



US007935259B2

(12) **United States Patent**  
**Gavalas**

(10) **Patent No.:** **US 7,935,259 B2**  
(45) **Date of Patent:** **May 3, 2011**

(54) **FILTERING APPARATUS AND METHOD OF USE**

(75) Inventor: **Lillian Susan Gavalas**, League City, TX (US)

(73) Assignee: **The United States of America as represented by the Administrator of the National Aeronautics and Space Administration**, Washington, DC (US)

(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 438 days.

(21) Appl. No.: **12/167,332**

(22) Filed: **Jul. 3, 2008**

(65) **Prior Publication Data**

US 2010/0000945 A1 Jan. 7, 2010

(51) **Int. Cl.**

**B01D 33/03** (2006.01)

**C02F 1/36** (2006.01)

(52) **U.S. Cl.** ..... **210/650**; 210/385; 210/321.67

(58) **Field of Classification Search** ..... 210/650, 210/385, 384, 321.67

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,779,891	A	7/1998	Andelman
6,630,073	B1	10/2003	Moskal et al.
6,680,044	B1	1/2004	Tonkovich et al.
6,719,147	B2	4/2004	Strano et al.
6,824,689	B2	11/2004	Aardahl et al.
7,008,563	B2	3/2006	Smalley et al.
7,011,760	B2	3/2006	Wang et al.
7,175,762	B1	2/2007	Noca et al.
7,264,876	B2	9/2007	Smalley et al.
2002/0187896	A1*	12/2002	Ryoo et al. .... 502/418
2003/0124717	A1*	7/2003	Awano et al. .... 435/287.2

2003/0153965	A1*	8/2003	Supronowicz et al. .... 607/116
2004/0007528	A1	1/2004	Bakajin et al.
2004/0173506	A1	9/2004	Doktycz et al.
2004/0211589	A1*	10/2004	Chou et al. .... 174/253
2005/0067346	A1	3/2005	Noack et al.
2005/0252857	A1	11/2005	Wilson et al.
2005/0263453	A1	12/2005	Collias et al.
2005/0263456	A1	12/2005	Cooper et al.
2005/0279696	A1	12/2005	Bahm et al.
2006/0027499	A1	2/2006	Ajayan et al.
2006/0163160	A1	7/2006	Weiner et al.

(Continued)

OTHER PUBLICATIONS

David S. Sholl and J. Karl Johnson, "Making High-Flux Membranes with Carbon Nanotubes" Science, vol. 312, May 19, 2006, pp. 1003-1004.

(Continued)

*Primary Examiner* — Walter D Griffin

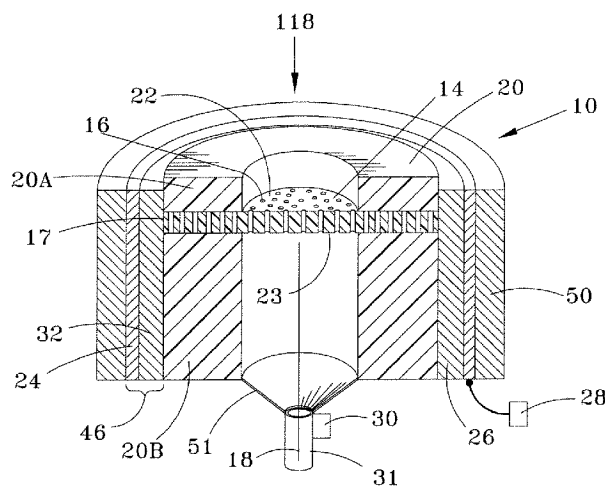
*Assistant Examiner* — Denise R Anderson

(74) *Attorney, Agent, or Firm* — Kurt G. Hammerle

(57) **ABSTRACT**

A filtering apparatus comprises a microporous membrane and an actuator. The membrane is positioned to traverse across the hollow interior of a conduit used for the transport of molecules in bulk. In one example, the pores of the membrane comprise a plurality of open-ended carbon nanotubes. The actuator comprises a transducing material such as a polyvinylidene fluoride film that is operatively positioned in contact with the membrane and is capable of propagating acoustic vibration onto the membrane at a particular frequency so as to hasten the movement of the molecules through the membrane. Similarly, a method of filtering water comprises the steps of: (a) sifting molecules of water through the membrane, the pores of the membrane comprising a plurality of carbon nanotubes; and (b) propagating acoustic vibration onto the microporous membrane at a libration frequency of ice so as to hasten movement of the water molecules within the carbon nanotubes.

**59 Claims, 1 Drawing Sheet**



U.S. PATENT DOCUMENTS

2006/0257638 A1\* 11/2006 Glatkowski et al. .... 428/292.1  
2007/0095678 A1\* 5/2007 West et al. .... 205/775

OTHER PUBLICATIONS

Jason K. Holt et al., "Fast Mass Transport Through Sub-2-Nanometer Carbon Nanotubes," *Science*, vol. 312, May 19, 2006, pp. 1034-1037.

William H. Noon et al., "Helical Ice-Sheets Inside Carbon Nanotubes in the Physiological Condition," *Chemical Physics Letters* 355 (2002) 445-448.

G. Reiter et al., "Water in Carbon Nanotubes Is Not the Same Old Stuff," May 16, 2006, pp. 1-10, available on line on Jul. 1, 2008 at: [http://arxiv.org/PS\\_cache/cond-mat/pdf/0601/0601072v1.pdf](http://arxiv.org/PS_cache/cond-mat/pdf/0601/0601072v1.pdf).

Lawrence Livermore National Laboratory News Release entitled "Nanotube Membranes Offer Possibility of Cheaper Desalination", May 18, 2006, NR-06-05-06, 3 pages, available on line on Jul. 1, 2008 at: [https://publicaffairs.llnl.gov/news/news\\_releases/2006/NR-06-05-06.html](https://publicaffairs.llnl.gov/news/news_releases/2006/NR-06-05-06.html).

L. Huang et al., "Self-Organizing High-Density Single-Walled Carbon Nanotube Arrays From Surfactant Suspensions", *Nanotechnology* 15 (2004), pp. 1450-1454.

M. J. O'Connell et al., "Reversible water-solubilization of single-walled carbon nanotubes by polymer wrapping" *Chemical Physics Letters* 342 (2001), pp. 265-271.

\* cited by examiner

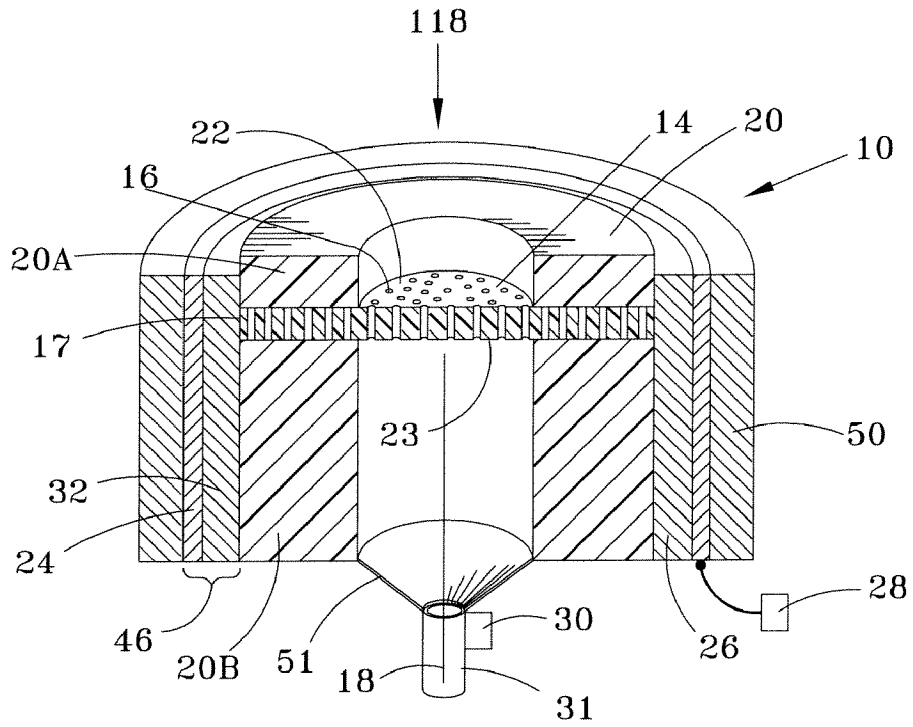


FIG. 1

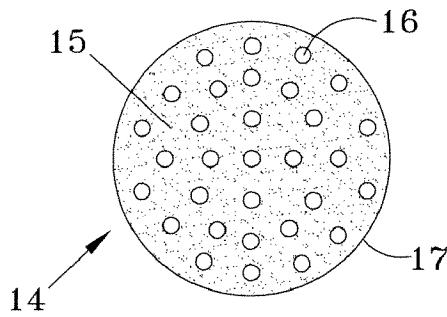


FIG. 2

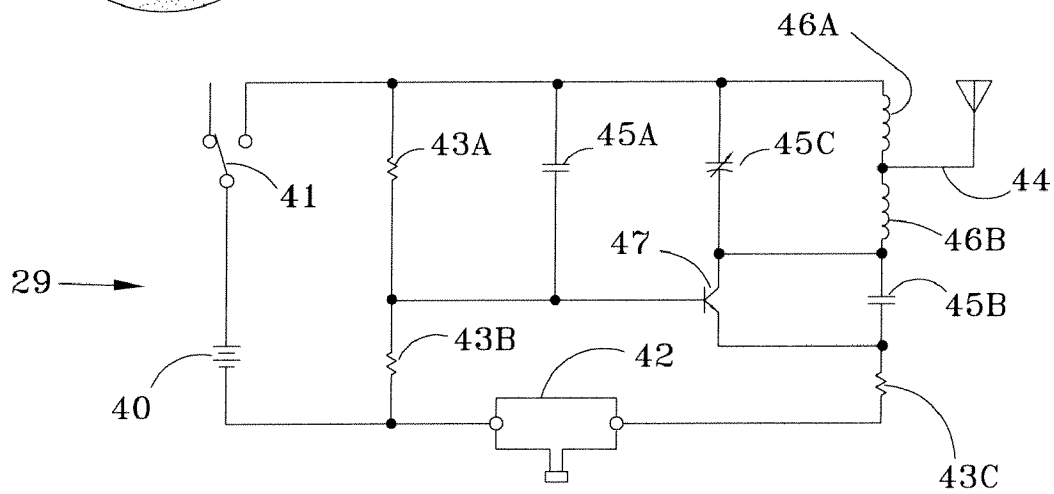


FIG. 3

## FILTERING APPARATUS AND METHOD OF USE

### ORIGIN OF THE INVENTION

The invention described herein was made by an employee or employees of the United States Government and may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

### FIELD OF INVENTION

The field of invention relates generally to an apparatus and method for separation of substances and fluids at the molecular level. More particularly, the field of invention relates to an apparatus comprising a microporous membrane that sifts molecules of certain size while leaving impurities behind and a method of implementing such a membrane for filtration.

### BACKGROUND OF INVENTION

Separation of substances such as fluids into their constituent parts is of particular interest for many industrial processes. Traditional separation methods for fluids include distillation and absorption. Another approach toward separation of substances comprises the use of a membrane, which may be quite cost and energy effective as compared to other traditional methods. An ideal membrane would have excellent stability under a variety of processing conditions, would have high selectivity for the constituent parts of interest, and would have a high molecular through-put or "flux" with a conversely small driving force. Materials with high flux tend to also have low selectivity, and vice versa. Thus, new materials and processes for fabrication of a membrane that can overcome these fundamental hurdles could drastically reduce the energy consumed in present-day operations toward separation of substances. As the long-felt need for development of a more efficient, low power separation or filtration system or apparatus capable of use at remote locations continues, new technologies are being examined and applied.

### SUMMARY OF THE INVENTION

In one embodiment, a filtering apparatus comprises a microporous membrane for sifting molecules of a substance and an actuator, operatively positioned near the microporous membrane, for propagating acoustic vibration onto the microporous membrane and onto the molecules at a particular frequency so as to hasten movement of the molecules through the microporous membrane.

In another embodiment, a filtering apparatus comprises a housing with a hollow interior, a microporous membrane, operatively positioned to traverse across the hollow interior of the housing, for sifting molecules of a substance, and an actuator, operatively positioned near the microporous membrane, for propagating acoustic vibration to the microporous membrane at a frequency onto the molecules of the substance so as to hasten movement of the molecules through the microporous membrane.

In yet another embodiment, an apparatus for filtering a fluid comprises a conduit having a hollow interior for transport in bulk of the fluid; a microporous membrane, operatively positioned to traverse across the hollow interior of the conduit, for sifting molecules of the fluid; and an actuator, operatively positioned near the microporous membrane, for propagating acoustic vibration onto the microporous mem-

brane and onto the molecules of the fluid at a particular frequency so as to hasten movement of the molecules through the microporous membrane.

In another embodiment, an apparatus for filtering a fluid comprises a conduit having a hollow interior for transport in bulk of the fluid; a microporous membrane, operatively positioned to traverse across the hollow interior of the conduit, for sifting molecules of the fluid, the microporous membrane comprising a plurality of carbon nanotubes substantially aligned along an axis that corresponds with the principal directional flow of the molecules when transported in bulk within the hollow interior of the conduit, the plurality of carbon nanotubes each having a hollow interior for providing a passage for the molecules to be sifted; and an actuator, operatively positioned near the microporous membrane, for propagating acoustic vibration onto the microporous membrane and the molecules of the fluid at a particular frequency onto the molecules of the fluid so as to hasten movement of the molecules through the plurality of hollow interiors of the carbon nanotubes.

In another embodiment, a method of filtering a fluid transported through a hollow interior of a conduit, comprises the steps of: (a) sifting molecules of the fluid through a microporous membrane and (b) propagating acoustic vibration to the microporous membrane at or near a particular frequency and onto the molecules of the fluid so as to hasten movement of said molecules through the membrane.

In another embodiment, a method of filtering water comprises the steps of: (a) sifting molecules of the water through a microporous membrane, the pores of the microporous membrane comprising a plurality of carbon nanotubes and (b) propagating acoustic vibration to the microporous membrane at a libration frequency of ice so as to hasten movement of said molecules of water through the pores of the membrane.

Other aspects and advantages of the embodiments described herein will become apparent from the following description and appended claims, taken in conjunction with the accompanying drawings, illustrating the principles of the embodiments by way of example only.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional perspective view of a filtering apparatus in accordance with an embodiment of the present invention;

FIG. 2 is a top view of a microporous membrane in the shape of a disk in accordance with an embodiment of the invention; and

FIG. 3 is an oscillator circuit incorporated by an actuator in accordance with an embodiment of the present invention.

### DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

Exemplary embodiments will now be described with reference to the accompanying drawings or figures. Throughout the drawings, like elements or components are denoted with the same reference characters for consistency.

Before beginning a detailed description of some exemplary embodiments, the meaning of certain terms as used herein will be given.

"Macroporous" means having or containing pores with diameters greater than about 50 nm, or about 500 Angstrom.

"Mesoporous", such as a "mesoporous material", means a material containing pores with diameters ranging between about 2 and about 50 nanometers, or about 20 to about 500 Angstrom.

“Microporous” means having or containing pores with diameters of less than about 2 nm or about 20 Angstrom.

A filtering apparatus in accordance with the exemplary embodiments of the invention comprises an acoustically driven molecular sieve which filters substances such as a fluid by passing through molecules of a particular size or smaller while collecting larger molecules, such as biological contaminants. The filtered substance passes through the pores of a microporous membrane. In one embodiment, the pores of the membrane comprise the substantially hollow interiors of a plurality of carbon nanotubes. The filtering apparatus further comprises an actuator which propagates an acoustic vibration onto the membrane and the substance being filtered at or near a particular frequency determined beforehand to be of interest. The acoustic vibration hastens movement of the molecules through the pores of the microporous membrane. The filtering apparatus may be used to purify wastewater for reuse aboard spacecraft or other non-earth based structures, but it also has various applications on earth suitable for generating potable, medical grade, or otherwise purified water from contaminated water supplies. The filtering apparatus may also be used to remove water from chemical compounds, such as removing water from alcohols. While the accompanying drawings may display only a single filtering apparatus, a filtering apparatus in accordance with the exemplary embodiments may be scalable to larger diameters and power levels, and to multiple assemblies of the filtering apparatus.

Referring now to FIG. 1, a filtering apparatus 10 comprises a microporous membrane 14, represented as a disk in the embodiment of FIG. 1, operatively positioned to traverse across the path of movement of a substance or of flow of a fluid positioned in a hollow interior of a conduit 20 or a housing 50. Both conduit 20 and housing 50 have a hollow interior for the transport or placement in bulk of a fluid or substance. While shown in FIG. 1 as essentially a pipe, tube, hose, or cylindrical structure having a circular cross-section for its hollow interior, conduit 20 and housing 50 may comprise structures having other cross-sectional shapes for the hollow interior, such as, for example, elliptical, rectangular, triangular, trapezoidal, pentagonal, hexagonal, octagonal, or other shapes. Operatively positioned near the microporous membrane 14 is an actuator 26 for propagating acoustic vibration to the membrane 14. Housing 50 may also serve to cover and protect actuator 26 and microporous membrane 14.

The membrane 14 of FIG. 1 has a circular cross-section with a representative diameter of about 4 millimeters (mm) and a thickness between about 1 and about 40 microns ( $\mu$  or “ $\mu$ ”, i.e.,  $1.0 \times 10^{-6}$  meters) thick. Within the microporous membrane 14 are a plurality of pores 16, a majority of which are each substantially aligned along an axis 18. Axis 18 corresponds with the directional flow or movement of molecules (represented by vector 118) when they are sifted through the membrane 14. In the embodiment of FIG. 1, axis 18 also represents the axis of the membrane 14 when it is in the shape of a disk. The aligned pores 16 are embedded in membrane 14 so as to provide a passage for molecules through the membrane 14. Filtering apparatus 10 performs its filtering function at least in part by sifting molecules of interest that are of a certain size or smaller as they fit into and pass through the pores 16, whereas larger-sized molecules cannot. The substance or fluid to be purified or separated may be travelling in bulk through the interior of the conduit 20 in the principal direction represented by vector 118.

The pores 16 in one exemplary embodiment comprise a plurality of carbon nanotubes, such as for example single-walled carbon nanotubes (SWNT), with at least a majority of the plurality of carbon nanotubes being open-ended once

assembled in the membrane 14 and having a substantially hollow interior passage of particular dimension. Carbon nanotubes are generally hydrophobic; therefore, the dynamical and structural properties of water located within the hollow interior of a carbon nanotube of two nanometers or less in diameter are expected to differ greatly from those of bulk water. For instance, as described with greater detail in the publication by William H. Noon et al. entitled “Helical Ice-Sheets Inside Carbon Nanotubes in the Physiological Condition,” *Chemical Physics Letters* 355 (2002) 445-448, the behavior of water inside a segment of a SWNT depends, at least in part, on the size of the interior diameter of the nanotube. Noon et al make their conclusions from computer-based simulations known as molecular dynamics (MD), in particular simulations of segments of pristine SWNT of different sizes submerged in a periodic hexagonal prism of water in the physiological condition (300° K and 1 atm). Noon et al. report that the size of a nanotube 6.75 Angstroms in diameter is too small to accommodate any water molecules inside, and that the behavior of water molecules inside a carbon nanotube of 20.26 Angstroms in diameter is the same as that of bulk water. However, Noon et al. conclude that the behavior of water molecules inside nanotubes of sizes intermediate these values in diameter is significantly different.

Specifically, simulations of a nanotube having an interior diameter of 8.11 Angstroms indicate the nanotube can accommodate a hydrogen-bonded single-file water network. Likewise, simulations of a nanotube having an interior diameter of 9.46 Angstroms indicate the nanotube can accommodate a hydrogen-bonded three-column water network, simulations of a nanotube having an interior diameter of 10.81 Angstroms indicate the nanotube can accommodate a four-column water network, and simulations of a nanotube having an interior diameter of 13.51 Angstroms indicate the nanotube can accommodate a seven-column water network. Based on the oxygen-oxygen radial distribution functions of water molecules, the water molecules tend to stay about 3 Angstroms away from the interior wall of the nanotube. Thus, computational simulations (and experimental evidence) have shown that water molecules, sifted inside a carbon nanotube having its interior diameter within a particular range above about 5 Angstroms to about 20 Angstroms become aligned into helical columns that exhibit properties of both excitable ice crystals and liquid water.

Accordingly, in yet another embodiment, at least a majority of the open-ended carbon nanotubes of the filtering apparatus 10 have a substantially hollow interior with a diameter ranging from about 5 to about 20 Angstroms, or more particularly from about 8.1 to about 13.5 Angstroms. In this particular embodiment, because the surface tension of water is low enough, water molecules are able to enter and travel within the hollow interior of the nanotube. The resulting movement or flow of the molecules is induced in part by polarity of the molecules.

The actuator 26 is capable of performing the function of propagating acoustic vibration onto the membrane 14 and the molecules being sifted therethrough at or near a particular frequency, such as the libration frequency of ice when the molecules are water, so as to hasten movement of the molecules through the pores 16. The actuator 26 may comprise a transducing subassembly 46 that converts an electrical energy input into mechanical energy output such as acoustic vibration. Once constructed, the transducing subassembly has an acoustic impedance that is substantially similar to the acoustic impedance of the microporous membrane. In one embodiment, actuator 26 comprises the transducing subassembly 46 of a transducing material 32 and an electrode 24. For

5

example, the transducing material **32** may comprise at least one layer of a polyvinylidene fluoride (PVDF) film that is approximately 9 microns ( $\mu$ ) thick. Alternately, the transducing material **32** may comprise an electroactive material like lead zirconate titanate (PZT), such as when the impermeable material **15** comprises a ceramic material so that the acoustic impedance of the membrane **14** and the transducing material **32** are substantially matched. The electrode **24** may comprise a copper film that is approximately 150 nanometers thick and that coats the transducing material **32**.

The actuator **26** is operatively positioned near the membrane **14**. In the embodiment of FIG. 1, the actuator **26** is positioned on at least a portion of the outer perimeter **17** of membrane **14** or the outer exterior surface of conduit **20**. In one embodiment, the transducing subassembly **46** is affixed in this position by an electrically non-conductive epoxy. The actuator **26** may further comprise an oscillator **28** capable of providing an electrical energy output by being tunable to operate within a frequency range from about 50 to about 200 MHz, or from about 50 MHz to about 20 GHz. This frequency output may be adjusted (automatically) to enhance efficiency. For instance, a flow sensor **30** may be positioned near the exit **51** of the conduit **20** (or housing **50**). The flow sensor **30** may be used to notify a controller (not shown) when the rate of flow slows to a specified value, prompting the controller to initiate the actuator **26** to propagate acoustic vibrations onto the microporous membrane and re-establish flow. Other transducing subassemblies may be used for operation above 20 GHz and at other vibrational modes.

Referring now to FIG. 3, oscillator **28** comprises in one embodiment an oscillating circuit **29**. The oscillating circuit **29** provides the function of a tunable, oscillating electrical energy output for the oscillator **28**. The oscillating circuit **29** includes a source **40** of electrical energy, a jumper **42**, and an antenna lead **44**. In one embodiment, the antenna lead **44** is operatively connected to the actuator **26** by bonding electrical wire from the antenna lead **44** directly to the electrode **24**. The circuit **29** further comprises a switch **41**, three resistors **43a**, **43b**, and **43c**, two capacitors **45a**, **45b**, and a dialable capacitor **45c**. The circuit **29** further comprises two inductors **46a** and **46b** and a transistor **47**. The dialable capacitor **45c** enables the circuit **29** to be operable at a variety of frequencies. In one embodiment, source **40** comprises a 9-volt battery, but other sources of electric energy, such as a household power line, an industrial power line, or a photovoltaic cell that converts solar energy into electric energy may also be used. Transistor **47** may comprise the NPN-type bipolar junction type transistor known as 2N3904 and sold commercially by the manufacturer Fairchild Semiconductor. Similarly, oscillating circuit **29** may comprise other electrical components in another arrangement than what is represented in FIG. 3 but apparent to the skilled artisan now having the benefit of this description.

Referring now to FIG. 2, a top view is shown of the microporous membrane **14** in the shape of a disk, as it was in FIG. 1. While the membrane **14** is shown with a circular cross-section, the membrane **14** may comprise other shapes in cross-section, including elliptical, triangular, rectangular, trapezoidal, pentagonal, octagonal, or other shapes. As shown in FIG. 2, the microporous membrane **14** may further comprise a matrix **15** for supporting the plurality of carbon nanotubes embedded therein. The matrix **15** is made of a material that is impermeable to the molecules of the substance or fluid being sifted by membrane **14**, such that only the open-ended carbon nanotubes permit movement of the molecules through the microporous membrane **14**. As will be discussed in further detail below, the impermeable material of matrix **15** may also

6

be hydrophobic and may comprise a thermoplastic polymer such as a polyvinyl chloride resin combined with a calcium carbonate of nanoscale grain size. The impermeable material may further comprise a plasticizer. In another embodiment, the impermeable material of the matrix comprises a clay with one or more of gold and silver contained therein.

Operation of the filtering apparatus **10** enables the process of the filtering a substance or fluid. In one embodiment, the process or method of filtering comprises the steps of: (a) sifting molecules of the substance or fluid through the microporous membrane and, (b) propagating acoustic vibration onto the microporous membrane and the molecules at a particular frequency so as to hasten movement of said molecules through the membrane. The step of propagating acoustic vibration is performed at a particular frequency ranging from about 50 to about 200 MHz, or from about 50 MHz to about 20 GHz. In another embodiment, a method of filtering water comprises the steps of: (a) sifting molecules of the water through a microporous membrane, the pores of the microporous membrane comprising a plurality of carbon nanotubes and (b) propagating acoustic vibration onto the microporous membrane at a libration frequency of ice so as to hasten movement of the molecules of water through the carbon nanotubes. For this method of filtering water, at least a majority of the carbon nanotubes each have a substantially hollow interior with a diameter ranging from about 8 Angstroms to about 14 Angstroms.

Operation of the filtering apparatus **10** begins by positioning a substance or fluid to be filtered, such as dirty water or a mix of alcohol and water, within the hollow interior of the conduit **20** or the housing **50** such that the substance or fluid is in contact with an upper face **22** of the membrane **14**. A container **31** may be placed on the exit side of the membrane to collect the substance or fluid after it is sifted through the membrane. The actuator **26** is then activated, such as by switching on the power source **40** of oscillating circuit **29**. The resulting acoustic vibration that is propagated forms acoustic waves that are coupled via the membrane **14** onto the pores **16** and the adjacent molecules of the fluid or substance.

For water, the mechanical energy transferred from the acoustic waves to the molecules as they enter and pass-through the nanotubes of the membrane may exceed the specific heat of fusion of ice. About 0.7 microvolts is the minimum amount of energy required for a change of state of one molecule of water. Energy levels at or above this amount are sufficient to cause the water molecules to become detached from one another, thereby behaving more like water in its liquid state, even though Noon et al. report that water molecules tend to organize themselves into a highly hydrogen-bonded network (i.e., solid-like wrapped-around ice sheets) as they are inside a carbon nanotube. The acoustic excitation, such as at the libration frequency of ice, enables water to flow more freely, or in other words, hasten its movement, along the hollow interior of the nanotubes and exit the membrane **14** on a lower face **23**.

An example of a process of manufacturing a microporous membrane **14** in accordance with one embodiment comprising a plurality of carbon nanotubes as the pores **16** will now be described. The plurality of carbon nanotubes may comprise single wall carbon nanotubes having a length of ranging from approximately 50 microns to about 100 microns or more. Carbon nanotubes are structurally strong and will not degrade over time. Suitable nanotubes are available from various commercial sources, and may initially be sonicated utilizing deionized, distilled water and a 1% solution of a surfactant, such as sodium dodecyl sulfate. The carbon nanotubes will become trapped in the surfactant, which takes the form of a

surfactant sleeve around the carbon of the nanotube and effectively separates the carbon nanotubes, which would otherwise tend to stick together because of strong van der Waals forces. The coated nanotubes may be collected by centrifugation and poured into a clean glass beaker. A glass slide may be suspended vertically in the final solution of cleaned and coated tubes. The beaker may be placed in a dust free environment, and the water in the solution will be allowed to evaporate. As the waterline lowers, a film will gradually deposit on the glass slides. This resulting film comprises length-aligned coated carbon nanotubes. The slides may then be rinsed to remove most of the surfactant, and dried through evaporation.

To form a matrix **15** that is impermeable to water molecules, a thermoplastic polymer compound such as polyvinyl chloride (PVC) resin may be combined with about 2% of precipitated calcium carbonate (PCC) of nanoscale grain size (mean size 40 nm). PVC is a long chain polymer with a planar configuration, which is self-miscible for both single run processing and for partial processing buildup. Precipitated calcium carbonate serves primarily as a strength material, but it is not required. A plasticizer, such as the chemical compound of 1,2-Cyclohexanedicarboxylic acid diisononyl ester and known as the commercially available product of Hexamoll® Dinch sold by the manufacturer BASF, may be mixed with the PVC resin. This particular compound is understood to be non-toxic to humans, and it is not phthalate-based. The mixture may be vacuum extruded to remove air bubbles. The resulting thermoplastic compound may be kept at room temperature until ready for use. Alternatively, the impermeable matrix **15** may be formed by selecting a ceramic material that has an acoustic impedance that is substantially matched to the acoustic impedance of transducing material **32**, such as the electroactive material lead zirconate titanate (PZT).

To build and cure a polymer-nanotube assembly so as to form a microporous membrane, a borosilicate roller and a diamond knife may be used to shape and cut the polymer compound into thin strips, which may then be placed over the partially rinsed carbon nanotubes on the glass side. The roller may be rolled over the polymer compound to embed the nanotubes into the opposing surface of the polymer. The polymer compound matrix with the nanotubes therein may be placed on a second slide with the partially imbedded nanotubes facing away from the surface of the slide, and the remainder of the surfactants rinsed from the nanotubes. This process may be repeated to build up the polymer-nanotube assembly. Processing the plurality of thin strips in this manner and then combining them together through successive rolling, a layered microporous membrane may be formed. This membrane may be shaped into a wafer or disk approximately 4 mm in diameter. The wafer may then be fired in an oven set at 250° F. for a minimum of 30 minutes. Alternatively, each half-imbedded thin strip may be partially cured at 250 degrees Fahrenheit before rinsing the remainder of the surfactant, and the partially cured, rinsed and dried strips may be assembled together for the final curing process. Gelation and curing of the material improves with longer firing times. Once cured, a three-dimensional workpiece of a polymer-based, microporous membrane may be obtained.

To machine and assemble the polymer workpiece into final form as a microporous membrane, a lapping tool may be used to cut a thin section from the wafer as it is adhered to a lapping fixture with a mounting wax. The wafer may be lapped down to a thickness of approximately 40 microns ( $\mu$ ) utilizing a lapping cloth and a slurry of diamond nano crystals. This lapping process will shave off the tops of the carbon nano-

tubes and with the effect of opening the ends of the carbon nanotubes. The wafer may then be removed from the lapping fixture.

Once machined, the thin, wafer-like membrane **14** may be sandwiched between layers of raw thermoplastic polymer such as the PVC resin to form an integrated unit with the conduit **20**. For instance, an upper conduit portion **20A** and a lower conduit portion **20B** are placed in position above and below, respectively, the membrane **14** such that conduit **20** is formed with an outer diameter of approximately 4 mm, while the exposed surface area of the thin wafer-like membrane **14** is approximately 1 mm in diameter. As shown in FIG. 1, the upper portion **20A** is relatively thin, and the lower layer **20B** is substantially thicker. One or more raw polymer layers may be provided, and the thickness of each layer may be altered for particular applications. The integrated assembly may be baked to cure the material.

Manufacture of the microporous membrane may also be accomplished by utilizing a selected gold or silver clay. In this embodiment, the carbon nanotubes are embedded in the clay and the matrix-nanotube assembly built up in the same manner as that of the polymer (PVC) manufacture embodiment. The metallic layer assembly may be baked in a kiln to a specified temperature for curing the clay. The binder cooks away and the metal coalesces and “shrinks” to encase the carbon nanotubes. This embodiment of manufacture may also use the same lapping process used for the polymer-based workpiece. The advantage of using gold and silver in the clay is that gold is impervious to harsh chemicals, and silver is a biocide.

As mentioned at the beginning of this description, the filtering apparatus discussed herein is scalable, and a bank of filters may be built and assembled inside the chassis of a large scale filtering assembly. The microporous membrane, when constructed with a water impermeable matrix and carbon nanotubes of particular size to form its pores, only permits water molecules to pass through the nanotubes, leaving contaminants such as alcohol or a virus behind.

While the filtering apparatus described herein has at least one embodiment particularly well suited for filtering contaminated water to produce purified, clean water, the filtering apparatus may also be used to remove various types of impurities, whether in liquid or solid form, from other liquids which are passed through the apparatus, so that the discharged fluid is substantially free of contaminants. A sizing range for the diameter of the carbon nanotubes or other material used to form pores within the microporous membrane would thus depend upon the substance or fluid which is filtered, so that the pores are sized to pass molecules that are clean or purified while preventing the passage of contaminants through the pores.

Similarly, the particular frequency at which the acuator propagates acoustic vibrations may need to be adjusted, depending upon the fluid or substance to be sifted and the desired degree of purity for the sifted substance or fluid. Accordingly, the filtering apparatus and the method as disclosed herein may be used to clean various types of substances or fluids.

Although only a few exemplary embodiments of this invention have been described in detail above, a skilled artisan will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims. In the claims, means-plus-function and step-plus-function clauses are intended to cover the structures

or acts described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures.

What is claimed is:

1. A filtering apparatus, comprising:  
a microporous membrane for sifting molecules of a substance; and  
an actuator, operatively positioned near the microporous membrane, for propagating acoustic vibration at a particular frequency onto the microporous membrane so as to hasten movement of said molecules through the microporous membrane.

2. An apparatus according to claim 1, wherein the microporous membrane comprises a plurality of carbon nanotubes substantially aligned along an axis that corresponds with the principal direction of movement of said molecules in bulk through the membrane.

3. An apparatus according to claim 2, wherein at least a majority of the plurality of carbon nanotubes each have an internal diameter ranging from about 8.1 to about 13.5 Angstroms.

4. An apparatus according to claim 3, wherein the microporous membrane further comprises a matrix for supporting the plurality of carbon nanotubes, the matrix being made of a material that is impermeable to said molecules such that only the carbon nanotubes permit movement of said molecules through the microporous membrane.

5. An apparatus according to claim 4, wherein the impermeable material comprises a polyvinyl chloride resin combined with a calcium carbonate of nanoscale grain size.

6. An apparatus according to claim 5, wherein the impermeable material further comprises a plasticizer.

7. An apparatus according to claim 4, wherein the impermeable material of the matrix comprises clay with one or more of gold and silver contained therein.

8. An apparatus according to claim 4, wherein the impermeable material of the matrix is hydrophobic.

9. An apparatus according to claim 4, wherein the impermeable material of the matrix comprises a ceramic.

10. An apparatus according to claim 1, wherein the actuator propagates acoustic vibration in a range of about 50 to about 200 MHz.

11. An apparatus according to claim 2, wherein the acoustic vibration imparted to the microporous membrane is at a frequency substantially similar to the natural frequency of water molecules in solid form.

12. An apparatus according to claim 4 wherein the microporous membrane is in the shape of a disk.

13. An apparatus according to claim 1, wherein the acoustic impedance of the actuator is substantially similar to the acoustic impedance of the microporous membrane.

14. A filtering apparatus, comprising:  
a housing with a hollow interior;  
a microporous membrane, operatively positioned to traverse across the hollow interior of the housing, for sifting molecules of a substance; and  
an actuator, operatively positioned near the microporous membrane, for propagating acoustic vibration at a particular frequency onto the microporous membrane so as to hasten movement of said molecules through the microporous membrane.

15. An apparatus according to claim 14, wherein the microporous membrane comprises a plurality of carbon

nanotubes substantially aligned along an axis that corresponds with the principal direction of movement of said molecules in bulk through the membrane.

16. An apparatus according to claim 15, wherein at least a majority of the plurality of carbon nanotubes each have an internal diameter ranging from about 8.1 to about 13.5 Angstroms.

17. An apparatus according to claim 16, wherein the microporous membrane further comprises a matrix for supporting the plurality of carbon nanotubes, the matrix being made of a material that is impermeable to said molecules such that only the carbon nanotubes permit movement of said molecules through the microporous membrane.

18. An apparatus according to claim 17, wherein the impermeable material comprises a polyvinyl chloride resin combined with a calcium carbonate of nanoscale grain size.

19. An apparatus according to claim 18, wherein the impermeable material further comprises a plasticizer.

20. An apparatus according to claim 17, wherein the impermeable material of the matrix comprises a clay with one or more of gold and silver contained therein.

21. An apparatus according to claim 17, wherein the impermeable material of the matrix is hydrophobic.

22. An apparatus according to claim 17, wherein the impermeable material of the matrix comprises a ceramic.

23. An apparatus according to claim 14 wherein the actuator propagates acoustic vibration in a range of about 50 to about 200 MHz.

24. An apparatus according to claim 15 wherein the acoustic vibration imparted to the microporous membrane is at a frequency substantially similar to the natural frequency of water molecules in solid form.

25. An apparatus according to claim 17 wherein the microporous membrane is in the shape of a disk.

26. An apparatus according to claim 14 wherein the hollow interior of the housing comprises a cross-sectional shape selected from the group consisting of circular, elliptical, rectangular, triangular, trapezoidal, pentagonal, hexagonal, and octagonal.

27. An apparatus for filtering a fluid, comprising:  
a conduit having a hollow interior for transport in bulk of the fluid;

a microporous membrane, operatively positioned to traverse across the hollow interior of the conduit, for sifting molecules of the fluid; and

an actuator, operatively positioned near the microporous membrane, for propagating acoustic vibration onto the microporous membrane at a particular frequency so as to hasten movement of said molecules through the microporous membrane.

28. An apparatus according to claim 27, wherein the microporous membrane comprises a plurality of carbon nanotubes substantially aligned along an axis that corresponds with the directional flow of said molecules when transported in bulk within the hollow interior of the conduit.

29. An apparatus according to claim 28, wherein at least a majority of the plurality of carbon nanotubes each have an internal diameter ranging from about 8.1 to about 13.5 Angstroms.

30. An apparatus according to claim 27, wherein the hollow interior of the housing has a cross-sectional shape selected from the group consisting of circular, elliptical, rectangular, triangular, trapezoidal, pentagonal, hexagonal, and octagonal.

31. An apparatus according to claim 29, wherein the microporous membrane further comprises a matrix for supporting the plurality of carbon nanotubes, the matrix being



made of a material that is impermeable to said molecules such that only the carbon nanotubes permit movement of said molecules through the microporous membrane.

32. An apparatus according to claim 31, wherein the impermeable material comprises a polyvinyl chloride resin combined with a calcium carbonate of nanoscale grain size.

33. An apparatus according to claim 32, wherein the impermeable material further comprises a plasticizer.

34. An apparatus according to claim 31, wherein the impermeable material of the matrix comprises a clay with one or more of gold and silver contained therein.

35. An apparatus according to claim 31, wherein the impermeable material of the matrix is hydrophobic.

36. An apparatus according to claim 31, wherein the impermeable material of the matrix comprises a ceramic.

37. An apparatus according to claim 27 wherein the actuator propagates acoustic vibration in a range of frequency of about 50 to about 200 MHz.

38. An apparatus according to claim 27, wherein the acoustic vibration imparted to the microporous membrane is at a frequency substantially similar to the natural frequency of water molecules in solid form.

39. An apparatus according to claim 29 wherein the microporous membrane has a cross-sectional shape selected from the group consisting of circular, elliptical, rectangular, triangular, trapezoidal, pentagonal, hexagonal, and octagonal.

40. An apparatus according to claim 27, wherein the acoustic impedance of the actuator is substantially similar to the acoustic impedance of the microporous membrane.

41. An apparatus for filtering a fluid, comprising:  
a conduit having a hollow interior for transport in bulk of the fluid;

a microporous membrane, operatively positioned to traverse across the hollow interior of the conduit, for sifting molecules of the fluid, the microporous membrane comprising a plurality of carbon nanotubes substantially aligned along an axis that corresponds with the principal directional flow of said molecules when transported in bulk within the hollow interior of the conduit, at least a majority of the plurality of carbon nanotubes each having a hollow interior for providing a passage for said molecules to be sifted; and

an actuator, operatively positioned near the microporous membrane, for propagating acoustic vibration onto the microporous membrane so as to hasten movement of said molecules through the plurality of hollow interiors of the carbon nanotubes.

42. An apparatus according to claim 41, wherein at least a majority of the hollow interiors of the plurality of carbon nanotubes have a diameter ranging from about 8.1 to about 13.5 Angstroms.

43. An apparatus according to claim 41 wherein the hollow interior of the conduit has a cross-sectional shape that is selected from the group consisting of circular, elliptical, rectangular, triangular, trapezoidal, pentagonal, hexagonal, and octagonal.

44. An apparatus according to claim 41 wherein the hollow interior of the conduit is generally circular in cross section.

45. An apparatus according to claim 42, wherein the microporous membrane further comprises a matrix for supporting the plurality of carbon nanotubes, the matrix being made of a material that is impermeable to said molecules of the fluid such that only the hollow interiors of the plurality of carbon nanotubes permit movement of said molecules through the microporous membrane.

46. An apparatus according to claim 45, wherein the impermeable material comprises a polyvinyl chloride resin combined with a calcium carbonate of nanoscale grain size.

47. An apparatus according to claim 46, wherein the impermeable material further comprises a plasticizer.

48. An apparatus according to claim 45 wherein the impermeable material of the matrix comprises a clay with one or more of gold and silver contained therein.

49. An apparatus according to claim 45 wherein the impermeable material of the matrix is hydrophobic.

50. An apparatus according to claim 45, wherein the impermeable material of the matrix comprises a ceramic.

51. An apparatus according to claim 41, wherein the actuator propagates acoustic vibration in a range of frequency of about 50 to about 200 MHz.

52. An apparatus according to claim 41, wherein the actuator comprises an oscillator circuit.

53. An apparatus according to claim 41, wherein the acoustic vibration imparted onto the microporous membrane is at a frequency substantially similar to the natural frequency of water molecules in solid form.

54. An apparatus according to claim 44 wherein the microporous membrane is in the shape of a disk.

55. An apparatus according to claim 41, wherein the acoustic impedance of the actuator is substantially similar to the acoustic impedance of the microporous membrane.

56. A method of filtering a fluid transported through a hollow interior of a conduit, comprising:  
sifting molecules of the fluid through a microporous membrane; and, propagating acoustic vibration to the microporous membrane at a particular frequency so as to hasten movement of said molecules through the membrane.

57. A method of filtering according to claim 56 further comprising the step of matching the acoustic impedance of the microporous membrane with the acoustic impedance of an actuator that propagates the acoustic vibration.

58. A method according to claim 56 wherein the step of propagating acoustic vibration is performed in the range of about 50 to about 200 MHz.

59. A method of filtering water, comprising:  
sifting molecules of said water through a microporous membrane, the pores of said microporous membrane comprising a plurality of carbon nanotubes, at least a majority of the carbon nanotubes each having a substantially hollow interior with a diameter ranging from about 8 Angstroms to about 14 Angstroms; and,  
propagating acoustic vibration to the microporous membrane at a vibration frequency of ice so as to hasten movement of said molecules of water through the interiors of the at least majority of carbon nanotubes.