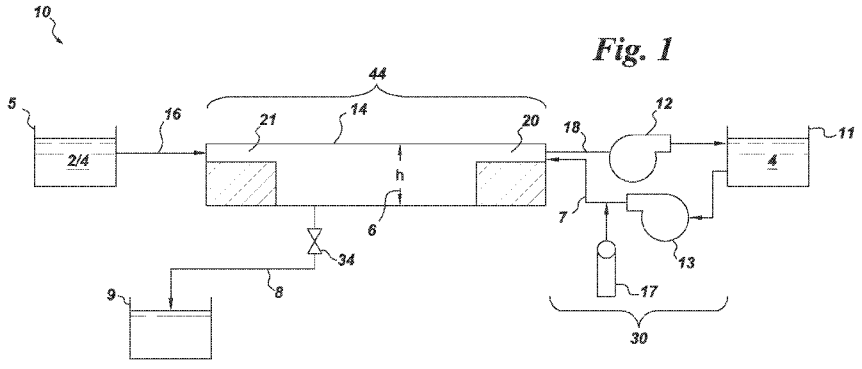


Fig. 1

(57) Abstract: A microclarification system is disclosed which can be used to separate solid particulates dispersed within a base fluid such as water. The microclarification system includes a plurality of microfluidic separator units disposed between and in fluid communication with a fluid inlet manifold and a fluid outlet manifold. The microclarification system enforces lamellar flow of fluid though it and as a result the rate at which particles settle is enhanced within a collection chamber associated with each microfluidic separator unit and through which the fluid being purified must pass. Each microfluidic separator unit includes a microfluidic outlet microchannel disposed between the microfluidic collection chamber and the fluid outlet manifold, and a gas-liquid flushing module configured to purge particulates from the collection chamber during a collection chamber purge cycle. Optionally, each microfluidic separator unit may include a microfluidic inlet microchannel. The system holds promise in municipal water purification among other applications.

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MICROCLARIFICATION SYSTEM AND METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of United States Provisional Application No. 61/916379, entitled "Systems for Separation of Particulates and Associated Methods and Devices", filed December 16, 2013, and which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] The invention relates to microfluidic separation systems, devices and methods useful for separating particulate materials from fluids. In a particular aspect, the invention relates to a method for separating solid particulates from fluid mixtures comprising such particulates.

[0003] While a substantial body of knowledge pertaining to the separation of solids from fluids such as water, for example as is practiced in municipal water treatment facilities, further enhancements and efficiencies are needed to keep pace with the needs of the world's people.

BRIEF DESCRIPTION

[0004] In one embodiment, the present invention provides microclarification system for separating particulates dispersed within a base fluid, the system comprising: a plurality of microfluidic collection chambers disposed between and in fluid communication with a fluid inlet manifold and a fluid outlet manifold; a plurality of outlet microchannels disposed between the microfluidic collection chambers and the fluid outlet manifold; and a gas-liquid flushing module configured to purge particulates from the collection chamber during a collection chamber purge cycle.

[0005] In an alternate embodiment, the present invention provides a method for separating particulates dispersed within a base fluid, the method comprising: (a) introducing, as part of a fluid purification cycle, a fluid comprising particulates dispersed within a base

fluid into a fluid inlet manifold of a microclarification system comprising: (i) a plurality of microfluidic collection chambers disposed between and in fluid communication with the fluid inlet manifold and a fluid outlet manifold; (ii) a plurality of microchannels disposed between the microfluidic collection chambers and the fluid outlet manifold; and (iii) a gas-liquid flushing module; wherein the system is configured such that the particulates dispersed within the base fluid pass from the fluid inlet manifold into the plurality of microfluidic collection chambers in which a substantial portion of the particulates are captured and through which a substantial portion of the base fluid passes and emerges at the fluid outlet manifold as a processed fluid depleted in particulates; and (b) introducing via the gas-liquid flushing module, as part of a collection chamber purge cycle, a gas and a purge liquid which together function as a collection chamber purge medium; and (c) repeating steps (a) and (b).

[0006] In yet another embodiment, the present invention provides a microclarification system for separating particulates from water, the system comprising: a plurality of microfluidic collection chambers disposed between and in fluid communication with a fluid inlet manifold and a fluid outlet manifold; a plurality of outlet microchannels disposed between the microfluidic collection chambers and the fluid outlet manifold; a plurality of inlet microchannels disposed between the inlet manifold and the microfluidic collection chambers; and a gas-liquid flushing module configured to purge particulates from the collection chamber during a collection chamber purge cycle; wherein the microfluidic collection chambers are characterized by a critical height of less than one centimeter; and wherein the outlet microchannels have an average height between about 1 micron and about 200 microns (μm) and a length in a range from about 1 millimeter to about 1 centimeter; and wherein the inlet microchannels have an average height in a range from about 1 micron to about 500 microns and a length in a range from about 1 millimeter to about 10 centimeters; and wherein the gas-liquid flushing module is configured to purge the collection chamber with a combination of a gas and a purge liquid.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

[0007] Various features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters may represent like parts throughout the

drawings. Unless otherwise indicated, the drawings provided herein are meant to illustrate key inventive features of the invention. These key inventive features are believed to be applicable in a wide variety of systems which comprising one or more embodiments of the invention. As such, the drawings are not meant to include all conventional features known by those of ordinary skill in the art to be required for the practice of the invention.

[0008] FIG. 1 illustrates a microclarification system provided by the present invention.

[0009] FIG. 2 illustrates a microclarification system provided by the present invention.

[0010] FIG. 3 illustrates a microclarification system provided by the present invention.

[0011] FIG. 4 illustrates a microclarification system provided by the present invention.

[0012] FIG. 5 illustrates a microclarification system provided by the present invention.

[0013] FIG. 6 illustrates a microclarification system provided by the present invention.

[0014] FIG. 7 illustrates a microclarification system provided by the present invention.

[0015] FIG. 8 illustrates a microclarification system provided by the present invention.

[0016] FIG. 9 illustrates a microfluidic separator unit provided by the present invention.

[0017] FIG. 10A illustrates a microfluidic separator unit provided by the present invention.

[0018] FIG. 10B illustrates a microfluidic separator unit provided by the present invention.

[0019] FIG. 11 illustrates a microclarification system for preparing drinking water provided by the present invention.

[0020] FIG. 12 illustrates a sewage treatment system provided by the present invention.

[0021] FIG. 13 illustrates a system for purifying a liquid product from a bioreactor provided by the present invention.

[0022] FIG. 14 illustrates a desalination system provided by the present invention.

[0023] FIG. 15 illustrates a system provided by the present invention.

DETAILED DESCRIPTION

[0024] In the following specification and the claims, which follow, reference will be made to a number of terms, which shall be defined to have the following meanings.

[0025] The singular forms "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

[0026] "Optional" or "optionally" means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where the event occurs and instances where it does not.

[0027] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about" and "substantially", are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Here and throughout the specification and claims, range limitations may be combined and/or interchanged, such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise.

[0028] As noted, in one embodiment, the present invention provides a microclarification system for separating particulates within a base fluid. The systems and methods provided by the present invention are especially promising for use in water purification processes which involve one or more settling steps to effect removal of suspended particulate matter. The present invention acts to enhance the rate at which suspended particles can be separated from a base liquid under the influence of gravity. The liquid to be purified, at times herein referred to as the unprocessed fluid, is passed through a microfluidic device, the microfluidic separator unit, which enforces a lamellar flow regime on the flowing liquid in which particle

settling rates are maximized in the absence of turbulent flow. The dimensions of the microfluidic device are such that the distance is minimized between a particle falling under the influence of gravity and a surface upon which the particle alights and is removed from a stream of horizontally flowing liquid. The devices can be operated at flow rates corresponding to particle residence times which are longer than the time required for a suspended particle to settle into contact with the bottom surface of the device collection chamber. As shown experimentally herein, the systems provided by the present invention are capable of particulate removal at much higher rates than conventional systems.

[0029] The microclarification systems provided by the present invention comprise a plurality of microfluidic collection chambers connected to and in fluid communication with a fluid inlet manifold and a fluid outlet manifold. Typically, the system is configured such that an unprocessed fluid requiring removal of particulates enters the collection chamber at a collection chamber fluid inlet and flows along the length of the collection chamber to a collection chamber fluid outlet. The dimensions of the collection chamber are microfluidic, meaning that at least one of the dimensions of the collection chamber is appropriately reported in microns. Table 1 of the Experimental Section of this disclosure provides specific, non-limiting examples of microfluidic collection chambers.

[0030] The collection chambers are characterized by a dimension, at times herein referred to as a critical height. This critical height is important for several reasons, among them, the critical height dimension is important to the enforcement of lamellar flow within the collection chamber and determines the distance a particle falling under the influence of gravity must travel before contacting the bottom of the collection chamber where it separates from the liquid flowing through the collection chamber. Particle behavior within the collection chamber is such that once coming into contact with the bottom surface of the collection chamber a particle is immobilized until its removal in a back flushing step. In one or more embodiments, the collection chambers are characterized by a critical height of less than one centimeter, i.e. less than 10000 microns, and corresponds to the average depth of the collection chamber.

[0031] The fluid inlet manifold is configured to deliver a fluid to be processed to the plurality of collection chambers. Thus, the fluid inlet manifold is sized appropriately to

deliver a flow of unprocessed fluid at a controlled flow rate to each collection chamber with which it is in fluid communication. Fluid communication between the fluid inlet manifold and the collection chamber may be direct, with no intervening structure, or may be indirect, as when fluid from the inlet manifold must first pass through an inlet microchannel prior to entering the collection chamber. In one or more embodiments the fluid inlet manifold is configured such that during back flushing, particles trapped within the collection chamber are directed through the fluid inlet manifold and to a waste collection vessel and/or a waste collection conduit. At times herein, particulate matter recovered from the collection chamber during a back flushing step is referred to as sludge.

[0032] The fluid outlet manifold is configured to receive processed fluid from the collection chamber and to direct the processed fluid to a processed fluid collection vessel and/or a processed fluid collection conduit. The fluid outlet manifold may be in direct fluid communication with the collection chamber or may be separated from the collection chamber by an intervening outlet microchannel. One purpose of the outlet microchannel is to create sufficient restriction at the outlet of the collection chamber such that a slight back pressure is created uniformly across each of the collection chambers of the microclarification system. While such outlet microchannels are not a requirement for operability of microclarification systems provided by the present invention, the outlet microchannels act to assure more uniform performance among the plurality of microfluidic collection chambers both from the stand point of uniform throughput and particle capture efficiency.

[0033] Inlet microchannels and outlet microchannels have dimensions smaller than the collection chamber. In one or more embodiments, the inlet microchannels and outlet microchannels are of uniform dimensions which are smaller than the dimensions of the collection chambers. In one or more embodiments, collection chambers, the inlet microchannels, and the outlet microchannels are of uniform height, such that the height of the inlet microchannels and outlet microchannels is a in a range from about one twentieth to about one tenth the height of the collection chambers. In one or more embodiments, the inlet microchannel and the outlet microchannels are characterized by an average height in a range from about 1 micron to about 200 microns (μm). In one or more embodiments, only outlet

microchannels are present and are characterized by an average height in a range from about 1 micron to about 200 microns (μm).

[0034] In one or more embodiments, the inlet microchannel and the outlet microchannels are characterized by a length in a range from about 1 millimeter to about 1centimeter. In one or more embodiments, only outlet microchannels are present and are characterized by a length in a range from about 1 millimeter to about 1 centimeter.

[0035] In one or more embodiments, both an inlet microchannel and an outlet microchannel are present in each microfluidic separator unit of the microclarification system provided by the present invention. Under such circumstances, a plurality of inlet microchannels are disposed between the fluid inlet manifold and the microfluidic collection chambers. In one such embodiment, the inlet microchannels have an average height in a range from about 1 micron to about 500 microns. In another such embodiment, inlet microchannels have length in a range from about 1 millimeter to about 10 centimeters.

[0036] In one or more embodiments, the gas-liquid flushing module is configured to deliver a mixture of gas and purge liquid to the collection chamber in order to clear collected particles from the collection chamber during a collection chamber purge cycle. The mixture of gas and purge liquid is at times herein referred to as a combination of a gas and a purge liquid. Upon entry of the combination of the gas and purge liquid, the limited height of the collection chamber causes rapid coalescence of gas bubbles dispersed in the purge liquid. As shown experimentally herein, this combination of a purge gas and purge liquid are especially effective at removal of captured solids from the collection chamber and maintaining collection chamber particle capture capacity, purge cycle after purge cycle. In one or more embodiments, the ratio of purge gas to purge liquid is in a range from about 1:10 to about 10:1.

[0037] Suitable purge gases include air, carbon dioxide, oxygen, nitrogen, argon, and mixtures of two or more of the foregoing gases. In one or more embodiments, the purge gas is primarily carbon dioxide. In an allied set of embodiments, the purge gas is greater than 95% carbon dioxide. In one or more embodiments, the purge gas employed is appreciably soluble in the purge liquid. For reference, carbon dioxide having a solubility in water at room

temperature of about 0.9mL CO_2 per mL of water is considered appreciably soluble in the purge liquid when the purge liquid is water.

[0038] Suitable purge liquids include water, aqueous ethanol, and clarate produced by the microclarification system. In one or more embodiments the purge liquid is water.

[0039] The microclarification system provided by the present invention may be operated essentially continuously through a plurality of full cycles each comprising a priming cycle, a fluid purification cycle, and a collection chamber purge cycle. Upon system start-up and following each purge cycle, the microclarification system is primed in order to eliminate trapped gas within the system. In various embodiments disclosed herein, the microclarification system is valved appropriately to bleed trapped gases out of the system. Suitable priming fluids include clarate produced by the system, water, aqueous ethanol, aqueous acetic acid and combinations of two or more of the foregoing priming fluids. In one or more embodiments, it may be useful to degas the priming fluid prior to its introduction into the system.

[0040] The microclarification systems provided by the present invention are anticipated to be useful in a host of applications and may be configured for use in treating municipal sewerage, indigenous water produced from a hydrocarbon reservoir, water produced as a by-product from hydraulic fracturing, water produced as a by-product of oil reservoir flooding, water produced as a by-product of a mining operation, water produced as a by-product of boiler operation, water as a byproduct of bitumen extraction, and combinations of two or more of the forgoing applications.

[0041] As noted, the present invention provides a method for separating particulates dispersed within a base fluid using one or more of the microclarification systems disclosed herein. As will be appreciated by those of ordinary skill in the art and having read this disclosure, the microclarification systems disclosed herein provide for essentially continuous operation in which, over a plurality of fluid purification cycles and following collection chamber purge cycles, the particulate capture capacity of the system remains essentially constant.

[0042] Turning now to the drawings, Fig. 1 illustrates essential features of microclarification systems 10 and associated methods provided by the present invention. For the sake of simplicity in illustrating the principles of operation of the microclarification systems provided by the present invention, Fig. 1 features only one collection chamber 14 and microfluidic separator unit 44 comprising such collection chamber. Thus, a slurry tank 5 holding a mixture of particulates 2 disposed in a base fluid 4 is linked via an inlet manifold 16 to a microfluidic separator unit 44 comprising collection chamber 14 having critical height 6 (h). The collection chamber is linked to and is in fluid communication with inlet manifold 16 via inlet microchannel 21. The limited height dimensions of the inlet microchannel 21 and the collection chamber 14, both are microfluidic as defined herein, enforce lamellar flow within the inlet microchannel and the collection chamber while allowing for relatively high throughput rates. Such a lamellar flow regime minimizes the time required for a particle entering the collection chamber to settle to the bottom of the collection chamber and become trapped there. An outlet microchannel 20 acts both as a weir-creating structure to further inhibit passage of particulates out of the collection chamber and as a back pressure regulating feature which helps assure uniform performance of a plurality of microfluidic separator units when such separator units are linked to a single inlet manifold. Further uniformity is achieved by providing for turbulent flow within both the slurry tank and the inlet manifold.

[0043] Outlet microchannel 20 is linked to and in fluid communication with outlet manifold 18 which is linked to pump 12 which serves to draw the suspension of particulates 2 in base fluid 4 through the microfluidic separator unit 44 to provide processed fluid comprising base fluid 4 which is substantially depleted in particulates 2. As used herein and with respect to a processed fluid, substantially depleted means that at least fifty percent of the particulates originally present in the fluid to be processed have been removed by the system. In the embodiment shown, the processed fluid is collected in a vessel, at times herein referred to as a clarate recovery tank 11. The term clarate may at times herein be used interchangeably with the term processed fluid. The microclarification system 10 may be operated in fluid purification mode until the collection chamber becomes saturated with particulates and particle capture efficiency begins to drop from optimal performance. Particulate breakthrough may be deemed to have occurred at any time during the fluid purification cycle but is typically associated with a rise in particulate level in the processed

fluid following a period of operation in which the processed fluid remains substantially depleted in particulates.

[0044] Upon particulate breakthrough, the fluid purification cycle is replaced by a fluid purge cycle. The system is equipped with a gas-liquid flushing module 30 configured to flush captured particulate matter from the collection chamber. During the purge cycle a relatively small volume of the clarate is drawn by pump 13 and mixed with a purge gas from purge gas source 17 and passed through purge cycle inlet line 7 into collection chamber 14. During the purge cycle valve 34 may be opened to allow a concentrated mixture of particulates and purge fluid to pass along purge cycle exit line 8 and into sludge recovery tank 9. Inlet manifold 16 may comprise valves as appropriate (not shown) to prevent fluid communication between slurry tank 5 and the collection chamber during the purge cycle. In a typical purge cycle, less than 10 percent of the clarate produced in the fluid purification cycle is expended in the purge cycle. In various embodiments, less than 5 percent of the clarate produced in the fluid purification cycle is expended in the purge cycle.

[0045] Following the purge cycle, the microclarification system is primed to eliminate gas bubbles, particularly within the microfluidic separator unit 44. In the embodiment shown, the system is configured to utilize a relatively small volume of the clarate as the priming fluid in the absence of the purge gas. In a typical priming cycle, less than 10 percent of the clarate produced in the fluid purification cycle is expended in the priming cycle. In various embodiments, less than 5 percent of the clarate produced in the fluid purification cycle is expended in the priming cycle. In one or more embodiments less than the volume of the collection chamber is required to effectively prime the system. Various wetting agents such as surfactants, ethanol, acetic acid and polethyelene glycol may aid in minimizing the volume of priming fluid required to effectively prime the system.

[0046] Referring to Fig. 2, the figure represents a portion of a microclarification system 10 provided by the present invention featuring a microfluidic separator unit 44 disposed between an inlet manifold 16 and an outlet manifold 18. The inlet manifold is shown as containing a fluid to be processed by the unit and comprising particulates 2 dispersed within a base fluid 4. The fluid to be processed enters the microfluidic separator unit via inlet microchannel 21 having average height 24 and length 25. In the embodiment shown, the

inlet microchannel of uniform dimensions and the average height is simply the height of the inlet microchannel along its length 25. As noted, the inlet microchannel serves to enforce lamellar flow on the fluid to be processed, and this lamellar flow continues in the collection chamber 14 and particles 2 settle rapidly to the bottom in the absence of turbulent flow. Lamellar flow is indicated in Fig. 2 and elsewhere herein as two or more parallel arrows. Collection chamber 14 is microfluidic in the sense that it is characterized by a critical height 6 which appropriately measured in microns and is under 10,000 microns, typically in a range from about 100 microns to about 2000 microns. Collection chamber 14 must be appropriately sized such that lamellar flow is enforced within it, but any pressure drop across the length of the collection chamber will be minimal. In the embodiment shown, the collection chamber is of uniform dimensions with a single critical height 6. The microfluidic separator unit 44 comprises an outlet microchannel 20 having height 22 and length 23. Together, the outlet microchannel and the inlet microchannel create a tub-like structure in which particulates are captured. Processed fluid exits the outlet microchannel and enters outlet manifold 18.

[0047] Referring to Fig. 3, the figure represents a portion of a microclarification system 10 provided by the present invention and features a plurality of microfluidic separator units of the type shown in Fig. 2. The microfluidic separator units are essentially identical and each comprises a collection chamber 14 disposed between and in fluid communication with fluid inlet manifold 16 and fluid outlet manifold 18.

[0048] Referring to Fig. 4, the figure represents a portion of a microclarification system 10 provided by the present invention wherein the microfluidic separator units each comprise a microporous body 26 which divides the collection chamber into an upper portion and a lower portion, the critical height 6 being shown as the distance between the top of the collection chamber 14 and the bottom of the collection chamber where particulates 2 are shown as accumulating.

[0049] In one or more embodiments, the microporous body 26 may be a membrane or a solid body through which holes have been created. In one or more embodiments the microporous body comprises pores originating at a first surface of the microporous body and terminating at a second surface of the microporous body. In one or more embodiments, the

microporous body is a film through which pores have been created. For example, pores traversing a film may be created by chemical etching techniques and/or laser ablative techniques. The term microporous is used herein because the pores have dimensions appropriately measured in microns (e.g., the average pore diameter is 1000 microns or less). In one embodiment, the pores have an average diameter between about 1 micron and about 500 microns. In an alternate embodiment, the pores have an average diameter between about 10 microns and about 250 microns. In yet another embodiment, the pores have an average diameter between about 20 microns and about 100 microns. In one embodiment, the porosity of the microporous body is between about 10 and about 75 percent. In an alternate embodiment, the porosity of the microporous body is between about 20 and about 65 percent. In yet another embodiment, the porosity of the microporous body is between about 30 and about 60 percent.

[0050] As noted, in one embodiment, the microporous body may be a microporous film such as a monofilament screen or mesh made from, for example, polyester, nylon, polypropylene, or a combination of such polymeric substances). Alternatively, the microporous body may be a chemically-etched KAPTON, titanium, or NiTinol film. In one embodiment, the microporous body is a laser etched organic film made from an organic polymeric material such as KAPTON.

[0051] Referring to Fig. 5, the figure represents a portion of a microclarification system 10 provided by the present invention in which the microfluidic separator units do not comprise an inlet microchannel 21, but do comprises an outlet microchannel 20. Thus, collection chamber 14 is in direct fluid communication with fluid inlet manifold 16. In the embodiment shown, fluid enters the collection chambers initially as turbulent flow and is converted to lamellar flow within the collection chamber. Processed fluid passes through outlet microchannels 20 into fluid outlet manifold 18.

[0052] Referring to Fig. 6, the figure represents a microclarification system 10 provided by the present invention and features a plurality of collection chambers 14 disposed between and in fluid communication with a fluid inlet manifold 16 and a fluid outlet manifold 18, the fluid inlet manifold and fluid outlet manifold being configured in parallel. Each of the collection chambers 14 is in fluid communication with the fluid outlet manifold 18 via an

outlet microchannel as in, for example, Fig. 3, Fig. 4 and Fig. 5. The microclarification system 10 operates as outlined in the description of Fig. 1 with the exception that the gas-liquid flushing module 30 utilizes a purge liquid drawn from purge liquid supply tank 32 which is separate from clarate recovery tank 11. The microclarification system comprises valves 34 which may be used to isolate purge cycle inlet and outlet lines 7 and 8 from fluid inlet manifold 16 and fluid outlet manifold 18 during purification cycles in which feed line 15 is in fluid communication with outlet conduit 19 and clarate recovery tank 11 via fluid inlet manifold 16, collection chambers 14 and fluid outlet manifold 18. Similarly, during collection chamber purge cycles, valves 34 may be used to isolate feed line 15 and outlet conduit 19 from the inlet and outlet manifolds while passing purge liquid and purge gas from the gas-liquid flushing module 30 into fluid outlet manifold 18, collection chambers 14 and fluid inlet manifold 16 and collecting particulates in sludge recovery tank 9.

[0053] Referring to Fig. 7, the figure represents a portion of a microclarification system 10 provided by the present invention and features a plurality of collection chambers 14 disposed between and in fluid communication with a fluid inlet manifold 16 and a fluid outlet manifold 18, the fluid inlet manifold and fluid outlet manifold being configured radially.

[0054] Referring to Fig. 8, the figure represents the microclarification system shown in Fig.7 but revealing additional system details. As noted with respect to Fig. 7, the fluid inlet manifold 16 and fluid outlet manifold 18 are arranged radially with the collection chambers 14 configured like the spokes of a wheel linking fluid inlet manifold 16 (the wheel hub) with the fluid outlet manifolds 18 (the wheel rim). The embodiment shown in Fig. 8 comprises a plurality of fluid outlet manifolds 18 arrayed along the axis of a single fluid inlet manifold 16. The collection chambers 14 are in fluid communication with fluid inlet manifold 16 and fluid outlet manifolds 18 via inlet microchannel 21 and outlet microchannel 20 (not shown). During a fluid purification cycle a mixture particulates 2 dispersed within a base fluid 4 passes from slurry tank 5 into fluid inlet manifold 16 in response to the action of forward pump 12. The mixture of particulates 2 dispersed within a base fluid enters the microfluidic separator units comprising collection chambers 14 wherein a lamellar flow regime is enforced as a result of the limited heights of the collection chambers and associated inlet and outlet microchannels. Notwithstanding the appearance in Fig. 8 and the reference to wheel spokes,

the microfluidic separator units 44 shown in Fig. 8 and comprising collection chambers 14 are shaped essentially like flattened boxes (or pie wedges) adapted for coupling to and fluid communication with the fluid inlet manifold 16 at one end and fluid outlet manifold 18 on the other. Processed fluid emerging from the microfluidic separator units 44 passes from each of the fluid outlet manifolds 18 to clarate recovery tank 11 via outlet conduits 19, valve 34 and forward pump 12.

[0055] Still referring to FIG. 8, during a collection chamber purge cycle slurry tank 5 and clarate recovery tank 11 are isolated from the system by closing one or more valves 34 while introducing a gas and a purge liquid which together function as a collection chamber purge medium into each of the fluid outlet manifolds 18 via purge cycle inlet line 7 while simultaneously collecting in sludge recovery tank 9 a mixture comprising particulates driven from the collection chambers 14 and purge liquid from purge liquid supply tank 32.

[0056] Referring to Fig. 9, the figure represents a portion of a microfluidic separator unit 44 which may be adapted for use in microclarification systems comprising either a radial or a parallel arrangement of the fluid inlet and fluid outlet manifolds. In the embodiment shown, the microfluidic separator unit is an orthotope open at each end and containing flow channel blocking members 46 at each end which create an inlet microchannel (not shown) and an outlet microchannel 20. The microfluidic separator unit may be made from simple plastic rectangles joined one to each of two others with adhesive 47. Flow blocking members 46 are joined with adhesive 47 to three of the rectangles but are not joined to upper portion 48. Alternatively, microfluidic separator unit 44 may be prepared using one or more art recognized plastics processing techniques, such as injection molding and/or extrusion. In one or more embodiments, one or more components of the microfluidic separator unit is prepared using an additive manufacturing technique.

[0057] Referring to Fig. 10A and Fig. 10B, these figures further exemplify techniques for building microfluidic separator units 44 which may be used according to one or more embodiments of the present invention. These figures are discussed in detail in the Experimental Part of this disclosure.

[0058] Referring to Fig.s 11- 14, the figures illustrate the use of microclarification systems 10 provided by the present invention in key human activities: the purification of fresh water for human consumption (Fig. 11); the treatment of sewage (Fig. 12); process steps involving the removal of particulates in a biological process such as the production of ethanol from sugarcane bagasse (Fig. 13); and the desalination of seawater (Fig. 14).

[0059] Referring to Fig. 11, system 50 is a system for producing drinking water from fresh, but otherwise non-potable water 51, the element 52 is a screen filter, the element 53 is a clarate stream produced by microclarification system 10, the element 54 is a sludge stream produced by the microclarification system 10, the element 55 is filtration unit configured to filter clarate stream 53; the element 56 is the filtrate produced by filtration unit 55, the element 57 is a stream of material rejected by the filtration unit 55 which is added to sludge stream 54 for sludge disposal. The element 58 is a disinfection unit which produces drinking water 59.

[0060] Referring to Fig. 12, the figure represents a sewage treatment system 60 in which the element 61 is raw sewage, the element 62 is an aeration tank, the element 63 is an activated sludge reactor, the element 64 is a stream of water recovered from activated sludge reactor 63, the element 65 is a stream of sludge produced by the activated sludge reactor, the element 66 is an overflow stream from aeration tank 62, and the element 67 is treated water from the sewage treatment plant. All other elements shown have been defined elsewhere in this disclosure.

[0061] Referring to Fig. 13, the figure represents a system 70 for conducting a biological manufacturing process in which 71 represents a feed stock serving as the starting material for the biological transformation, for example chopped bagasse to be converted into a mixture of sugars useful in ethanol production via fermentation. The element 72 is a stream of air used in the biological transformation which takes place in aerated bioreactor 73. The element 74 is the product stream from the bioreactor. The elements 10, 53, 54 and 55 have been defined elsewhere in this disclosure. The element 75 represents a stream of material rejected by filtration unit 55. The element 77 represents a stream of clean product produced by system 70.

[0062] Referring to Fig. 14, the figure represents a system 80 for the desalination of seawater 81. In one or more embodiments, the element 81 is brackish water. The elements 10, 52, 53 and 54 have been defined elsewhere in this disclosure. The element 82 is a filtration device. In one or more embodiments the element 82 is a microfilter. In one or more embodiments the element is an ultrafilter. The element 83 is an aqueous stream produced by filtration device 82. The element 84 is a stream of material rejected by filtration device 82. The element 85 represents a reverse osmosis separation membrane unit. The elements 86 and 87 represent a substantially salt free permeate stream and a salt rich concentrate stream respectively. The elements 58 and 59 have been defined elsewhere in this disclosure.

[0063] Referring to Fig. 15, the figure represents a microclarification system 10 provided by the present invention in which the fluid inlet manifold is configured as an immersion tank. In the embodiment shown, the microfluidic separator units 44 are arranged as a stack of flattened cylinders having a largely open rim defining the inlet of the collection chamber 14 and closed upper 48 and lower surfaces 28. The collection chambers are in fluid communication with a cylindrical fluid outlet manifold 18 via outlet microchannels 20. The immersion tank serving as the fluid inlet manifold 16 comprises a raised surface 94 which may support the stack of cylindrical microfluidic separator units 44 and the fluid outlet manifold 18, and defines a particulate sump 92. In the embodiment shown, the immersion tank serving as the fluid inlet manifold 16 is configured to receive a vented (See valved vents 134 and 136)tank cover 96 which prevents tank overfill during fluid purification cycles and allows gas pockets introduced during a collection chamber purge cycle to be escape from the immersion tank.

EXPERIMENTAL PART

Methods and Materials

[0064] Silica particle standards were purchased from Fisher Scientific and used as received. Influent and effluent turbidity was measured using an OAKTON® TN-100/T-100 portable turbidimeter. Particle size distributions were measured by forward light scattering method. Medical grade polyamide woven mesh (purchased from SEFAR (MEDIFAB, 07-40/40)) was employed in embodiments comprising a microporous body and had 40 micron pores and 40% porosity. Rapid prototyping of microfluidic separator unit components was performed at a commercial vendor using a photopolymerizable acyronitrile-butadiene-styrene (ABS) copolymer (DSM Somos WaterShed XC 11122). Pressure sensitive adhesive (VHB double-sided pressure sensitive adhesive tape) used in the construction of microfluidic separator units was purchased from 3M.

Microfluidic Separator Device Construction

[0065] A series of microfluidic separator devices (Devices 1-8) were assembled from three parts created on the rapid prototyping instrument. With the exception of Device 1, which comprised a microporous body made of a polyamide woven mesh dividing the collection chamber into an upper and a lower portion, all of the Devices possessed undivided collection chambers. A set of pressure sensitive adhesive films appropriately sized and shaped were used to join the component parts of the microfluidic separator units together into a unitary whole. Useful reference may be made to FIG. s 10A and 10B and Table 1 below. Dimensions for 1- 8 are given in Table 1 below. Reference elements A-H and J-K are illustrated in figures 10A and 10B and wherein:

A is the height of the of the microfluidic separator unit measured from surface 28 of base 49 (Fig. 10B) to the top of the inlet microchannel (21), where A = E =H;

B is the height of the inlet microchannel (21);

C is the length of the inlet microchannel (21);

D is the length of the collection chamber (14);

E is height of the collection chamber (14) where E = A = H;

F is the length of the outlet microchannel (20);

G is the is the height of the outlet microchannel (20);

H is the height of the of the microfluidic separator unit measured from surface 28 of base 49 (Fig. 10B) to the top of the outlet microchannel (20) where H = A = E;

J is the width of the inlet microchannel (21);

K is the width of the collection chamber (14); and

L is the width of the outlet microchannel (20).

Table 1

Dimension	A mm	B mm	C mm	D mm	E mm	F mm	G mm	H mm	J cm	K cm	L cm
Device 1	2.0	0.1	16.5	40.0	2.0	16.5	0.1	2.0	1.0	1.0	1.0
Device 2	2.0	0.1	16.5	40.0	2.0	16.5	0.1	2.0	1.0	1.0	1.0
Device 3	0	0	0	40.0	2.0	0	0	0	0	1.0	0
Device 4	2.0	0.1	66.5	40.0	2.0	16.5	0.1	2.0	1.0	1.0	1.0
Device 5	0	0	0	262	2.0	0	0	0	0	25.4	0
Device 6	0	0	0	40.0	4.0	0	0	0	0	1.0	0
Device 7	0	0	0	40.0	6.0	0	0	0	0	1.0	0
Device 8	0	0	0	222	2.0	0	0	0	0	38	0

[0066] The following exemplifies the construction of a microfluidic separator device 44 comprises an inlet microchannel 21, an outlet microchannel 20 and a microporous body 26 from three components prepared on the rapid prototyping instrument. Again, useful reference may be made to figures 10A and 10B. A first part 41 (Fig. 10A) comprising a fluid inlet 42 linked to an inlet microchannel 21 and fluid outlet 43 linked to an outlet microchannel 20.

The second part 45 (Fig. 10B) substantially defined the depth of collection chamber 14. A third part 49 (Fig 10B) served as the base of the device and served as the bottom surface 28 of the collection chamber 14. Device components could be joined with appropriately cut pressure sensitive adhesive films 47. For example, a 50 micron (μm) thick pressure sensitive adhesive 47 may be used to secure the first part 41 to the surface of the microporous body 26 and create thereby a channel extending from upper portion 48 of the microfluidic separator device to the upper surface of the microporous body 26. Appropriately shaped pressure sensitive adhesive comprised features cut out using a cutter/plotter (Graphtec Craft Robo ProS). Additional cut adhesive films 47 were used to fix the second part 45 to the lower surface of the microporous body 26 and the third part 49 respectively. In one or more embodiments, the collection chamber 14 had dimensions of 40 millimeters by 10 millimeters and varied in depth from 2 millimeters (Devices 1-4), to 4 millimeters (Device 6), to 6 millimeters (Device 7). Devices 1-4, 6 and 7 had collection chamber volumes ranging from about 750 to about 2250 microliters (μL). Devices 5 and 8 had collection chamber volumes of about 13.3 cm^3 and 16.9 cm^3 respectively.

Laboratory Operation of Microfluidic Separator Devices

[0067] In a typical experiment, a feed suspension was prepared by addition of about 40 mg of a silica particle standard in a single portion to 100 mL of deionized water, creating a 0.04 wt% suspension in a 200 mL glass beaker. The feed suspension was stirred throughout the experiment. Turbidity measurements are reported in Nephelometric Turbidity Units (NTU).

[0068] The feed line was connected between the device inlet 42 (Fig 10A) and the beaker containing the stirred feed suspension. A syringe pump was attached to the device outlet 43 and was used to pull the feed suspension through the device inlet at a controlled flow rate. The effluent (clarate) was collected in the syringe in 10 mL increments. The experiments were run in batch mode, with no recirculation of the effluent stream. Syringe pump flow rates were confirmed by recording the volume increase in the syringe over time. In general, an amount of feed suspension equivalent to ten times the volume of the collection chamber was processed before measuring effluent turbidity to ensure the device had reached a representative state of operation.

Example 1: Effect of Microporous Body

[0069] Devices 1 and 2 (Table 1) comprised collection chambers having dimensions 40mm x 10mm x 2.0 mm. Each device comprised inlet and outlet microchannels having dimensions of 16.5 mm x 10 mm x 0.1 mm. Device 1 comprised a 40 µm mesh microporous body 26 screen whereas, Device 2 did not. A feed suspension containing 0.04 w/v% of 2 µm silica standard particles and a measured turbidity of 560 NTU was prepared in deionized water. The feed suspension was presented to each device at a feed rate of 200 microliters per minute (µL/min) and corresponded in each case to a residence time of approximately 4 minutes. The residence time is arrived at by dividing the nominal volume of the device (800 µL) by the 200 µL/min throughput rate. The effluent turbidities of the device with and without the microporous body were 105 NTU and 135 NTU respectively. This result demonstrates that while the presence of the microporous body incrementally improves the performance of the device under the conditions of this Example 1, the device may achieve a substantial clarifying effect in the absence of such microporous body as well.

Example 2: Effect of Particle Size

[0070] Device 2 was presented sequentially with two feed suspensions; first a 1,600 NTU suspension containing 0.08 w/v% of 2 µm silica particles, and second a 1,087 NTU suspension containing 0.04 w/v% 10 µm silica particles. Each feed suspension was prepared in deionized water and presented to the device at a throughput rate of 200 µl/min. The effluent turbidities of the 2 µm and 10 µm particle experiments were 320 NTU and 2.3 NTU respectively, and indicated both the effectiveness of the device in removing the smaller particles, and the greater susceptibility of larger particles to capture in the collection chamber.

Example 3: Effect of Inlet and Outlet Microchannels

[0071] In this experiment the performance of Device 2 comprising 16.5 mm long inlet and outlet microchannels and was compared with the performance of Device 3 having no inlet and outlet microchannels. A feed suspension containing 0.04 w/v% of 2 µm silica standard particles was prepared in deionized water. Each device was tested against the feed suspension processed at 200 µL/min. The height of the collection chamber was 2.0 millimeters in each case. The measured influent and effluent turbidities from the device with

the microchannels (Device 2) were 589 and 175 NTU respectively. The measured influent and effluent turbidities from the device with no microchannels (device 3) were 597 and 236 NTU respectively. The experimental results illustrate an incremental beneficial effect of the inlet and outlet microchannels on product clarate quality.

Example 4: Effect of Inlet Microchannel Length

[0072] Device 2 comprising a 16.5 mm long inlet and 16.5 mm long outlet microchannel was compared with Device 4 comprising a 66.5 mm long inlet and 16.5 mm long outlet microchannel. A 700 NTU feed suspension containing 0.04 w/v% of 2 μm silica standard particles was prepared in deionized water. Each device was tested against the feed suspension processed at 200 μL/min (a 4 min residence time). The effluent turbidities from the devices with 16.5 mm and 66.5 mm long inlet microchannels were 274 NTU and 135 NTU respectively suggesting that a longer inlet microchannel can substantially improve clarate quality.

Example 5: Effect of Device Scale

[0073] The performance of Device 3 having a nominal collection chamber volume of 0.8 cm^3 was compared with the performance of Device 5 having a nominal collection chamber volume of 13.3 cm^3. Neither device comprised an inlet or outlet microchannel, and thus the feed suspension was presented directly through the device fluid inlet into the collection chamber. Processed fluid exited directly from the collection chamber through the device fluid outlet. Each device was presented with a 526 NTU feed suspension containing a 0.04 w/v% 2 μm silica standard particles prepared in deionized water. The 0.8 cm^3 and 13.3 cm^3 devices were tested against the feed suspension processed at 0.2 mL/min and 2.0 mL/min respectively, corresponding to a 4 min residence time in each device. The effluent turbidities of the 0.8 cm^3 and 13.3 cm^3 devices were 206 NTU and 137 NTU, respectively, and indicated that performance observed for smaller device may be scaled to larger devices at correspondingly higher flow rates.

Example 6: Continuous Operation and Solids Clearance

[0074] A 22.2 x 3.8 x 0.2 cm device (Device 8) without microchannels or a microporous sieve was assembled and its performance evaluated. In a typical experiment, 6 g of tan clay particles were added in a single portion to 3,000 mL of deionized water, creating a 2,000 mg/L suspension in a 4 L glass beaker. The solution was stirred for the entirety of the experiment. A schematic of the lab process for monitoring solid settling in the device and collection chamber (tub) clearance using different backwashing designs is provided in Fig. 1 with the exception that no inlet microchannel 21 or outlet microchannel 20 was present, the feed suspension being introduced directly into the collection chamber 14. Prior to the experiment, the device was primed with deionized water and placed on a balance. The balance was tared and the system was configured to record weight change in the device over time. During forward operation, a peristaltic pump attached to the device outlet pulled the feed suspension through the device inlet and controlled flow rates. The effluent was collected in a graduated cylinder in 1,200 mL increments. The experiments were run in batch mode, with no recirculation of the effluent stream. Pump flow rates were confirmed by recording the volume increase in the cylinder over time. The solids accumulation in the device was recorded from the balance every 15 seconds until 1,200 mL of processed liquid had collected. Following forward processing, one of several solids clearance protocols was implemented in the reverse direction to flush out the accumulated solids into a waste beaker in a backwash cycle. Following a backwash cycle, the device was re-primed in the forward direction to begin a new forward cycle. The weight remaining in the collection chamber represented the amount of solids that could not be cleared using the solids clearance protocol employed. Several cycles consisting of a forward and back wash mode were run for each protocol tested. The accumulated solids in the collection chamber following each backwash cycle was recorded for the total volume of feed processed.

Protocol 1: High Flow Backflush – Water Only

[0075] Device 8 (Table 1) was tested against a 2,000 mg/L TAN clay feed suspension processed at 24 mL/min. After each 1200 mL of volume processed, the pump direction was reversed and deionized water was pumped through the device at 300 mL/min for 60 seconds. The flushed solids were emptied into a separate waste container. Following the 60 second water backwash, the pump speed was decreased back to 24 mL/min and the system was placed back into forward service. The weight remaining in the device was recorded on the

balance after the device had been re-primed. This forward and back wash cycle was repeated three times and in each case 1,200 mL processed was collected in each cycles. The data are shown in Table 2.

Table 2 Performance of Device 8 Over Three Cycles Water Only Backflush

Cycle Data	Cycle 1	Cycle 2	Cycle 3
Irreversible Solid Accumulation (g)	1.43	2.15	2.9
Cycle Collection Chamber Capacity	1.34	2.33	3.11
% Collection chamber Clearance (cycle to cycle)	0	7.7	6.8
Cycle Time (min)	45.5	48.75	49.25
Volume Processed (mL)	1092	1170	1182
% Water Recovery	72.5	74.4	74.6
Cumulative Volume Processed (mL)	1092	2262	3444

Protocol 2 Alternating Air-Water Backflush

[0076] Device 8 (Table 1) was tested against a 2,000 mg/L TAN clay feed solution processed at 24 mL/min. After 1200 mL of the feed solution had been processed, the pump direction was reversed and deionized water was pumped through the device at 300 mL/min for 45 seconds. During this time, the deionized water inlet was lifted out of the beaker every 5 seconds for durations of 5 seconds to draw into the flush line an approximately 25 mL confined air bubble followed by a 5 second flush with deionized water. Alternating air-water cycles were repeated 5 times during a single back wash cycle. The flushed solids were emptied into a separate waste container. Following the 45 second confined air bubble and water backwash, the pump speed was decreased back to 24 mL/min and the system was placed back into forward service. The weight remaining in the device was recorded on the balance after the device re-primed. This forward and back wash cycle was repeated after every additional 1,200 mL processed volume for a total of three complete cycles. The data are gathered in Table 3.

Table 3: Performance of Device Using Alternating Air-Water Backflush Protocol

Cycle Data	Cycle 1	Cycle 2	Cycle 3
Irreversible Solid Accumulation (g)	0.96	1.02	1.28

Average Breakthrough Capacity (g)*	1.49		
% Collection Chamber Clearance *	35.6	31.5	14.1
Cycle Breakthrough Capacity (g)	1.13	1.59	1.75
% Clearance (cycle to cycle)	15	35.8	26.9
Cycle Time (min)	45	47.75	46.75
Volume Processed (mL)	1080	1146	1122
% Water Recovery	83.8	84.7	84.4
Cumulative Volume Processed (mL)	1080	2226	3348

Protocol 3 Low and High Flow Dual Fluid – Air/Water Backflush.

[0077] Device 8 was tested against a 2,000 mg/L TAN clay feed solution processed at 24 mL/min. After 1,200 mL of volume processed, the pump direction was reversed and a mixture of deionized water and air was fed into device for 45 seconds. The water flow rate was 150 mL/min and the air flow rate was 0.1 scfh. After 45 seconds of air and water flushing, the air flow feed line was switched off and water-only was flushed back through the device for an additional 15 seconds completing the back wash cycle. The flushed solids were collected in a separate waste container. Following the 60 second low velocity air and water flush, the pump speed was decreased back to 24 mL/min and the system was placed back into forward service. The weight remaining in the device was recorded on the balance after the device had been fully re-primed, i.e. there were no visible air bubbles or air pockets within the device. This forward and back wash cycle was repeated after every additional 1,200 mL processed volume for a total of four complete cycles. The data are shown in Table 4. An analogous experiment was carried out over five cycles at a water flow rate of 300 mL/min and an air flow rate of 0.2 scfh during the back wash cycles. The data are shown in Table 5.

Table 4 Low Flow Dual Fluid Solids Clearance Protocol

Cycle Data	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Irreversible Solid Accumulation (g)	0.21	0.6	0.8	0.9
Average Breakthrough Capacity (g)*	1.31			
% Collection chamber Clearance *	83.9	54.1	38.8	31.2
Cycle Breakthrough Capacity (g)	1.01	1.08	1.68	1.46
% Collection chamber Clearance (cycle to cycle)	79.2	44.4	52.4	38.4
Cycle Time (min)	45.5	48.25	50.75	53.5
Volume Processed (mL)	1092	1158	1218	1284

% Water Recovery	86.3	87	87.7	88.3
Cumulative Volume Processed (mL)	1092	2250	3468	4752

*Average of solids accumulated each cycle- used to calculated % clearance

Table 5 High Flow Dual Fluid Solids Clearance Protocol

Cycle Data	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Irreversible Solid Accumulation (g)	0.24	0.24	0.22	0.24	0.2
Average Breakthrough Capacity (g)*	0.9025				
% Collection chamber Clearance *	73.4	73.4	75.6	73.4	77.8
Cycle Breakthrough Capacity (g)	0.91	0.94	0.91	0.7	0.85
% Collection chamber Clearance (cycle to cycle)	73.6	74.5	75.8	65.7	76.5
Cycle Time (min)	46.5	49	47.5	51	48.75
Volume Processed (mL)	1116	1176	1140	1224	1170
% Water Recovery	73.1	74.5	73.7	75.5	74.4
Cumulative Volume Processed (mL)	1116	2292	3432	4656	5826

*Average of solids accumulated each cycle- used to calculated % clearance

Discussion of Experimental Results

[0078] A simple relationship between device critical height, i.e. the height of the device collection chamber and residence time accounts for nearly all of the performance variations in the devices studied. As demonstrated herein, the device can be optionally configured with and without inlet and outlet microchannels, and with or without a microporous body. It should be noted that a single outlet microchannel, or a combination of an inlet microchannel and an outlet microchannel can confer enhanced performance characteristics, as can the presence of a microporous body. The key performance governing dimension of the device is the height between the top of the device inlet (or the top of the device outlet) and the floor of the collection chamber (14). This dimension is at times herein referred to as the critical height, largely determines device performance, and corresponds to the height of the collection chamber. Highly efficient particle separation can be achieved when the critical height is matched to the settling characteristics the particulates being removed.

[0079] A series of experiments established the relationship between device critical height and particle settling characteristics. The devices (Devices 3, 6 and 7) had 4 x 1 cm collection chambers with varying depths and had no microchannels or microporous sieves. A transfer

function was established which accounted for 99.4% of the performance variability and the relationship between residence time and critical height for a monodisperse sample of 2 μm silica particles. The experimental results were used to generate the transfer function. A time to capture was calculated using Stoke's settling velocity and the critical height for each experiment. The capture time results can also be found in Table 6.

Table 6

RUN	Critical Height (cm)	V (cm^3)	t_R (sec)	F (mL/min)	Turbidity IN (NTU)	Turbidity OUT (NTU)	Expt. Particle Capture (%)	Capture Time (s)
1	0.60	2.4	480	0.30	656	364	45	1775
2	0.60	2.4	240	0.60	759	387	49	1775
3	0.20	0.8	480	0.10	679	58	91	600
4	0.60	2.4	360	0.40	822	464	44	1775
5	0.40	1.6	240	0.40	717	426	41	1183
6	0.20	0.8	240	0.20	534	204	62	600
7	0.40	1.6	480	0.20	717	306	57	1183
8	0.20	0.8	360	0.13	633	137	78	600

[0080] The trend in capture efficiency mirrors the trend in capture time relative to residence time. The highest capture efficiency occurs when the residence time is closest to the particle capture time at a given critical height (Run 3). Conversely, the worst efficiency occurs when the residence is much shorter than the theoretical particle capture time (Runs 1, 2, and 4). Additional factors contribute to particle capture in the device beyond particle settling physics, and these factors include edge effects, dead volumes, variable device height as the collection chamber becomes saturated with particulates. Edge effects, dead volumes, and variations in collection chamber height resulting from sedimentation likely account for some of the additional capture efficiency observed over that predicted by the capture times in Table 6.

[0081] As noted, improved particle removal was observed when the microfluidic devices comprised inlet and/or outlet microchannels and a microporous body subdividing the collection chamber. Capture efficiencies for 2 μm particles with various device configurations are presented in Table 7. The devices had a 4 x 1 x 0.2 cm collection chamber and feed rates were employed such that the residence time of a particle traversing the device

was about 240 seconds. Microchannel lengths were varied at the device inlet and outlet between 0 and 66.5 mm. The effect of the presence or absence of a 40 μm microporous body dividing the collection chamber was also examined. The baseline capture efficiency for a device with neither microchannels nor a microporous sieve was 60% (Entry 1). Incorporation of an inlet microchannel resulted in increased capture efficiencies of up to 81% (Entries 1-3). Alternatively, the presence of a microporous body also increased capture efficiencies up to 81% (Entries 2 and 4).

Table 7

Entry	Microchannel Length, mm (Inlet/Outlet)	Microporous Sieve (+/-)	Capture Efficiency (%)
1	0/0	-	60
2	16.5/16.5	-	71
3	66.5/16.5	-	81
4	16.5/16.5	+	81

[0082] Fluid dynamics models suggested that the presence of one or more microchannels influences particle trajectories within the device to reduce the effective critical height. A COMSOL fluid dynamics package was used to model the particle settling behavior in the microclarification device. The model incorporated settling physics, drag force, lift force, and edge effect parameters. While the model could not fully predict all of the particle capture behavior observed, it reliably predicted important behavioral trends. Thus, the predicted 50% capture efficiency for 2 μm particles at a 240 second residence time was a modest underestimation of the 60% capture efficiency observed experimentally. The underpinning physical behavior was modeled well enough to understand the impact of microchannel geometry on capture efficiency.

[0083] Predicted particle trajectories and flow line patterns were calculated using the COMSOL fluid dynamics modeling package. The model suggests that during operation the particles in the lower portions of the inlet microchannel enter the collection chamber along trajectories tracking the lower portions of the collection chamber. It is believed that the limited height of the microchannel allows particles to settle into the bottom portion of the flow volume in the relatively short time required for the particles to traverse the microchannel and enter the collection chamber. Thus, the effective critical height in the collection chamber

is decreased, and capture efficiency is increased, compared to a chamber without an inlet microchannel. The phenomenon can be understood by considering the expansion of lamellar flow lines from the microchannel into the collection chamber. As a particle passes from the inlet microchannel into the collection chamber, it follows its respective lamellar flow line and the particle distribution is preserved as a function of relative channel height. The microchannel acts as a high speed concentrator for the lowest flow line and decreases the time required to capture particles in the collection chamber resulting in increased capture efficiency at equivalent residence times.

[0084] The COMSOL model was used to evaluate flow characteristics in the presence and absence of a microporous body. The COMSOL model suggested that the microporous body tends to influence lamellar flow within the collection chamber improves particle capture efficiency. It is believed that the microporous body acts like a weir and directs flow towards the bottom of the collection chamber and creates dead volumes near the top of the collection chamber. The particles do not have enough inertia under the lamellar flow conditions to exit the flow lines and are carried toward the bottom of the collection chamber. Synergy between microchannel and microporous body occurs because the inlet microchannel concentrates particles and directs them towards the lowest flow lines within the collection chamber. Moreover, the microporous body increases the total fraction of flow in the bottom of the collection chamber. The increased flow carries more particles deeper into the collection chamber thereby reducing the effective critical height of the collection chamber and increasing capture efficiency.

Example 7: Chemical Treatment and Particle Size.

[0085] Device 8 having a 22.2 x 3.8 x 0.2 cm collection chamber but configured without inlet and outlet microchannels or a microporous body. A tan clay slurry with a turbidity of 1484 NTU was prepared in deionized water at a particle concentration of 2000 mg/L and presented to the device at a flow rate corresponding to a residence time of 170 seconds. The processed fluid collected from the device outlet had a turbidity of 384 NTU, which corresponds to 75% particle capture efficiency.

[0086] The 170 second residence time was chosen to be intermediate between a theoretically high capture efficiency of 10 μm particles and low capture efficiency for 2 μm particles. Particle size analysis of the influent, effluent, and sludge produced by back flushing the device show the enrichment of small particles in the effluent and large particles in the sludge. The particle size distribution in the sludge was centered above 10 μm while that of the effluent was centered near 2 μm. Treating the TAN clay feed suspension with 5 mg/L of the coagulant PC2700 re-centered the particle size distribution at nearly 100 μm. The PC2700 treated feed was presented to the device at a flow rate corresponding to a residence time of 40 seconds yielded an effluent having a turbidity of 15 NTU; which corresponds to 98% particle capture efficiency. The increased capture efficiency despite the shorter residence time is a direct result of the coagulant and its effect on particle size distribution.

Particle Clearance and Continuous Operation

[0087] A key feature of a practical inline clarification device is the ability to clear the accumulated solids and maintain a continuous process. Four different back flushing protocols were examined with the objective of fluidizing particles captured during fluid purification and clearing them from the device using a minimal amount of water. Incomplete clearance of captured particles was shown to result retained solids after each back wash over a series of cycles and was shown to result in a progressive loss of collection chamber capacity over time. An efficient protocol would minimize retained solids and have a collection chamber capacity loss rate near 0 mg/mL.

[0088] The initial back flush protocol relied on water at high flow to clear the solids. The small scale of the microfluidic separation devices enforces lamellar flow for most flow regimes less than 6 L/min. A flow rate of 300 mL/min was used to establish a baseline with respect to the other strategies employed. The high flow water protocol resulted in 0.74 g of retained solids and a capacity loss rate of approximately 0.6 mg/mL of processed volume. A confined air bubble strategy was tested where a series of approximately 25 mL air bubbles were used to push the solids from the device at an air-water interface. The air bubble strategy resulted in similar retained solids value of 0.77 g, but decreased the collection chamber capacity loss rate to 0.1 mg/mL. A dual fluid strategy was tested in which both air and water were used simultaneously at low flow without creating a uniform air water interface. The

dual fluid strategy reduced the retained solids value to 0.35g, but only marginally reduced the loss rate to 0.12 mg/mL. Doubling the air/water flows in the dual fluid approach slightly improved retained solids to 0.25 g, but yielded an optimal clearance protocol where the capacity loss rate was negligible. The microclarifier system was continuously run for five cycles using the high flow air/water backwash at a water recovery rate of 85%.

Comparative Example

[0089] A comparative test was performed using 2 μL particles in both the microfluidic separation device provided by the present invention and a labscale upflow clarifier. A residence time of 8 minutes was used for each device and a rise rate of 12.2 LPM/m^2 (0.3 gpm/ft^2) was maintained in the upflow clarifier. The microfluidic separation device captured 90% of particles reducing turbidities to 58 NTU from 560 NTU. The upflow clarifier captured only about 2% of particles reducing turbidities to 541 NTU from 551 NTU. At equivalent residence times the use of the microfluidic separation device provided by the present invention was clearly superior to the conventional clarification technique.

[0090] The foregoing examples are merely illustrative, serving to illustrate only some of the features of the invention. The appended claims are intended to claim the invention as broadly as it has been conceived and the examples herein presented are illustrative of selected embodiments from a manifold of all possible embodiments. Accordingly, it is the Applicants' intention that the appended claims are not to be limited by the choice of examples utilized to illustrate features of the present invention. As used in the claims, the word "comprises" and its grammatical variants logically also subtend and include phrases of varying and differing extent such as for example, but not limited thereto, "consisting essentially of" and "consisting of." Where necessary, ranges have been supplied, those ranges are inclusive of all sub-ranges there between. It is to be expected that variations in these ranges will suggest themselves to a practitioner having ordinary skill in the art and where not already dedicated to the public, those variations should where possible be construed to be covered by the appended claims. It is also anticipated that advances in science and technology will make equivalents and substitutions possible that are not now contemplated by reason of the imprecision of language and these variations should also be construed where possible to be covered by the appended claims.

CLAIMS

What is claimed is:

1. A microclarification system for separating particulates dispersed within a base fluid, the system comprising:

a plurality of microfluidic collection chambers disposed between and in fluid communication with a fluid inlet manifold and a fluid outlet manifold;

a plurality of outlet microchannels disposed between the microfluidic collection chambers and the fluid outlet manifold; and

a gas-liquid flushing module configured to purge particulates from the collection chamber during a collection chamber purge cycle.

2. The system according to claim 1, wherein the plurality of collection chambers are characterized by a critical height of less than one centimeter.

3. The system according to claim 1, wherein the fluid inlet manifold and the fluid outlet manifold are configured in parallel.

4. The system according to claim 1, wherein the fluid inlet manifold and the fluid outlet manifold are configured radially.

5. The system of claim 1, wherein the outlet microchannels have an average height in a range from about 1 micron to about 200 microns (μm).

6. The system of claim 1, wherein the outlet microchannels have a length in a range from about 1 millimeter to about 1centimeter.

7. The system according to claim 1, wherein a plurality of inlet microchannels are disposed between the fluid inlet manifold and the microfluidic collection chambers.

8. The system according to claim 7, wherein the inlet microchannels have an average height in a range from about 1 micron to about 500 microns.

9. The system according to claim 7, wherein the inlet microchannels have length in a range from about 1 millimeter to about 10 centimeters.

10. The system of claim 1, wherein the gas-liquid flushing module is configured to purge the collection chamber with a combination of a gas and a purge liquid.

11. The system of claim 10, wherein a ratio of gas to purge liquid employed is in a range from about 1:10 to about 10:1.

12. The system according to claim 10, wherein the gas is appreciably soluble in the purge liquid.

13. The system according to claim 10, wherein the gas is selected from the group consisting of air, carbon dioxide, oxygen, nitrogen, argon, and mixtures of two or more of the foregoing gases.

14. The system of claim 1, wherein the collection chambers are divided into at least two portions by a microporous body.

15. The system according to claim 14, wherein the microporous body comprises pores with an average diameter between about 10 microns and about 500 microns.

16. The system of claim 1, wherein the particulates are characterized by an average particle size in a range from about 2 to about 100 μm and the base fluid comprises water.

17. The system according to claim 1 configured to produce potable water.

18. The system according to claim 1 configured for use in treating municipal sewage, indigenous water produced from a hydrocarbon reservoir, water produced as a by-product from hydraulic fracturing, water produced as a by-product of oil reservoir flooding, water produced as a by-product of a mining operation, water produced as a by-product of boiler operation, water as a by-product of bitumen extraction and combinations of two or more of the forgoing.

19. The system according to claim 1 configured for use with a biomass reactor.

20. The system according to claim 1, wherein configured for use in a water desalination facility.

21. A method for separating particulates dispersed within a base fluid, the method comprising:

(a) introducing, as part of a fluid purification cycle, a fluid comprising particulates dispersed within a base fluid into a fluid inlet manifold of a microclarification system comprising:

(i) a plurality of microfluidic collection chambers disposed between and in fluid communication with the fluid inlet manifold and a fluid outlet manifold;

(ii) a plurality of microchannels disposed between the microfluidic collection chambers and the fluid outlet manifold; and

(iii) a gas-liquid flushing module;

wherein the system is configured such that the particulates dispersed within the base fluid pass from the fluid inlet manifold into the plurality of microfluidic collection chambers wherein a substantial portion of the particulates are captured and through which a substantial portion of the base fluid passes and emerges at the fluid outlet manifold as a processed fluid depleted in particulates; and

(b) introducing via the gas-liquid flushing module, as part of a collection chamber purge cycle, a gas and a purge liquid which together function as a collection chamber purge medium; and

(c) repeating steps (a) and (b).

22. The method according to claim 21, wherein over a plurality of fluid purification cycles and following collection chamber purge cycles the particulate capture capacity of the system remains essentially constant.

23. The method according to claim 21, wherein the fluid inlet manifold and the fluid outlet manifold are configured in parallel.

24. The method according to claim 21, wherein the fluid inlet manifold and the fluid outlet manifold are configured radially.

25. A microclarification system for separating particulates from water, the system comprising:

a plurality of microfluidic collection chambers disposed between and in fluid communication with a fluid inlet manifold and a fluid outlet manifold;

a plurality of outlet microchannels disposed between the microfluidic collection chambers and the fluid outlet manifold;

a plurality of inlet microchannels disposed between the inlet manifold and the microfluidic collection chambers; and

a gas-liquid flushing module configured to purge particulates from the collection chamber during a collection chamber purge cycle;

wherein the microfluidic collection chambers are characterized by a critical height of less than one centimeter; and wherein the outlet microchannels have an average height between about 1 micron and about 200 microns (μm) and a length in a range from about 1 millimeter to about 1centimeter; and wherein the inlet microchannels have an average height in a range from about 1 micron to about 500 microns and a length in a range from about 1 millimeter to about 10 centimeters; and wherein the gas-liquid flushing module is configured to purge the collection chamber with a combination of a gas and a purge liquid.

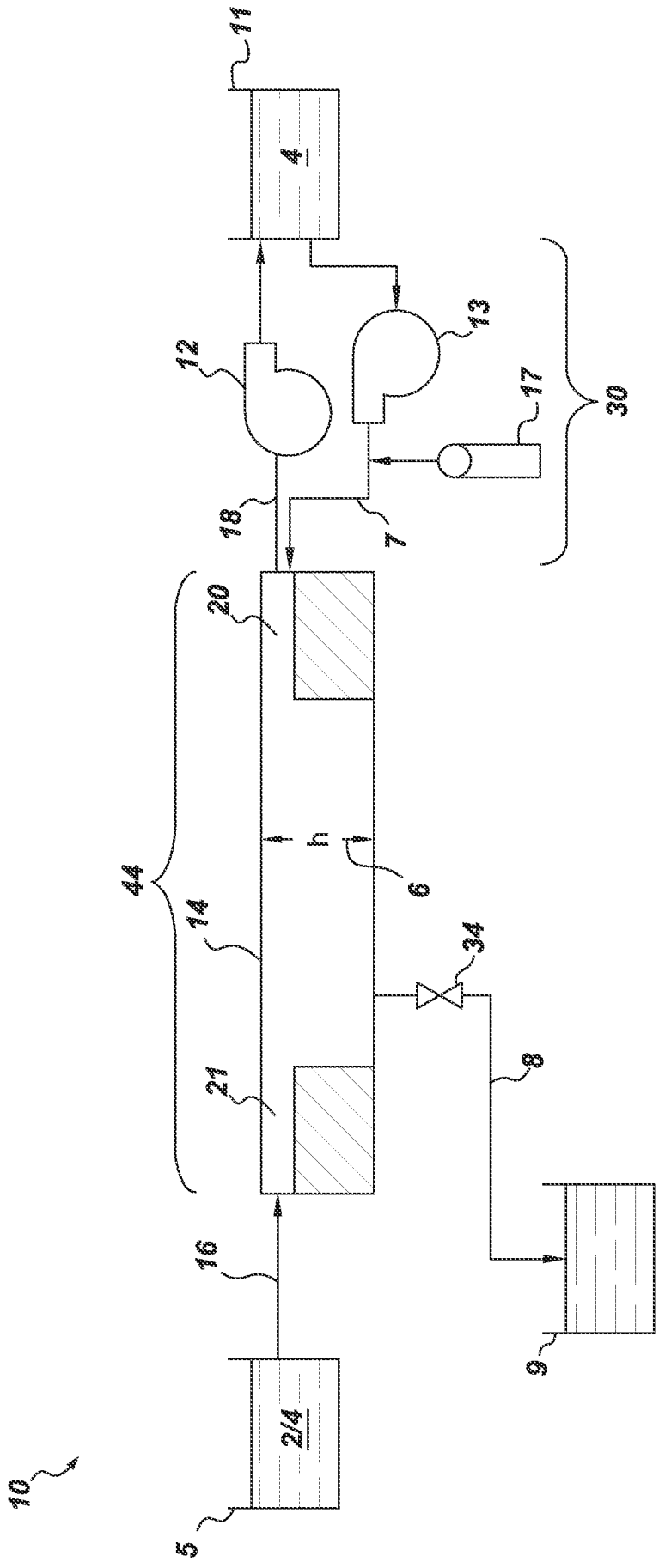


Fig. 1

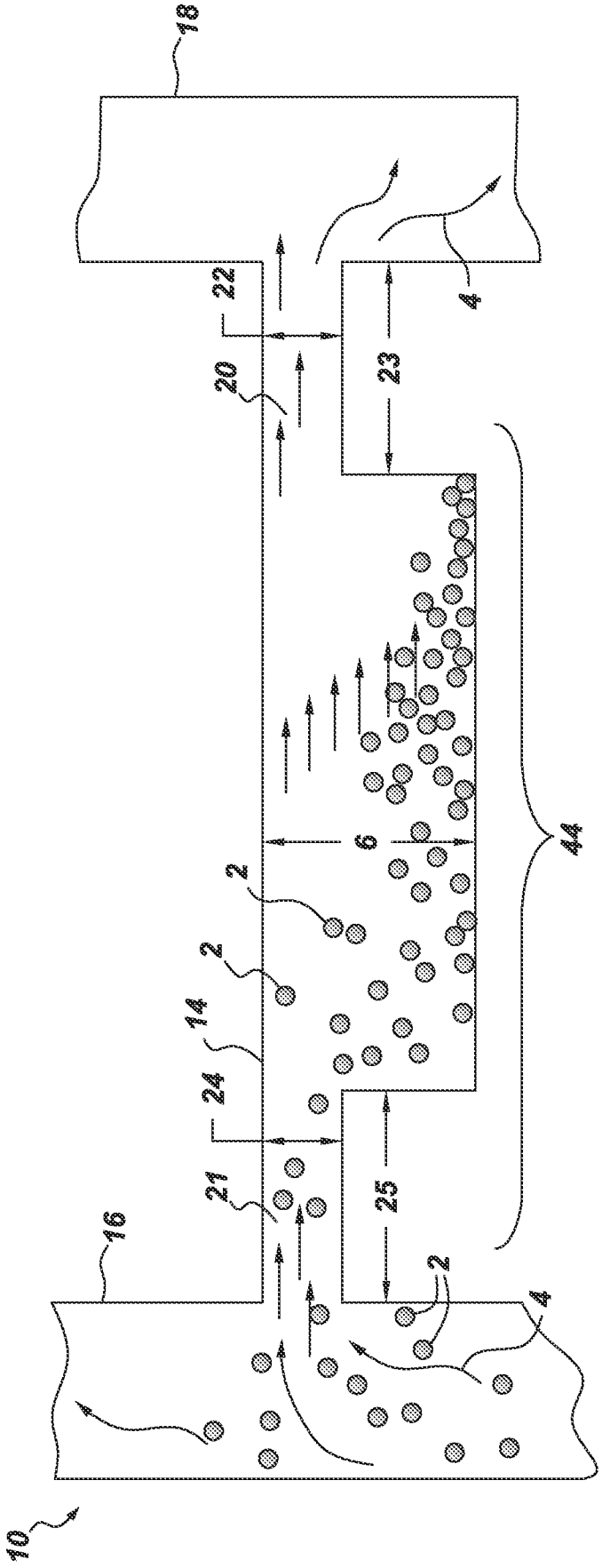


Fig. 2

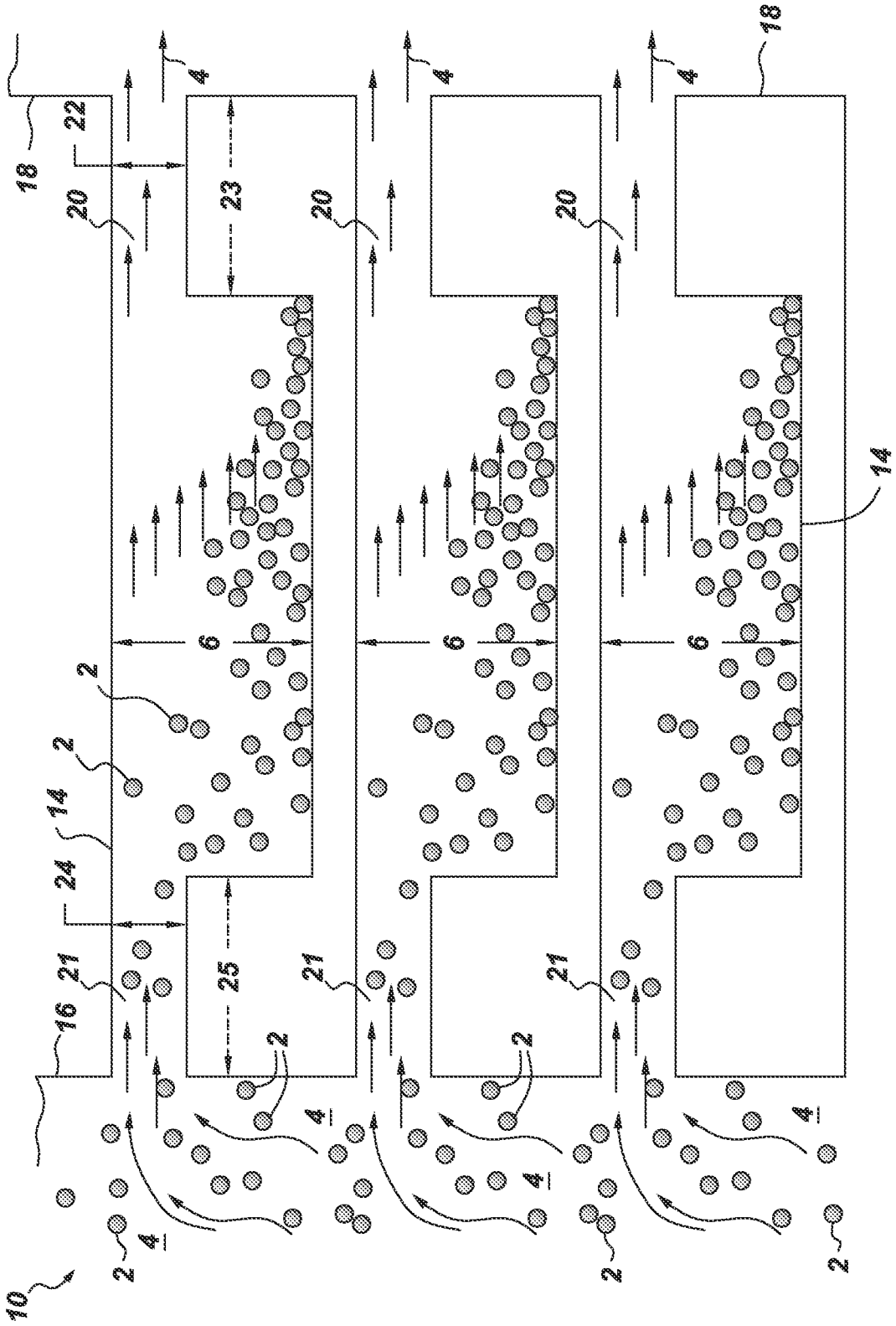


Fig. 3

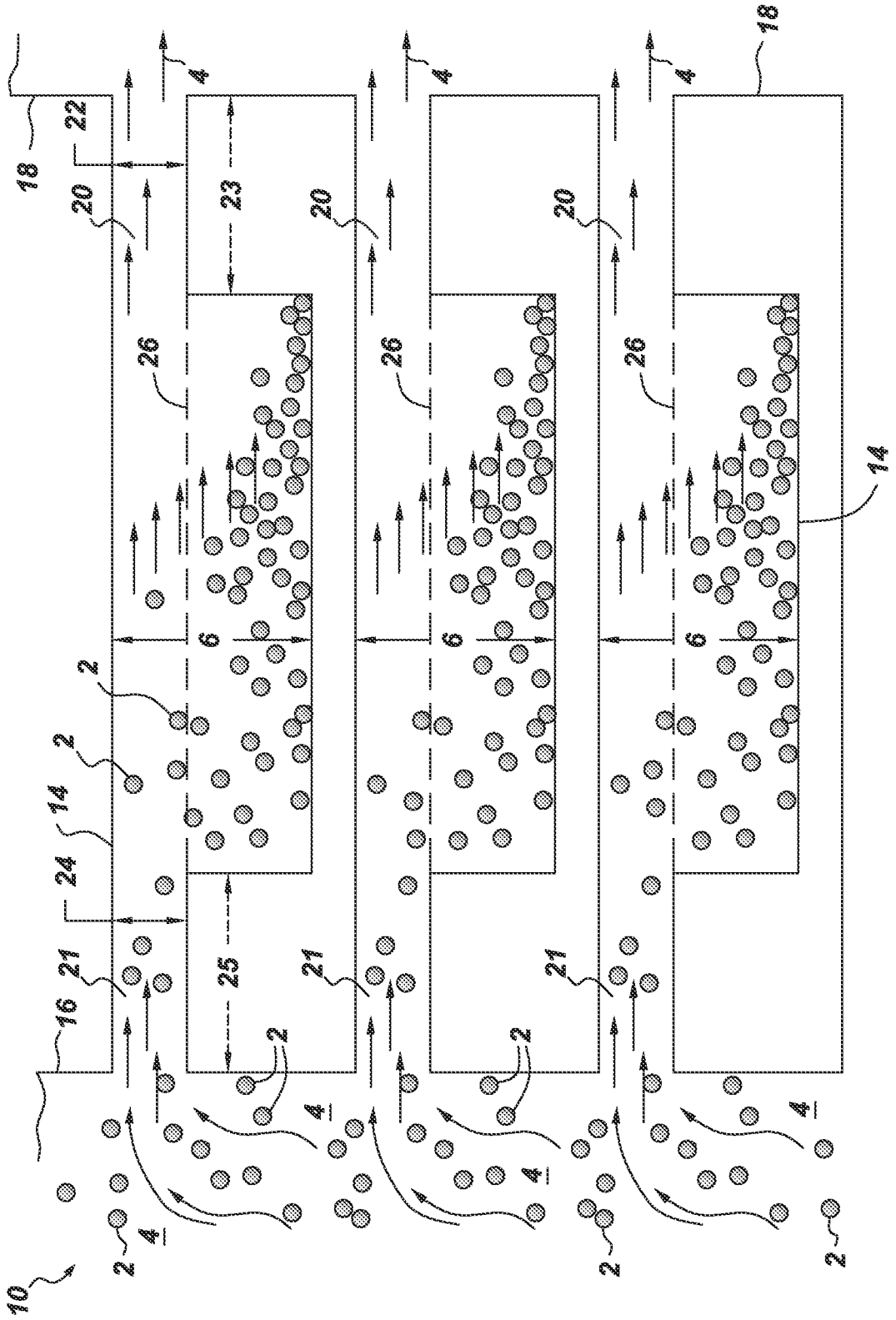


Fig. 4

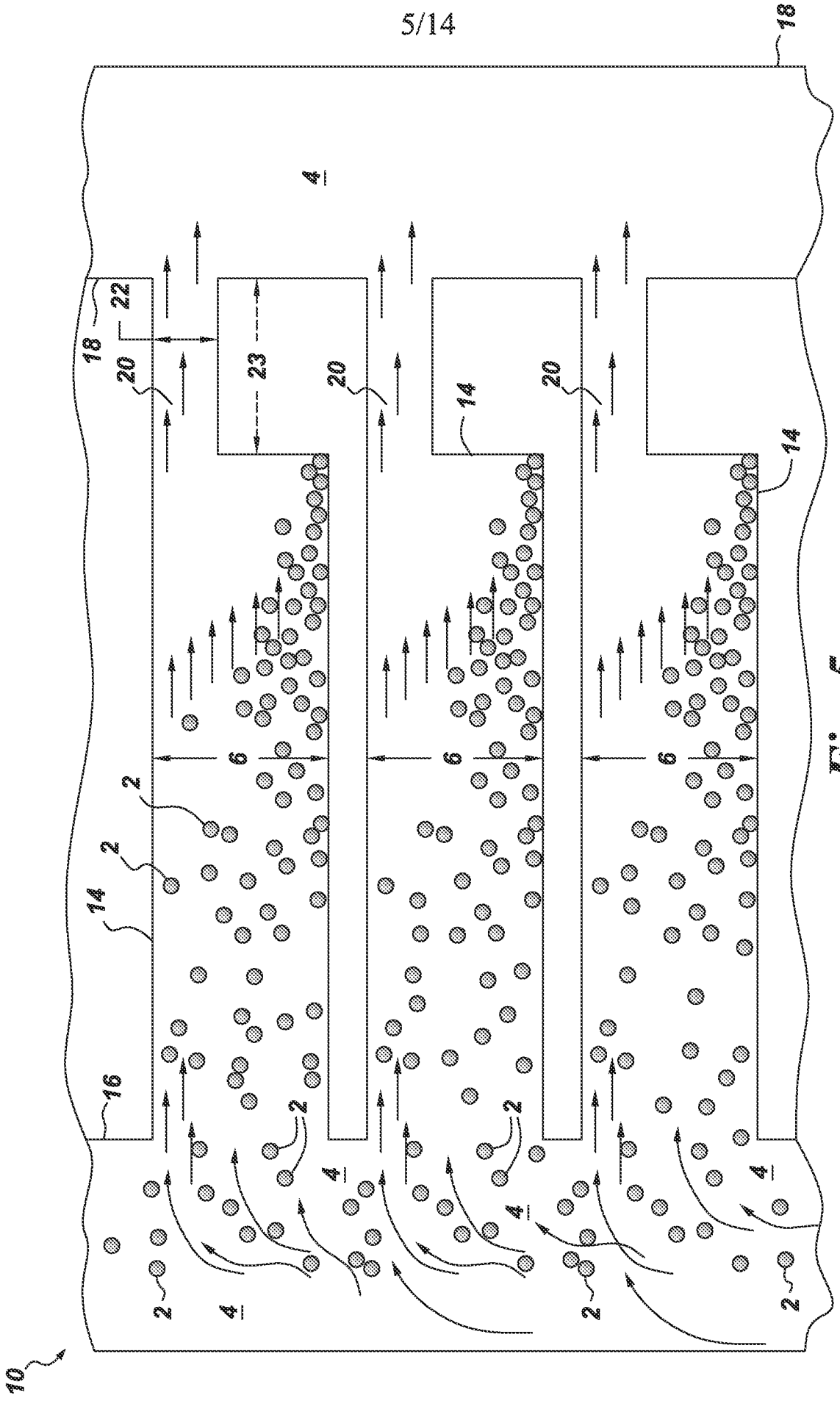


Fig. 5

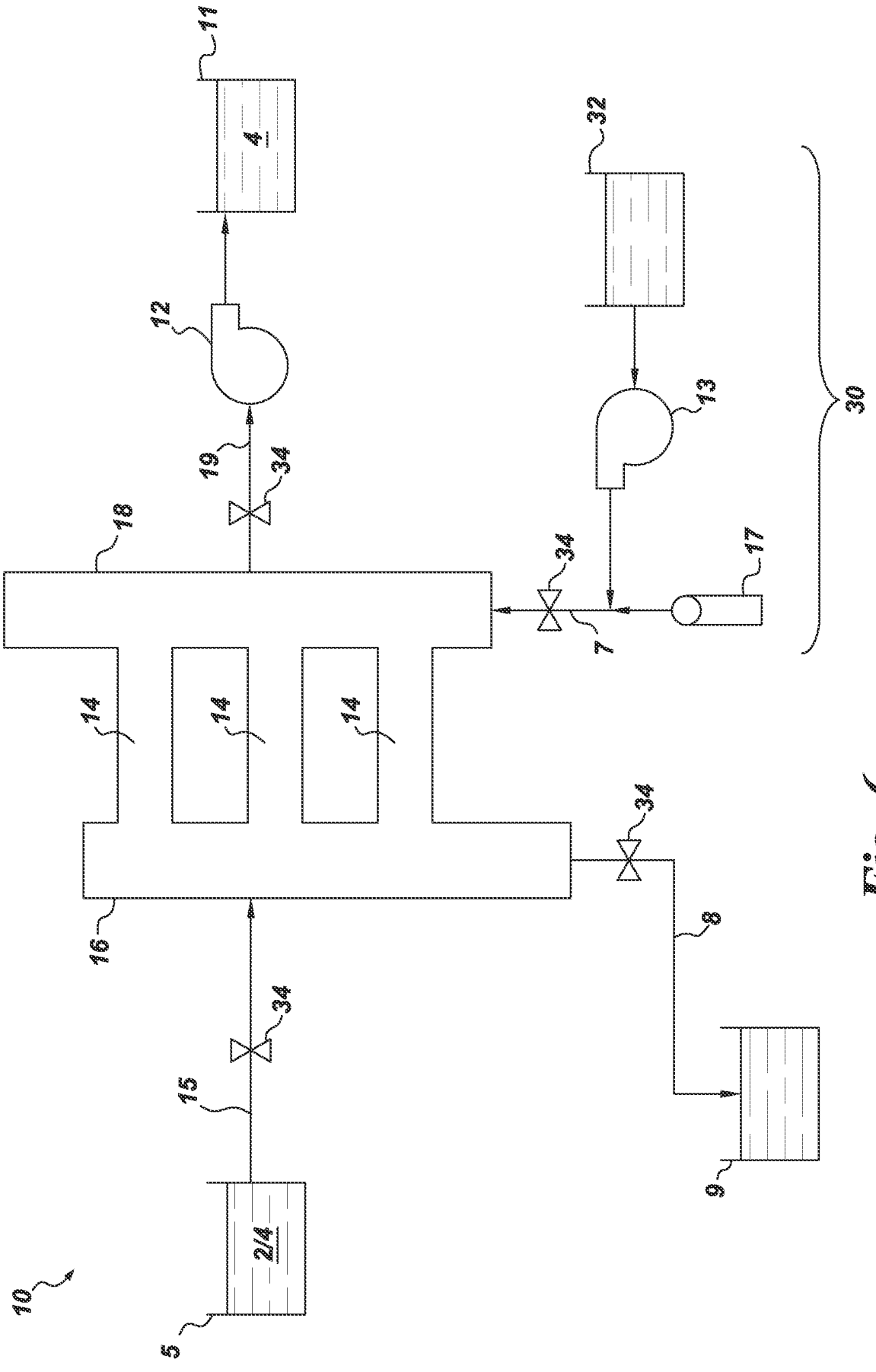


Fig. 6

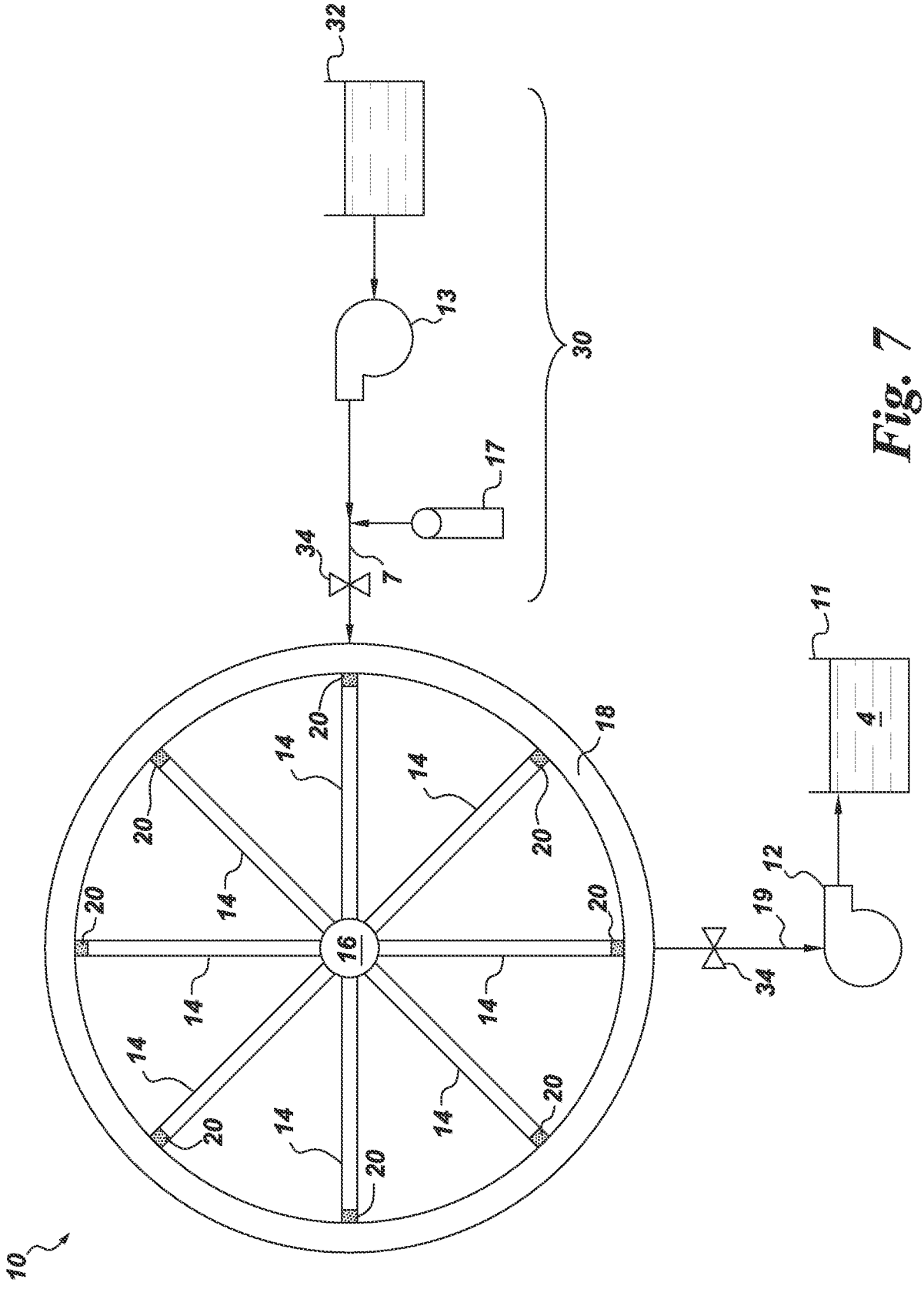


Fig. 7

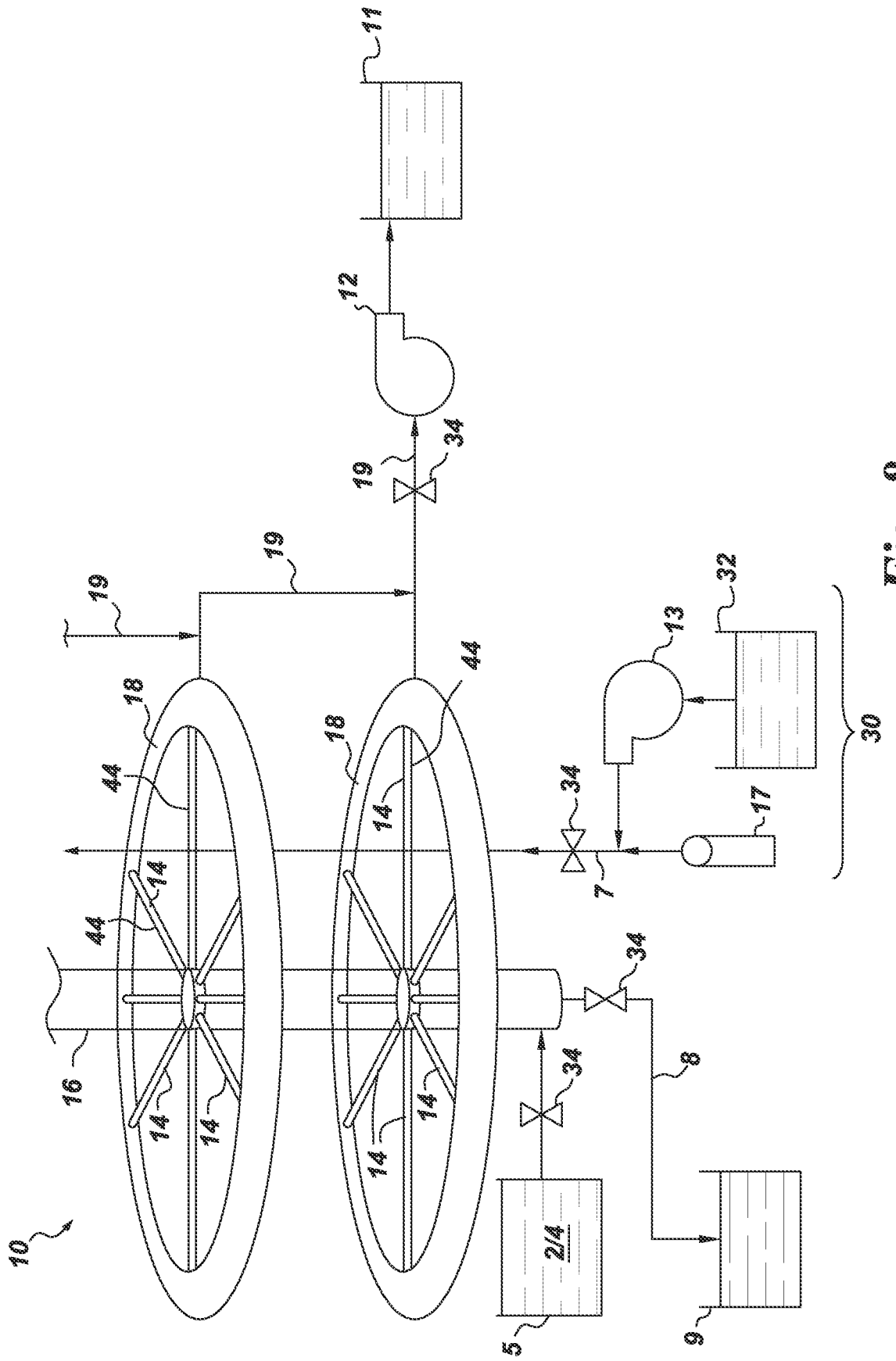

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Fig. 8

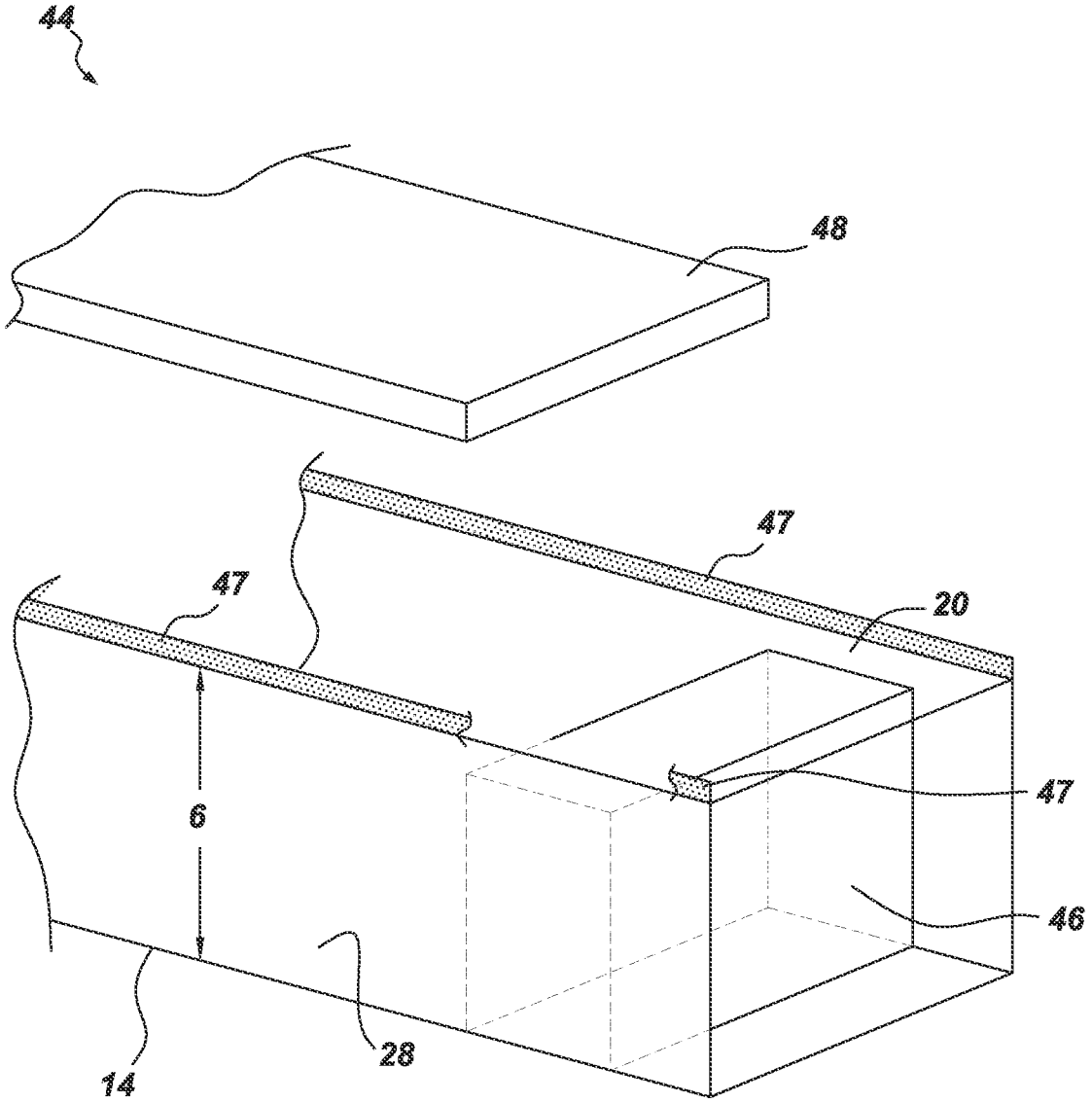


Fig. 9

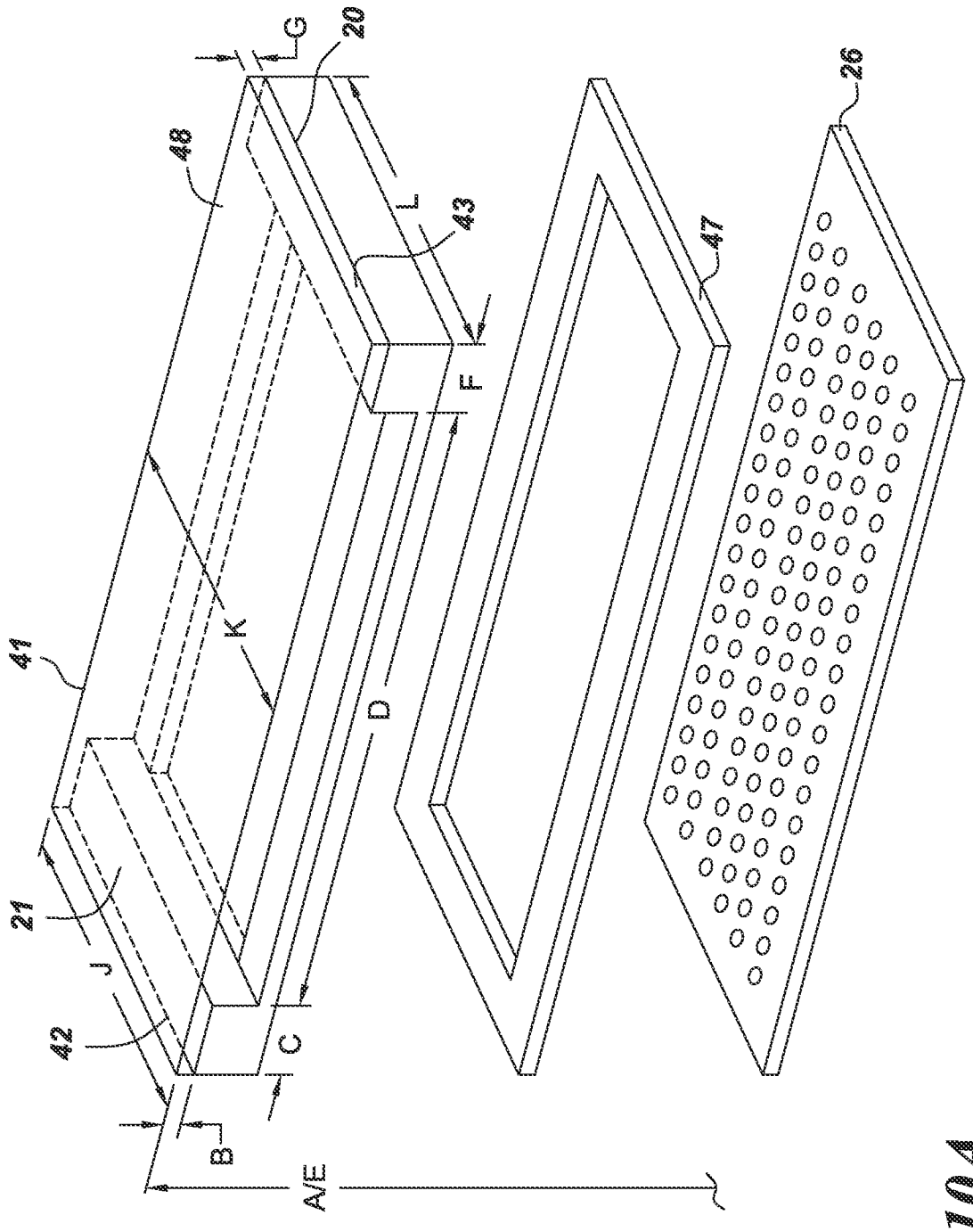


Fig. 10A

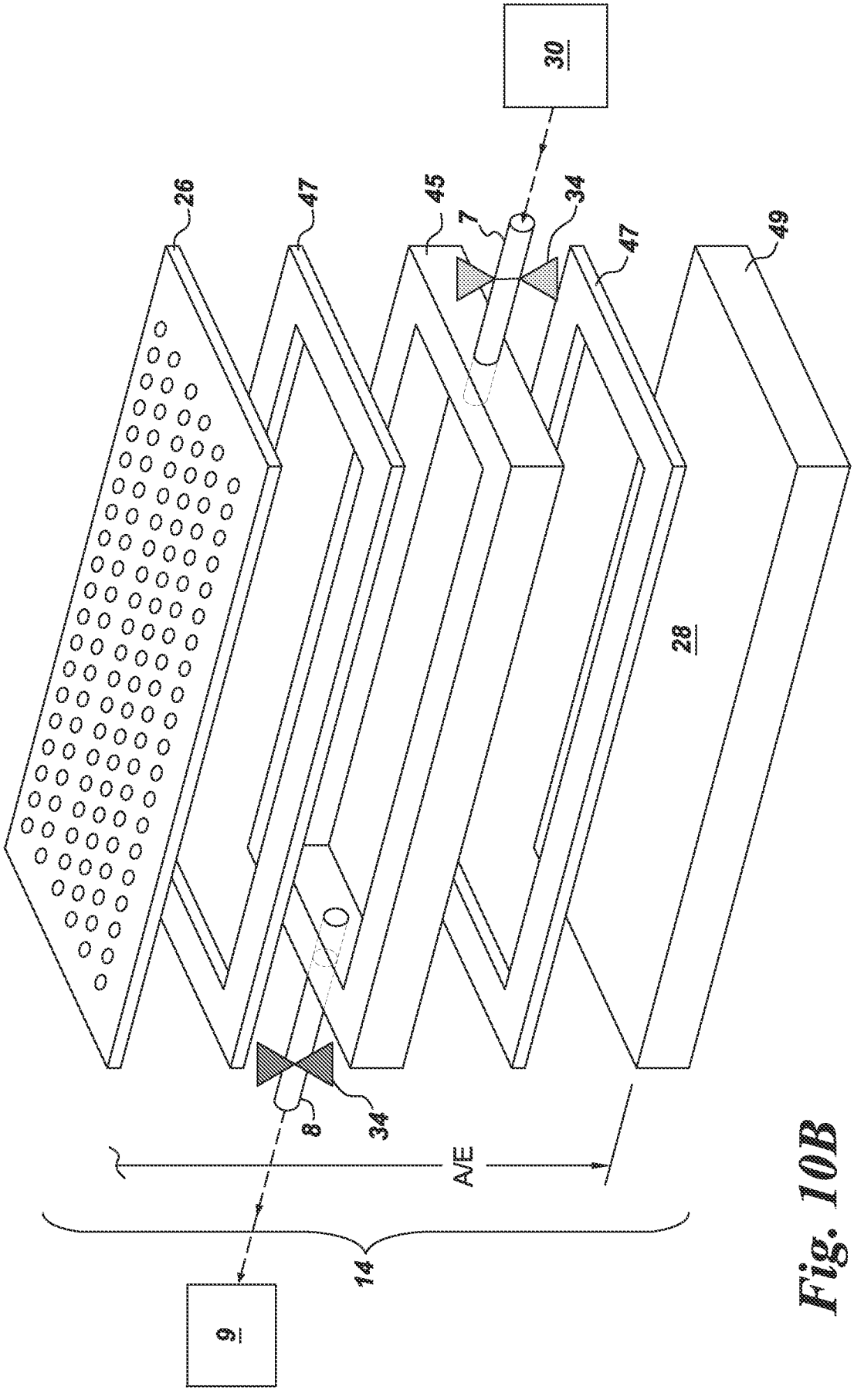


Fig. 10B

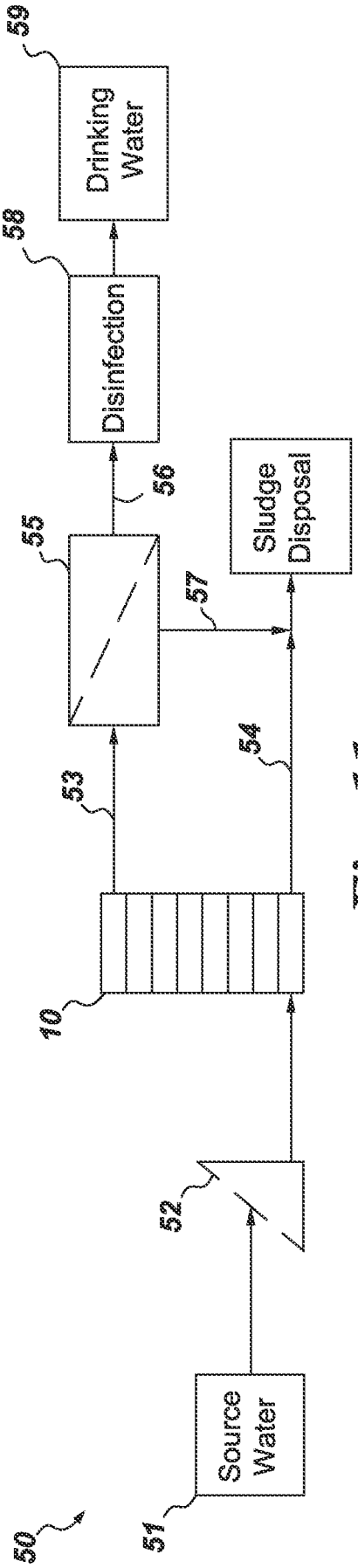

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Source Water
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Disinfection
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Drinking Water
Sludge Disposal

Fig. 11

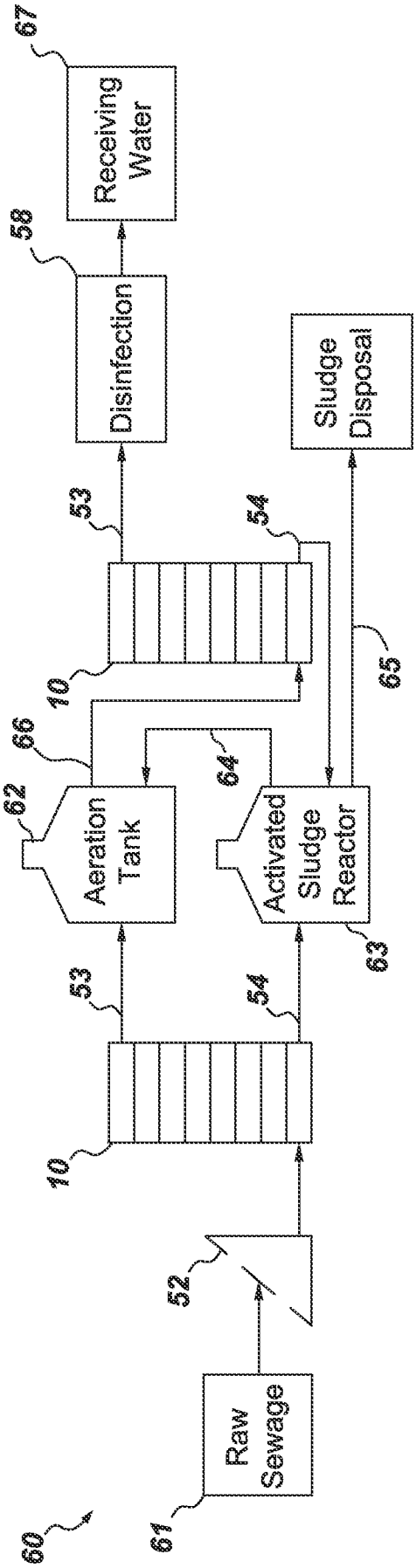

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Raw Sewage
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Aeration Tank
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Activated Sludge Reactor
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Disinfection
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Receiving Water
Sludge Disposal

Fig. 12

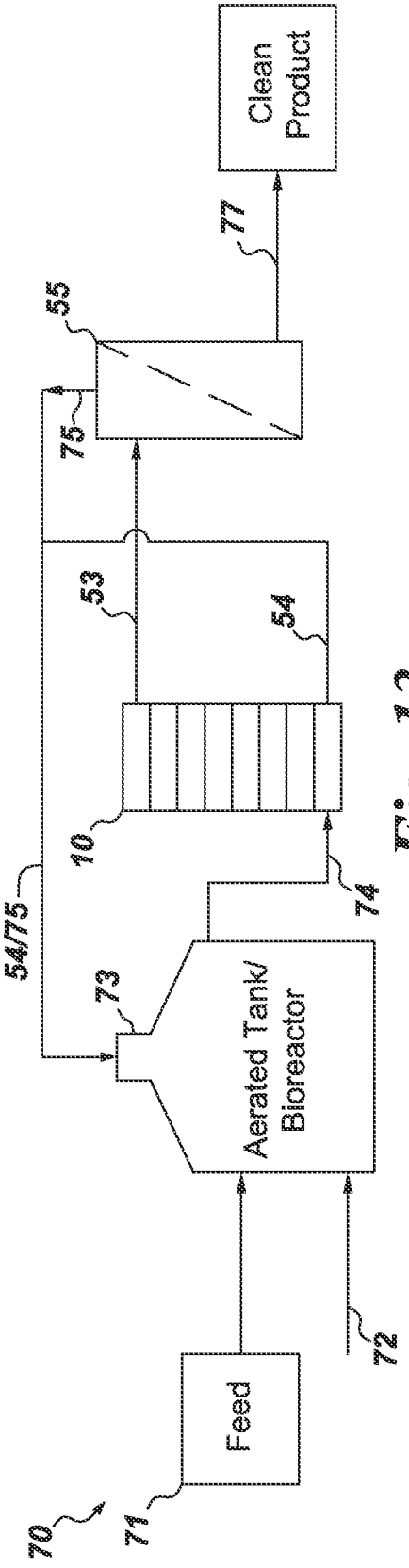

Clean Product
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Aerated Tank/ Bioreactor
Feed
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Fig. 13

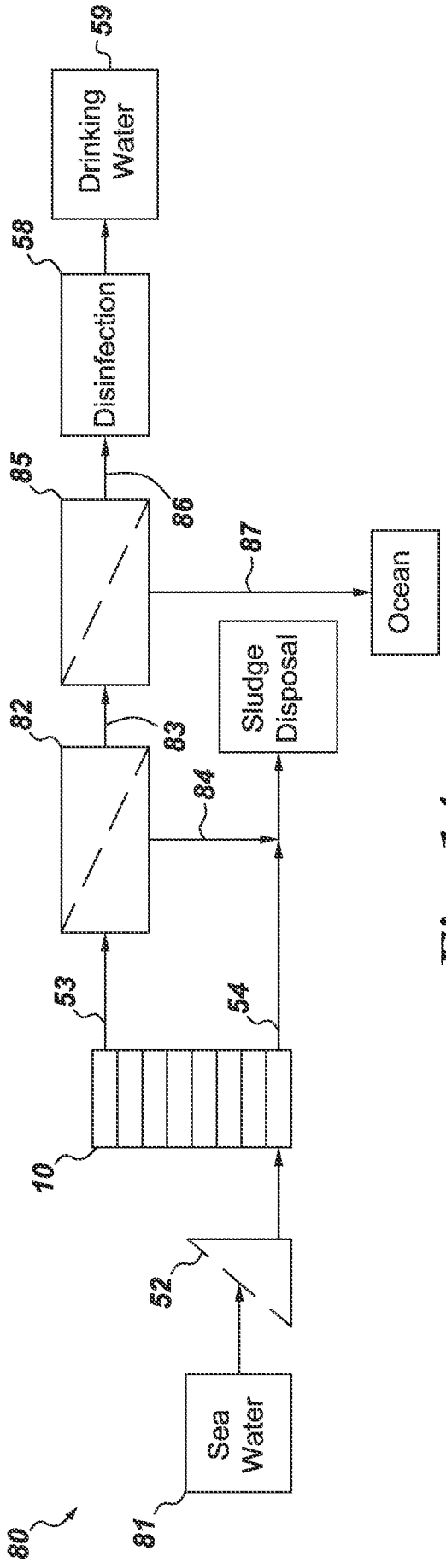

Drinking Water
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Disinfection
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Ocean
Sludge Disposal
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Sea Water
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Fig. 14

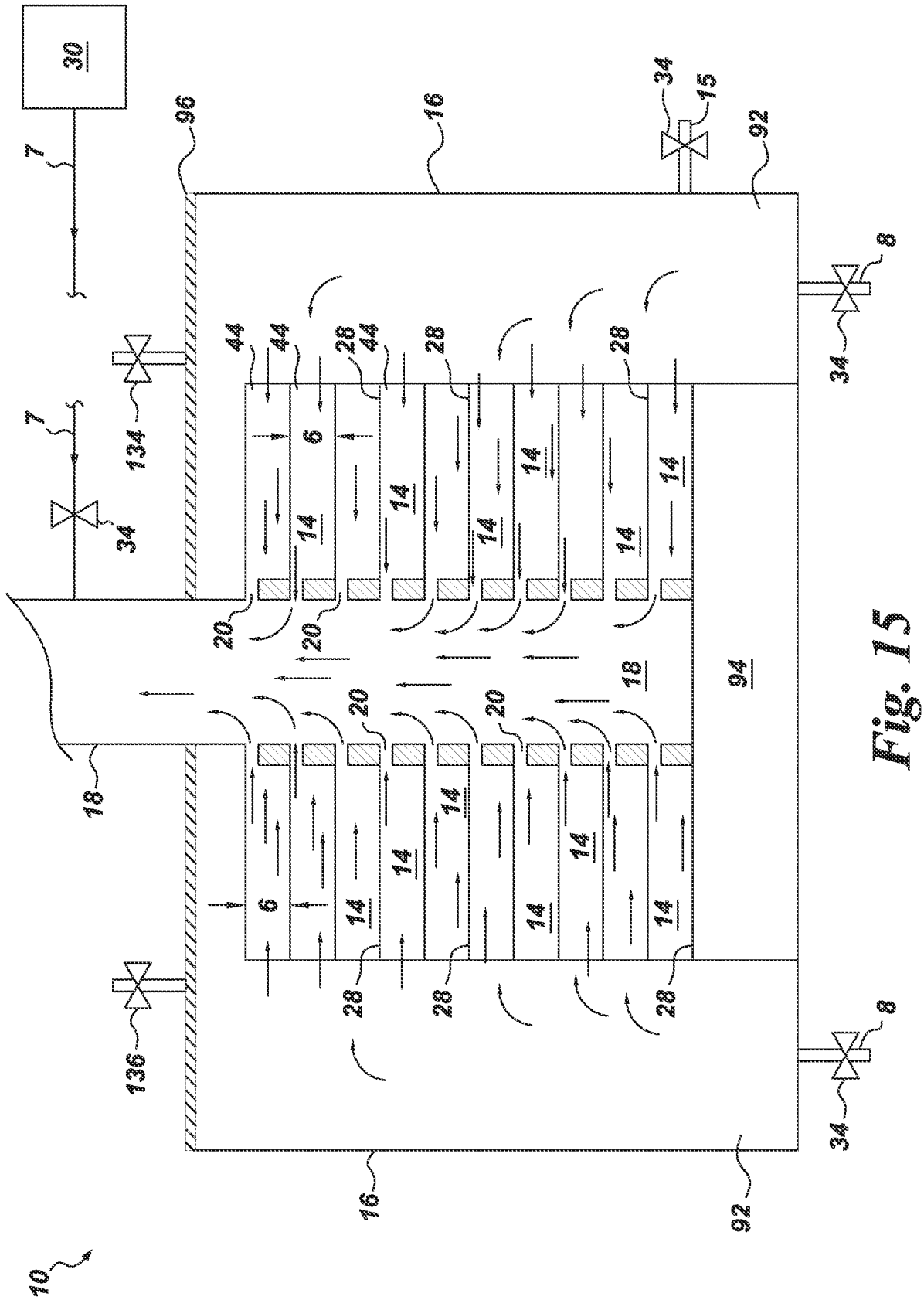

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Fig. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/070571

A. CLASSIFICATION OF SUBJECT MATTER
INV. B01L3/00
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)
B01L B08B

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2012/149021 A1 (YUNG CHONG WING [US] ET AL) 14 June 2012 (2012-06-14) paragraphs [0020], [0022], [0027], [0030] - [0036], [0038], [0040] - [0042], [0049] - paragraphs [0051], [0063], [0071], [0072], [0074], [0086], [0137] figures 1, 2A-2D, 3A, 4A, 4B, 6 claim 21	1-9, 14-20 10-13, 21-25
Y	US 2006/198766 A1 (MULLER TORSTEN [DE] ET AL) 7 September 2006 (2006-09-07) pages 0001,002	10-13, 21-25
A	US 2005/148064 A1 (YAMAKAWA MINEO [US] ET AL) 7 July 2005 (2005-07-07) the whole document	1-25

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 March 2015	20/03/2015

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Bischoff, Laura

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/070571

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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3

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2014/070571

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		WO 2007044642 A2	19-04-2007