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(54) Title: PIEZOELECTRIC PUMPING MECHANISM

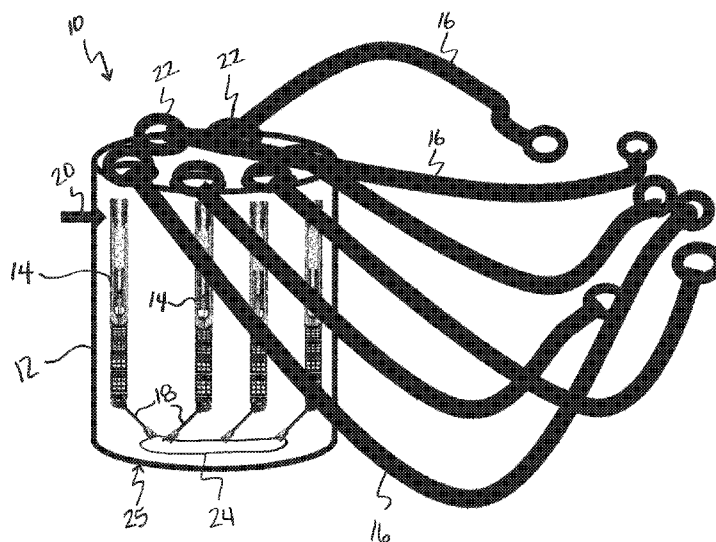


Fig. 1

(57) Abstract: A piezoelectric pumping mechanism, comprising a pump body, at least one pumping element housed within the pump body, the at least one pumping element including a body, at least one stack of piezoelectric material, an amplifying element, a plunger, and a fluid volume, at least one electrical connector coupled to the at least one stack of piezoelectric material within the at least one pumping element, and at least one pressurized fluid delivery line fluidly coupled to the fluid volume of the at least one pumping element, wherein the plunger is positioned above the amplifying element and the at least one stack of piezoelectric material and the fluid volume is positioned between a top of the plunger and the body of the at least one pumping element.



EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

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- *with international search report (Art. 21(3))*
- *with amended claims (Art. 19(1))*

PIEZOELECTRIC PUMPING MECHANISM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of and priority to U.S. Application No. 62/861,063, filed June 13, 2019, the content of which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD OF THE DISCLOSURE

[0002] The present disclosure relates to a pumping mechanism using piezoelectric materials to provide pressurized fluid.

BACKGROUND OF THE DISCLOSURE

[0003] Current fuel systems typically utilize mechanical high-pressure pumps to generate highly pressurized fuel for use in an engine. However, high pressure fuel pumps often have various issues including high costs, higher weights, oil to fuel transfer, sticking plungers, roller damage, inlet metering valve sticking, and barrel cracking, among others. Thus, it would be beneficial to have a pumping mechanism capable of generating and providing pressurized fluid without similar issues.

SUMMARY OF THE DISCLOSURE

[0004] In one embodiment of the present disclosure, a piezoelectric pumping mechanism is provided. The piezoelectric pumping mechanism comprises a pump body, at least one pumping element housed within the pump body, the at least one pumping element including a body, at least one stack of piezoelectric material, an amplifying element, a plunger, and a fluid volume, at least one electrical connector coupled to the at least one stack of piezoelectric material within the at least one pumping element, and at least one pressurized fluid delivery line fluidly coupled to the fluid volume of the at least one pumping element, where the plunger is positioned above the amplifying element and the at least one stack of piezoelectric material and the fluid volume is positioned between a top of the plunger and the body of the at least one pumping element.

[0005] In one aspect of the piezoelectric pumping mechanism, the at least one electrical connector is coupled to the at least one stack of piezoelectric material through an opening within a bottom of the pump body.

[0006] In another aspect of the piezoelectric pumping mechanism, the at least one stack of piezoelectric material is a ceramic-based piezoelectric material having an asymmetric crystalline structure.

[0007] In a further aspect of the piezoelectric pumping mechanism, the at least one pumping element includes 1 to 100 pumping elements.

[0008] In another aspect of the piezoelectric pumping mechanism, an upper surface of the at least one stack of piezoelectric material abuts a lower surface of the amplifying element, and an upper surface of the amplifying element abuts a lower surface of the plunger.

[0009] In a further aspect of the piezoelectric pumping mechanism, the piezoelectric pumping mechanism further comprises a valve positioned along each of the at least one pressurized fluid delivery lines, the valve being configured to control when pressurized fluid within the fluid volume is released from the fluid volume.

[0010] In another aspect of the piezoelectric pumping mechanism, the at least one stack of piezoelectric material is configured to expand within the at least one pumping element body when a voltage is provided to the at least one electrical connector coupled to the at least one stack of piezoelectric material, thereby causing movement of the amplifying element and the plunger to pressurize fluid in the fluid volume.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Advantages and features of the embodiments of this disclosure will become more apparent from the following detailed description of exemplary embodiments when viewed in conjunction with the accompanying drawings, wherein:

[0012] Fig. 1 is a schematic diagram of an embodiment of a piezoelectric pumping mechanism of the present disclosure including a pump body, a plurality of pumping elements, a plurality of electrical connectors, and a plurality of pressurized fluid delivery lines with both the pump body and each of the plurality of pumping elements being shown in cross-section;

[0013] Fig. 2 is a schematic diagram of another embodiment of a piezoelectric pumping mechanism of the present disclosure including a pump body, a plurality of pumping elements, and a plurality of electrical connectors with the pump body being shown in cross-section;

[0014] Fig. 3 is a schematic diagram of a fuel system including a fuel tank, a low-pressure pump, a piezoelectric pumping mechanism of the present disclosure, and an engine;

[0015] Fig. 4A is a schematic cross-sectional diagram of one of the plurality of pumping elements of Fig. 2; and

[0016] Fig. 4B is a schematic cross-sectional diagram of one of the plurality of pumping element of Fig. 1.

[0017] Corresponding reference characters indicate corresponding parts throughout the several views. Although the drawings represent embodiments of the present disclosure, the drawings are not necessarily to scale and certain features may be exaggerated in order to better illustrate and explain the present disclosure. The exemplifications set out herein illustrate embodiments of the disclosure, in one form, and such exemplifications are not to be construed as limiting the scope of the disclosure in any manner.

DETAILED DESCRIPTION OF THE DRAWINGS

[0018] Referring to Figs. 1-3, a piezoelectric pumping mechanism 10, 10' generally includes a pump body 12, 12', a plurality of pumping elements 14, 14', a plurality of pressurized fluid delivery lines 16, and a plurality of electrical connectors 18, 18' configured to couple a power source 101 (i.e., a battery or other voltage source) (Fig. 3) of the vehicle to each of pumping elements 14. In various embodiments, piezoelectric pumping mechanism 10 may include one or up to 100 pumping elements 14, where there is a pressurized fluid delivery line 16, and an electrical connector 18 for each pumping element. Piezoelectric pumping mechanism 10 is generally coupled to at least one injector 102 of an engine 104 (Fig. 3) of a vehicle (not shown) via pressurized fluid delivery lines 16 and is configured to provide fluid pressurized to up to approximately 2000 bar. In various embodiments, a common rail 106 is positioned between fluid delivery lines 16 and injector(s) 102 and/or engine 104 such that all of the pressurized fluid may be received in one volume prior to being provided to engine 104 and/or injector(s) 102. The fluid transferred using pumping mechanism 10 may include gasoline fuel, diesel fuel, or urea, among other fluids.

[0019] Still referring to Figs. 1-3, pump body 12 generally includes an inlet 20, 20' for each pumping element 14, an outlet 22, 22' for each pumping element 14, and at least one opening 24, 24' along a bottom 25, 25' of pump body 12 through which power source 101 of the vehicle may be coupled to each pumping element 14. Inlet(s) 20 are fluidly coupled to a low pressure pump 108 (Fig. 3) and configured to allow fluid to be provided to inlets 26 (Fig. 4) for each pumping element 14 from a fuel tank 110. Outlet(s) 22, 22' are coupled to outlets 28 (Fig. 4) of pumping element 14 via a channel (not shown) coupling outlets 22, 22' and 28 or via delivery lines 16, 16' extending through outlets 22, 22' and coupling to outlets 28 such that pressurized fluid within pumping element 14 may exit pumping element 14 through outlet 28 and pump body 12 through outlet 22 into one of fluid delivery lines 16. Opening 24 may be a single opening that is configured to receive a single electrical connector 18 that may split into a plurality of connectors 18, if there are multiple pumping elements 14, once within pump body 12 or a plurality of openings each configured to receive one of the plurality of connectors 18.

[0020] With reference to Figs. 4A and 4B, pumping elements 14, 14' each generally include a body 30, 30', at least one stack of piezoelectric material 32, 32' that includes a number of layers, an amplifying element 34, 34', a plunger 36, 36', and a fluid volume 38, 38', where piezoelectric material 32, amplifying element 34, plunger 36, and fluid volume 38 are configured to be positioned within body 30. Stacked piezoelectric material 32 is coupled directly to one of connectors 18 such that power source 101 of the vehicle may supply a voltage to piezoelectrical material 32 through connector 18. In various embodiments, wires of connector 18 may be coupled to or embedded into piezoelectric material 32 to provide the voltage thereto.

Amplifying element 34 abuts against an uppermost extent of piezoelectric material 32 and a lowermost surface of plunger 36. Plunger 36 is seated on an upper surface of amplifying element 34 above piezoelectric material 32. Fluid volume 38 is positioned above plunger 36 and includes the volume between a top 40 (Fig. 4A) of plunger 36 and a top 42 (Fig. 4A) of body 30. Inlet 26 and outlet 28 are fluidly coupled to fluid volume 38 of pumping element 14 such that the fluid is provided to volume 38 from inlet 26 and pushed out of volume 38 through outlet 28.

[0021] Stacked piezoelectric material 32 may be any ceramic-based piezoelectric material having an asymmetric crystalline structure that has lower dielectric losses, high mechanical quality factor, lower permittivity, and lower dielectric constant relative to other ceramic materials. For example, relative permittivity may be in the range of 25 to 4000 or any smaller range within said

range, thermal expansion coefficient maybe in the range of $\sim 1 \times 10^{-6}$ to 6×10^{-6} meter/meter $^{\circ}\text{C}$ or within any smaller range within said range, density may be in the range of 5000 to 9000 kg/meter ^{3} or within any smaller range within said range, elastic modulus may be in the range of 2×10^{10} to 9×10^{10} Newton/meter ^{2} or within any smaller range within said range, electrical constants may be in the range of -25 to 40 $10^{-3}\text{V}\cdot\text{m}/\text{N}$ or within any smaller range within said range, coupling coefficient may be in the range of 0.20 to 1.50 or within any smaller range within said range, Curie Temperature range may be between 100 $^{\circ}\text{C}$ to 800 $^{\circ}\text{C}$ or within any smaller range within said range, operating temperature may be in the range of 100 $^{\circ}\text{C}$ to 800 $^{\circ}\text{C}$ or within any smaller range within said range (e.g., from about 100 $^{\circ}\text{C}$ to about 350 $^{\circ}\text{C}$, at which point fuel begins to boil), mechanical quality factor (also known as mechanical Q factor) may be in the range of 40 to 500 or within any smaller range within said range, and electrical volume resistivity may be in the range of 0.005 $\Omega\cdot\text{m}$ to 10 $\Omega\cdot\text{m}$ or within any smaller range within said range. Some examples of stacked piezoelectrical material 32 may include quartz, barium titanate (BaTiO_3), lead titanate (PbTiO_3), and lead zirconate titanate (PZT) (PbZrTiO_3), or any other material capable of expanding or contracting when charged electrically. Amplifying element 34 may also be made of various materials. For example, amplifying element 34 may be a medium grade steel or any other material capable of transferring the mechanical force from piezoelectric material 32 further upward to plunger 36.

[0022] In operation, fluid is supplied to each fluid volume 38 separately through line(s) from low pressure pump 108. In various embodiments, the line from low pressure pump 108 may be a single line that couples to a single inlet 20 of pump body 12 that then splits into multiple lines within pump body 12 that couple an inlet 20 to each of inlets 26 of pumping elements 14. In other various embodiments, multiples lines may extend from low pressure pump 108 to multiple inlets 20 on pump body 12, where each inlet 20 couples to a single pumping element 14 through inlet 26. Once fluid is in each fluid volume 38, an electrical voltage is supplied to each stacked piezoelectric material 32 from power source 101 within the vehicle through electrical connectors 18. The electrical voltage causes piezoelectric material 32 to experience an inverse piezoelectric effect and expand, pushing upward against amplifying element 34, which then translates upward increasing the overall upward movement caused by piezoelectric material 32. Amplifying element 34 then pushes plunger 36 upward creating pressure on the fluid within fluid volume 38 above the top 40 of plunger 36. The accumulated

pressure causes the fluid to be delivered through outlet 28 of pumping element 14 into one of the fluid delivery lines 16. In various embodiments, fluid passing through outlet 28 may pass directly into fluid delivery lines 16 coupled thereto that pass-through outlet(s) 22 of body 12. In other various embodiments, outlet 28 may be fluidly coupled to outlet 22 of body 12, and outlet 22 may be coupled to delivery lines 16 such that the fluid passes through outlets 22 and 28 and then into delivery lines 16.

[0023] In various embodiments, piezoelectric pumping mechanism 10 further includes a valve (not shown) along each fluid delivery line 16 that controls when fluid leaves fluid volume 38. In general, the valve opens once a set pressure within volume 38 is exceeded. The range of pressures is tailored for various applications. For example, the valve may open to allow fluid to flow to the common rail 106 and/or injector(s) 102 when the pressure of the fluid within fluid volume 38 is up to 3000 bar. Specific applications may include emission solutions, where the pressure would be approximately 20 bar or less, a low-pressure pump, where the pressure would be up to approximately 100 bar, and a high-pressure pump, where the pressure would be greater than 100 bar and up to 3000 bar.

[0024] A valve such as an inlet metering valve may also be placed along the line(s) extending between low pressure pump 108 and pump body 12 that controls when fluid is supplied to fluid volume(s) 38 in pumping element(s) 14.

[0025] While various embodiments of the disclosure have been shown and described, it is understood that these embodiments are not limited thereto. The embodiments may be changed, modified and further applied by those skilled in the art. Therefore, these embodiments are not limited to the detail shown and described previously, but also include all such changes and modifications.

[0026] Furthermore, the connecting lines shown in the various figures contained herein are intended to represent exemplary functional relationships and/or physical couplings between the various elements. It should be noted that many alternative or additional functional relationships or physical connections may be present in a practical system. However, the benefits, advantages, solutions to problems, and any elements that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as critical, required, or essential features or elements. The scope is accordingly to be limited by nothing other than the appended claims, in which reference to an element in the singular is not intended

to mean “one and only one” unless explicitly so stated, but rather “one or more.” Moreover, where a phrase similar to “at least one of A, B, or C” is used in the claims, it is intended that the phrase be interpreted to mean that A alone may be present in an embodiment, B alone may be present in an embodiment, C alone may be present in an embodiment, or that any combination of the elements A, B or C may be present in a single embodiment; for example, A and B, A and C, B and C, or A and B and C.

[0027] In the detailed description herein, references to “one embodiment,” “an embodiment,” “an example embodiment,” etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art with the benefit of the present disclosure to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described. After reading the description, it will be apparent to one skilled in the relevant art(s) how to implement the disclosure in alternative embodiments.

[0028] Furthermore, no element, component, or method step in the present disclosure is intended to be dedicated to the public regardless of whether the element, component, or method step is explicitly recited in the claims. No claim element herein is to be construed under the provisions of 35 U.S.C. § 112(f), unless the element is expressly recited using the phrase “means for.” As used herein, the terms “comprises,” “comprising,” or any other variation thereof, are intended to cover a non-exclusive inclusion, such that a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus.

WHAT IS CLAIMED IS:

1. A piezoelectric pumping mechanism, comprising:
a pump body;
at least one pumping element housed within the pump body, the at least one pumping element including a body, at least one stack of piezoelectric material, an amplifying element, a plunger, and a fluid volume;
at least one electrical connector coupled to the at least one stack of piezoelectric material within the at least one pumping element; and
at least one pressurized fluid delivery line fluidly coupled to the fluid volume of the at least one pumping element, wherein the plunger is positioned above the amplifying element and the at least one stack of piezoelectric material and the fluid volume is positioned between a top of the plunger and the body of the at least one pumping element.
2. The piezoelectric pumping mechanism of claim 1, wherein the at least one electrical connector is coupled to the at least one stack of piezoelectric material through an opening within a bottom of the pump body.
3. The piezoelectric pumping mechanism of claim 1, wherein the at least one stack of piezoelectric material is a ceramic-based piezoelectric material having an asymmetric crystalline structure.
4. The piezoelectric pumping mechanism of claim 1, wherein the at least one pumping element includes 1 to 100 pumping elements.
5. The piezoelectric pumping mechanism of claim 1, wherein an upper surface of the at least one stack of piezoelectric material abuts a lower surface of the amplifying element, and an upper surface of the amplifying element abuts a lower surface of the plunger.
6. The piezoelectric pumping mechanism of claim 1 further comprising a valve positioned along each of the at least one pressurized fluid delivery lines, the valve configured to control when pressurized fluid within the fluid volume is released from the fluid volume.

7. The piezoelectric pumping mechanism of claim 1, wherein the at least one stack of piezoelectric material is configured to expand within the body of the at least one pumping element when a voltage is provided to the at least one electrical connector coupled to the at least one stack of piezoelectric material, thereby causing movement of the amplifying element and the plunger to pressurize fluid in the fluid volume.

8. A pumping element comprising:

a body, at least one stack of piezoelectric material, an amplifying element, a plunger, and a fluid volume; the plunger being positioned above the amplifying element and the at least one stack of piezoelectric material and the fluid volume being positioned between the body of the pumping element and a top of the plunger; and

the fluid volume being configured to receive a supply of fluid; the at least one stack of piezoelectric material being configured to receive an electrical voltage and expand within the body in response thereto to thereby pressurize the supply of fluid in the fluid volume.

9. The pumping element of claim 8, wherein the amplifying element is positioned between the at least one stack of piezoelectric material and the plunger.

10. The pumping element of claim 9, wherein the amplifying element abuts against an uppermost extent of piezoelectric material and a lowermost surface of plunger such that the plunger is seated on an upper surface of amplifying element above the at least one stack of piezoelectric material.

11. The pumping element of claim 8, further comprising an inlet and an outlet both of which are fluidly coupled to the fluid volume such that the supply of fluid is received by the fluid volume from the inlet and pushed out of the fluid volume through the outlet.

12. The pumping element of claim 8, wherein the at least one stack of piezoelectric material is a ceramic-based piezoelectric material having an asymmetric crystalline structure.

13. The pumping element of claim 8, wherein the at least one stack of piezoelectric material expanding within the body causes movement of the amplifying element and the plunger to pressurize fluid in the fluid volume.

14. The pumping element of claim 8, wherein an electrical wire is coupled to or embedded into the at least one stack of piezoelectric material and is configured to receive the electrical voltage.
15. The pumping element of claim 8, wherein the pumping element is configured to achieve within the fluid volume a set pressure corresponding to when fluid leaves the fluid volume.

AMENDED CLAIMS**received by the International Bureau on 04 November 2020 (04.11.2020)**

1. A piezoelectric pumping mechanism, comprising:
a pump body;
at least one pumping element housed within the pump body, the at least one pumping element including a body, at least one stack of piezoelectric material, an amplifying element, a plunger, and a fluid volume;
at least one electrical connector coupled to the at least one stack of piezoelectric material within the at least one pumping element; and
at least one pressurized fluid delivery line fluidly coupled to the fluid volume of the at least one pumping element, wherein the plunger is positioned above the amplifying element and the at least one stack of piezoelectric material and the fluid volume is positioned between a top of the plunger and the body of the at least one pumping element.
2. The piezoelectric pumping mechanism of claim 1, wherein the at least one electrical connector is coupled to the at least one stack of piezoelectric material through an opening within a bottom of the pump body.
3. The piezoelectric pumping mechanism of claim 1, wherein the at least one stack of piezoelectric material is a ceramic-based piezoelectric material having an asymmetric crystalline structure.
4. The piezoelectric pumping mechanism of claim 1, wherein the at least one pumping element includes 1 to 100 pumping elements.
5. The piezoelectric pumping mechanism of claim 1, wherein an upper surface of the at least one stack of piezoelectric material abuts a lower surface of the amplifying element, and an upper surface of the amplifying element abuts a lower surface of the plunger.
6. The piezoelectric pumping mechanism of claim 1 further comprising a valve positioned along each of the at least one pressurized fluid delivery lines, the valve configured to control when pressurized fluid within the fluid volume is released from the fluid volume.
7. The piezoelectric pumping mechanism of claim 1, wherein the at least one stack of piezoelectric material is configured to expand within the body of the at least one pumping element when a voltage is provided to the at least one electrical connector coupled to the at least one stack of piezoelectric material, thereby causing movement of the amplifying element and the plunger to pressurize fluid in the fluid volume.
8. A pumping element comprising:

a body, at least one stack of piezoelectric material, an amplifying element, a plunger, and a fluid volume; the plunger being positioned above the amplifying element and the at least one stack of piezoelectric material and the fluid volume being positioned between and defined by the body of the pumping element and a top of the plunger; and

the fluid volume being configured to receive a supply of fluid; the at least one stack of piezoelectric material being configured to receive an electrical voltage and expand within the body in response thereto to thereby pressurize the supply of fluid in the fluid volume.

9. The pumping element of claim 8, wherein the amplifying element is positioned between the at least one stack of piezoelectric material and the plunger.

10. The pumping element of claim 9, wherein the amplifying element abuts against an uppermost extent of piezoelectric material and a lowermost surface of plunger such that the plunger is seated on an upper surface of amplifying element above the at least one stack of piezoelectric material.

11. The pumping element of claim 8, further comprising an inlet and an outlet both of which are fluidly coupled to the fluid volume such that the supply of fluid is received by the fluid volume from the inlet and pushed out of the fluid volume through the outlet.

12. The pumping element of claim 8, wherein the at least one stack of piezoelectric material is a ceramic-based piezoelectric material having an asymmetric crystalline structure.

13. The pumping element of claim 8, wherein the at least one stack of piezoelectric material expanding within the body causes movement of the amplifying element and the plunger to pressurize fluid in the fluid volume.

14. The pumping element of claim 8, wherein an electrical wire is coupled to or embedded into the at least one stack of piezoelectric material and is configured to receive the electrical voltage.

15. The pumping element of claim 8, wherein the pumping element is configured to achieve within the fluid volume a set pressure corresponding to when fluid leaves the fluid volume.

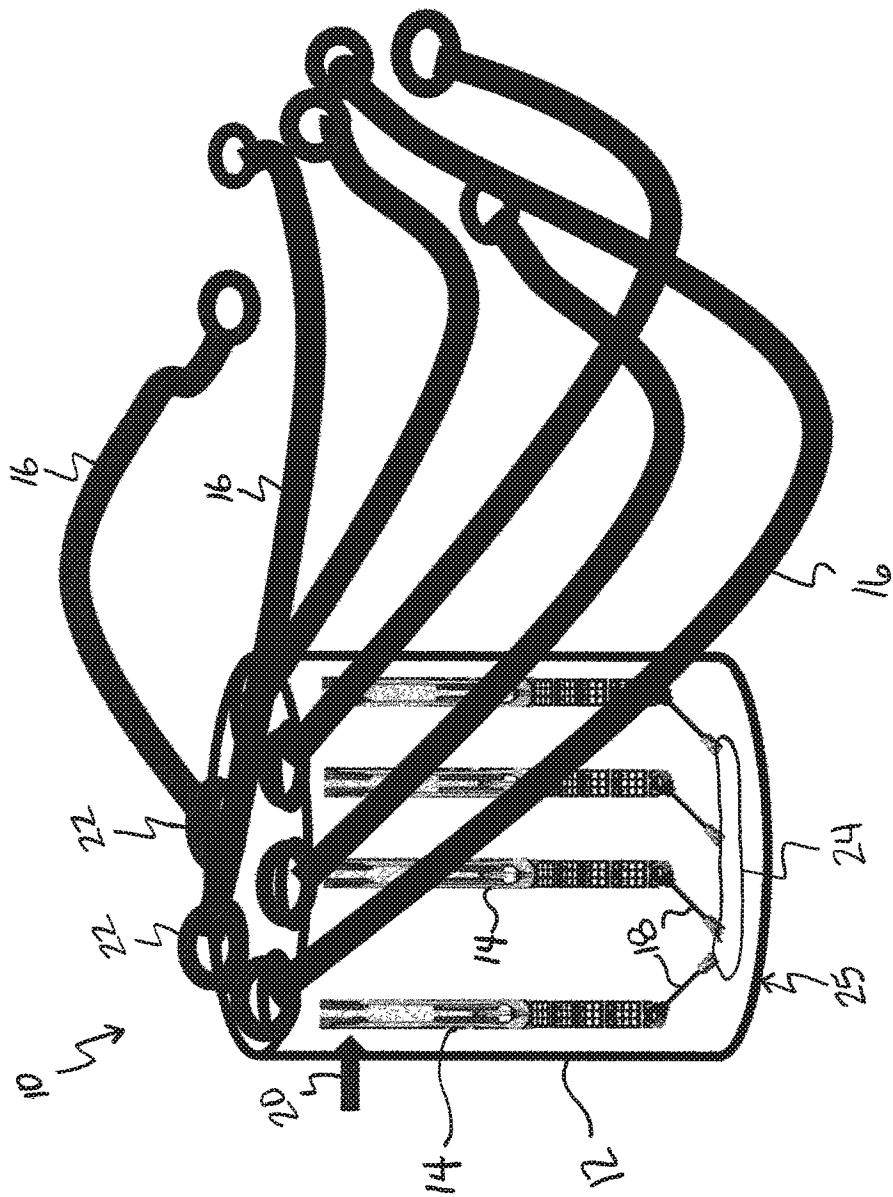
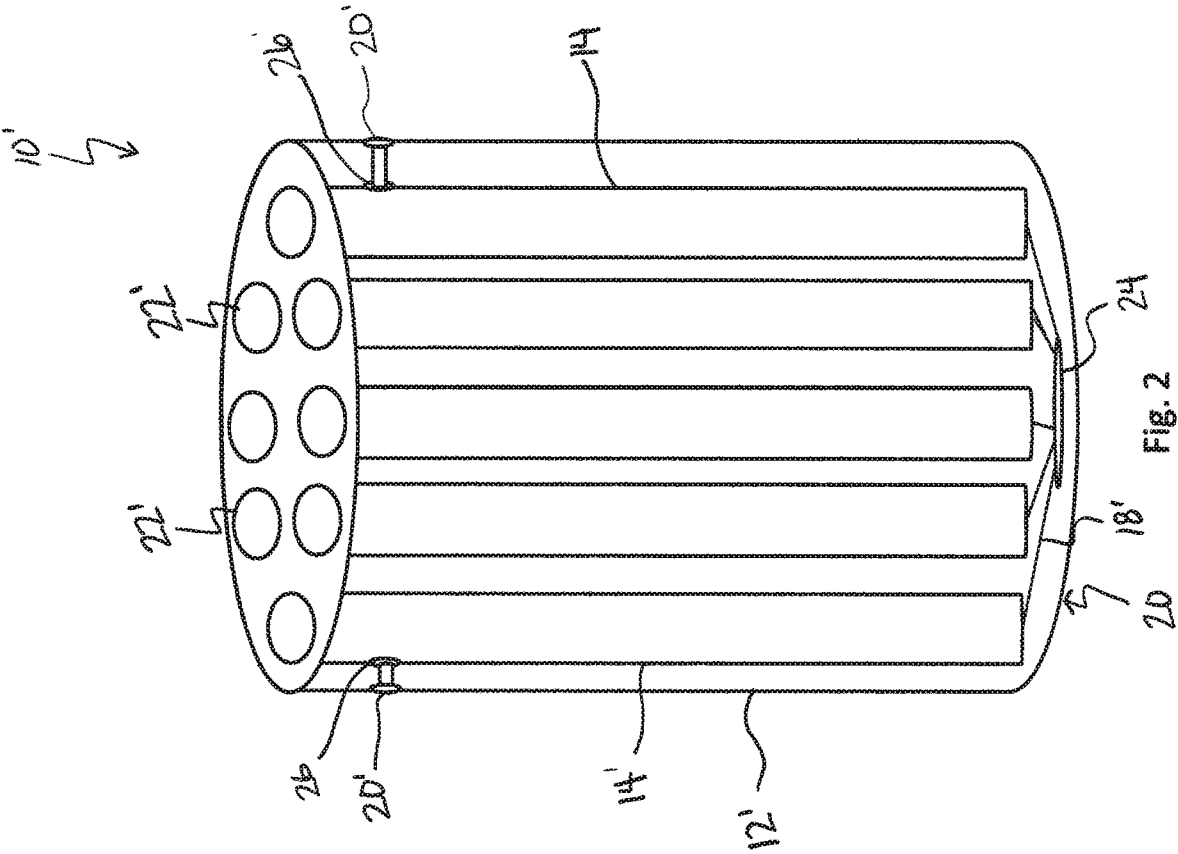


Fig. 1



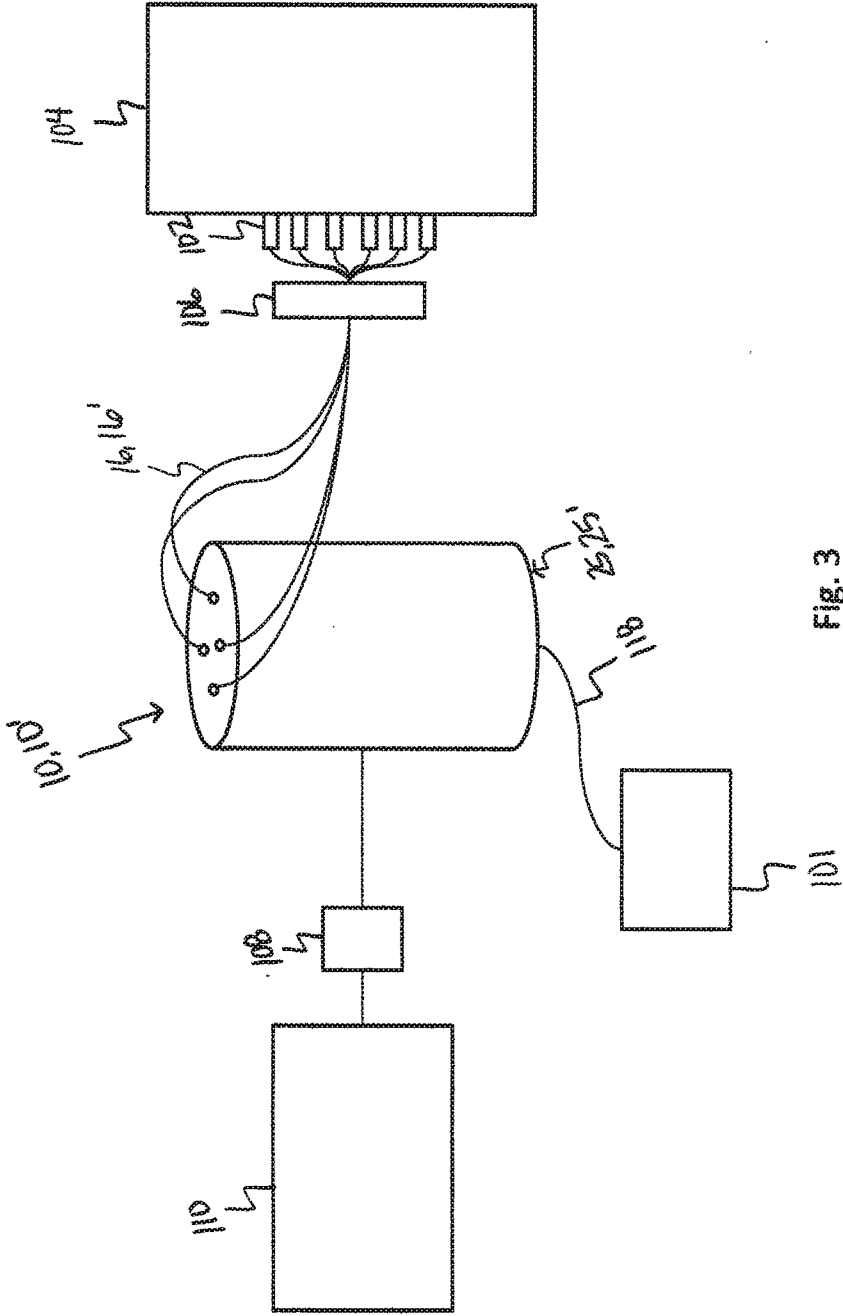


FIG. 3

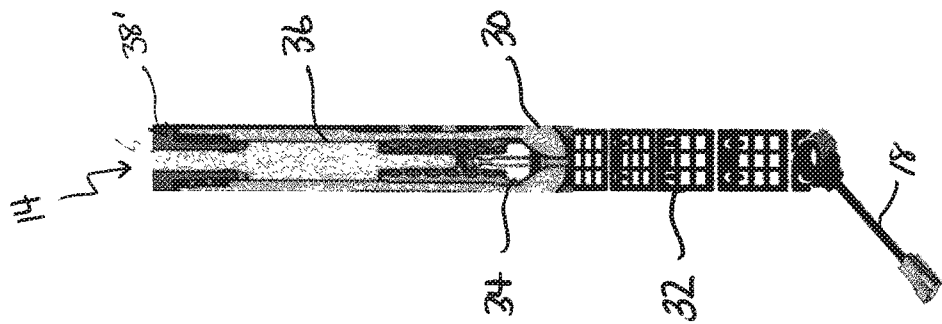


Fig. 4B

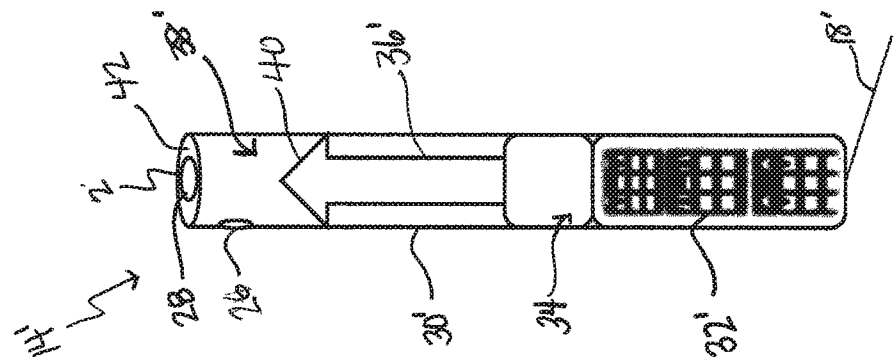


Fig. 4A

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2020/037259

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F04B 17/00; F04B 17/03; F04B 19/00; F04B 43/00; F04B 43/04 (2020.01)

CPC - F04B 17/003; F04B 17/00; F04B 17/03; F04B 19/00; F04B 43/00; F04B 43/009; F04B 43/04; F04B 43/043; F04B 43/046 (2020.08)

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)

see Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

see Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

see Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/0037471 A1 (KUZNETSOV) 06 February 2014 (06.02.2014) entire document	1-15
A	US 2013/0343918 A1 (FRIPP et al) 26 December 2013 (26.12.2013) entire document	1-15

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

06 August 2020

Date of mailing of the international search report

28 AUG 2020

Name and mailing address of the ISA/US

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