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(54) Title: CENTRIFUGAL PUMP

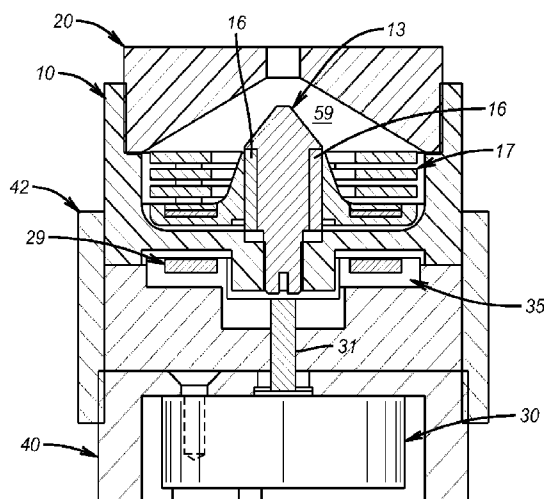


**FIG. 8**

(57) Abstract: The invention is directed to a multi-disk centrifugal pump suitable for pumping fluids, including biocompatible fluids, such as blood. The design of the pump components is optimized to reduce or eliminate the probability of clotting and hemolysis when pumping blood, and to be energy efficient and resistant to physical shock for portable applications.

**TITLE: CENTRIFUGAL PUMP**

**INVENTORS: BRIJESH GILL, CHARLES S. COX, JR., KEVIN R. AROOM**

#### PRIORITY INFORMATION

**[0001]** This application claims the benefit of U.S. Provisional Application No. 61/074,053, filed on June 19, 2008.

#### FIELD OF THE INVENTION

**[0002]** The invention is directed to a multi-disk centrifugal pump suitable for pumping fluids, including biocompatible fluids, such as blood. The design of the pump components is optimized to reduce or eliminate the probability of clotting and hemolysis when pumping blood, and to be energy efficient and resistant to physical shock for portable applications.

#### GOVERNMENT RIGHTS

**[0003]** This invention was made with United States Government support under Grant No. W81XWH-07-1-0496, awarded by the United States Army. The United States Government has certain rights in the invention.

#### BACKGROUND OF THE INVENTION

**[0004]** Existing centrifugal blood pumps are large and waste electrical energy. Accordingly, they are not well suited for portable use. Existing ventricular assist devices (“VADs”) do not scale down in size so that they can not be used in the pediatric application. These pumps have elaborate configurations of the inlet and outlet geometries to reduce turbulence, in order to provide high flow at acceptable rates of hemolysis. These complex features, when scaled down in size, no longer act to reduce turbulence but instead act to increase shear forces. The inlet and outlet of this pump design have a wide, continuous (uninterrupted) cross section without complex surface features, allowing the pump to be scaled down in size while still retaining acceptable performance

#### DETAILED DESCRIPTION OF THE DRAWINGS

**[0005]** Figure 1a is a top view of the bottom housing of a preferred embodiment of the invention.

**[0006]** Figure 1b is a side view of the bottom housing of a preferred embodiment of the invention.

[0007] Figure 1c is a bottom view of the bottom housing of a preferred embodiment of the invention.

[0008] Figure 1d is an isometric view of the bottom housing of a preferred embodiment of the invention.

[0009] Figure 2a is a top view of the top housing of a preferred embodiment of the invention.

[0010] Figure 2b is a side view of the top housing of a preferred embodiment of the invention.

[0011] Figure 2c is a bottom view of the top housing of a preferred embodiment of the invention.

[0012] Figure 2d is an isometric view of the top housing of a preferred embodiment of the invention.

[0013] Figure 3 is a cross sectional view of a preferred embodiment of the invention.

[0014] Figure 4a is a top view of the rotor of a preferred embodiment of the invention.

[0015] Figure 4b is a side view of the rotor of a preferred embodiment of the invention.

[0016] Figure 4c is a bottom view of the rotor of a preferred embodiment of the invention.

[0017] Figure 4d is an isometric view of the rotor of a preferred embodiment of the invention.

[0018] Figure 5 is an exploded side view of a preferred embodiment of the invention.

[0019] Figure 6 is a side view of a preferred embodiment of the invention.

[0020] Figure 7a is a side view of a single piece rotor suitable for use with the present invention.

[0021] Figure 7b is a bottom view of the single piece rotor shown in Figure 7a.

[0022] Figure 7c is an isometric view of the single piece rotor shown in Figure 7a.

[0023] Figure 8 is a side cross sectional view of the embodiment of the invention shown in Figure 8a.

[0024] Figure 9a is a bottom view of another embodiment of a rotor suitable for use with the present invention.

[0025] Figure 9b is an isometric view of the rotor shown in Figure 9a.

[0026] Figure 9c is an exploded side view of the rotor shown in Figure 9a.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0027] A preferred embodiment of the invention is directed to a Tesla centrifugal pump for pumping biocompatible fluids, such as blood. In one preferred embodiment, the pump is made from biocompatible materials, thereby making it suitable for implantation in a patient, including in a human patient. In another preferred embodiment, the pump is made from non-biocompatible materials and coated with a biocompatible material coating. The Tesla design was chosen because it creates less turbulence and is less susceptible to cavitation than traditional bladed centrifugal pumps. Therefore, the Tesla design should produce less hemolysis. Additionally, the bladeless geometry of the Tesla impeller allows the design to be scaled down in size while less susceptible to performance variability from the dominance of viscous forces at a small scale.

[0028] A preferred embodiment of the invention comprises a pump housing bottom **10**, as shown in Figures 1a-1d, 7b and 9a. In a preferred embodiment, the pump housing bottom is circular. A preferred embodiment of the invention comprises a post **12** located in the center of the top surface of the pump housing bottom and protruding outward. The post defines a longitudinal axis. In a preferred embodiment, the post is integrally formed with the pump housing bottom. In a preferred embodiment, the pump housing bottom is made from a biocompatible material.

[0029] A preferred embodiment of the invention further comprises a first sheath **14** mounted over the post **12**, as shown in Figures 3 and 5. In a preferred embodiment, the first sheath is made from a fluoro carbon polymer, such as polytetrafluoroethylene ("PTFE"). In a preferred embodiment, the invention further comprises a second sheath **16** mounted over the first sheath, as shown in Figure 3. In a preferred embodiment, the second sheath is made from stainless steel. In a preferred embodiment, the first sheath comprises a thrust bearing.

[0030] A preferred embodiment of the invention further comprises a pump housing top **20**, as shown in Figures 2a-2d. The pump housing top and bottom collectively form the pump housing. In a preferred embodiment, the pump housing top is circular. In another preferred embodiment, as shown in Figure 8, the pump housing top comprises a conically shaped interior **59**. This conically shaped interior reduces the rapid acceleration of fluid as it enters this pump.

**[0031]** The pump housing top comprises an inlet conduit **22** centrally located in the pump housing. As shown in Figure 5, the pump housing top is mounted on the pump housing bottom to form the pump housing. In a preferred embodiment, the inlet conduit is oriented in substantial alignment with the longitudinal axis. In another preferred embodiment, the inlet conduit is centered over the post. In a preferred embodiment, no vanes or diffusers are present inside the inlet conduit. In a preferred embodiment, the inlet conduit permits fluid to enter the housing along an axis that is substantially parallel to the longitudinal axis. In a preferred embodiment, the inlet conduit **22** is circular.

**[0032]** The pump housing top further comprises an outlet conduit **24** located in an outer radial region of the pump housing. In a preferred embodiment, the outlet can be integrally formed as part of the pump housing bottom. In a preferred embodiment, the outlet conduit **24** is circular. In another preferred embodiment, the orientation of the inlet conduit is substantially perpendicular to the orientation of the outlet conduit. In another preferred embodiment, the outlet conduit extends beyond the outer radial edge of the pump housing top. In a preferred embodiment, the pump housing top is made from a biocompatible material. In a preferred embodiment, the inlet conduit and the outlet conduit are integrally formed in the pump housing top.

**[0033]** A preferred embodiment of the invention further comprises a rotatably mounted pump rotor, **18**, as shown in Figures 3 and 4a-4d. The rotor design used in a preferred embodiment of the invention is commonly known in the centrifugal pump arts as a “Tesla” design. In a preferred embodiment, the rotor comprises multiple disks **15** stacked in a longitudinally aligned configuration as shown in Figures 3 and 4d. In a preferred embodiment, the rotor comprises four disks. In a preferred embodiment, the rotor is made from a polycarbonate material. In a preferred embodiment, the rotor comprises a central channel **21**, as shown in Figure 4d. As shown in Figure 3, the rotor is positioned such that the second sheath **16** protrudes through the central channel.

**[0034]** In a preferred embodiment, a cap **13** is mounted on the top central region of the rotor, as shown in Figure 8. The cap holds the rotor in a fixed axial position, thereby preventing lift and subsequent decoupling.

**[0035]** In one preferred embodiment, the rotor disk diameters are substantially equivalent to each other, as shown in Figure 4b. In another preferred embodiment, the top rotor disk has a

smaller diameter than all rotor disks below it and the second rotor disk from the top has a smaller diameter than all rotor disks below it, as shown in Figure 7a. In this embodiment, the outer edges of the top three rotor discs are beveled, as shown in Figure 7a. The embodiment of the invention shown in Figures 7a and 7c provides a more gradual acceleration of the fluid in the pump, than does the embodiment shown in Figure 4b. This more gradual acceleration reduces the shear forces caused by elevated velocity gradients.

**[0036]** The term “third of said disk” is used herein to refer to a one third slice of a disk extending from the radial center to the disk to the outer periphery of the disk and comprising a 120 degree arc length of the disk. In another preferred embodiment, the top disk has at least two diametrically opposed studs **46** protruding downward and each remaining disk comprises at least one hole aligned with and positioned to receive each stud, thereby aligning all of the disks, as shown in Figure 9c. In another preferred embodiment, each disk comprises at least three spacers **47**, each positioned in a separate third of said disk, as shown in Figure 9c.

**[0037]** In a preferred embodiment, the spacing between each disk is greater than or equal to 0.02”. In a preferred embodiment, it is desirable to make the disks as thin as possible, while maintaining the desired structural integrity for pumping biocompatible fluids. In a preferred embodiment, the disk thickness is greater than or equal to 0.03”. Thinner disks allow for greater total surface area of the rotor at the cost of reducing the strength of the disks and increasing the risk of vibration or breakage. A larger moment of inertia would require more energy to turn, hence reducing motor battery life. For pumps of constant overall volute volume, thicker disks reduce overall priming volume of the pump.

**[0038]** In one preferred embodiment, the disks are integrally formed as one piece of the pump, as shown in Figure 7a. This one piece or “monolithic” construction provides increased strength to the rotor. This monolithic construction also avoids the vibration or jitter problems associated with multipiece stacked rotor designs of prior art Tesla centrifugal pumps. Such mechanical vibration is particularly undesirable in a pump intended to pump biocompatible fluids, such as blood, because higher rates of hemolysis are produced and energy consumption is increased. Additionally, the monolithic construction is more resistant to external forces, including random vibrations and shocks, than a multipiece rotor design. This attribute further reduces the probability of hemolysis when pumping blood with this pump.

[0039] In a preferred embodiment, the rotor has an outer diameter that is less than 1.75", and an inner diameter that is less than 1.25". In another preferred embodiment, the inner diameter is at least 0.7" and the outer diameter is at least 1.3".

[0040] In order to eliminate the need to create a shaft seal for power transfer, a preferred embodiment of the invention comprises a magnetic coupling system. In a preferred embodiment, this coupling comprises a first set of magnets, comprising an even number of magnets **17** embedded in the bottom of the rotor in a circular fashion or arrangement. In another preferred embodiment, the first set of magnets comprises two magnets embedded in the bottom of the rotor, as shown in Figure 3. In a preferred embodiment, each of the magnets in a set is substantially equal in mass to each of the other magnets in the set. In another preferred embodiment, the first set of magnets contains eight magnets, and the rotor bottom is configured to hold eight magnets, as shown in Figures 7b and 9a. In another preferred embodiment, the magnets are sealed with a cap **50** in the bottom of the rotor, as shown in Figure 9c.

[0041] In a preferred embodiment, a second set of magnets **29** identical in number and geometry to the first set is operatively coupled to a motor **30** located outside the pump housing, as shown in Figure 8. In a preferred embodiment, the motor is located in a motor housing **40**, as shown in Figure 8. In a preferred embodiment, the motor housing is connected to the bottom housing by a coupler **42**, as shown in Figure 8. In a preferred embodiment, the motor comprises a shaft **31** that is coupled to the second set of magnets, such that rotation of the shaft causes rotation of the second set of magnets, as shown in Figure 8. In a preferred embodiment, the shaft comprises at least two fins.

[0042] In a preferred embodiment, the second set of magnets are mounted in a magnet housing **35**, as shown in Figure 8. The magnets of opposite polarity are attracted to each other, and one set of magnets tries to maintain its position relative to the other set, creating a magnetic coupling through the housing. This coupling provides effective torque transfer to the rotor. This design eliminates the need for a shaft seal. In a preferred embodiment, the motor is battery powered. In another preferred embodiment, the motor is a DC flat motor.

[0043] In a preferred embodiment, this pump is not designed to replace the cardiac output capacity of an adult's heart. Such high flow requirements would demand power levels that are neither suitable nor necessary for mobile use. In one embodiment, a target flow rate for this pump is approximately 1L/min at a pressure head of 120 mm Hg.

[0044] In a preferred embodiment, the rotor further comprises at least two washout fins 19 on the bottom of the rotor, as shown in Figure 4c. These washout fins keep pumped fluid moving in an area where it could otherwise become stagnant and begin to clot.

[0045] In a preferred embodiment, the central bearing is quite wide by comparison to other pump designs. This allows external perturbing forces to be distributed across a much larger area than with other pumps, giving greater resistance to external shock/vibration. The cross section of the overall central spindle is a segment of a cone (frustum) with the smaller diameter pointed into the inlet stream. This allows both a more gradual acceleration of the fluid and less resistance to flow through the inlet, reducing the overall pressure drop across the pump and reducing hemolysis.

[0046] Those skilled in the art of pumping blood will appreciate that a tradeoff occurs in the design of a blood pump between keeping the fluid moving to reduce the chances of clot (thrombus) formation within the pump. It is important to avoid introducing areas of excessive shear rate that can cause the destruction of red blood cells (hemolysis). This tradeoff manifests itself in the design process through selecting proper clearances between the rotor and the housing.

[0047] The differences in centrifugal pump disk support structure design lie in the location and shape of the support. The tradeoff between hemolysis and thrombosis is important. Disk supports that are too close to the center of the rotor could produce eddies where stagnation could occur, causing thrombi formation. Alternatively a set of disk supports on the outermost edge may create an unacceptably high level of trauma to blood cells due to the increased velocity present at the outer radii of the disks. A teardrop shaped disk support structure that is narrow near the center and widens as it moves radially outward acts as an effective shape that eliminates areas of stagnation while allowing smooth movement around it, limiting both hemolysis and thrombosis.

[0048] An important design criterion for a pediatric ventricular assist device ("VAD") is the priming volume of the device, which cannot use a significant percentage of the infant's overall blood volume simply to fill up the pump. In a preferred embodiment, this pump minimizes priming volumes in two ways: first, the inter-disc spacing is reduced to just above the point where hemolysis begins to increase (~1 mm, a function of blood viscosity and surface roughness of the rotor). In a preferred embodiment, the overall rotor is elevated off the bottom

of the housing in order to prevent excessive hemolysis. In another preferred embodiment, the fluid encounters disks of successively increasing diameter, as it flows from inlet to outlet, as shown in Figure 7.

**[0049]** The foregoing disclosure and description of the inventions are illustrative and explanatory. Various changes in the size, shape, and materials, as well as in the details of the illustrative construction and/or an illustrative method may be made without departing from the spirit of the invention.

## WHAT IS CLAIMED IS:

1. A centrifugal pump comprising:
  - a. a pump housing bottom comprising a top surface;
  - b. a post located in the center of the top surface of the pump housing bottom and protruding outward to define a longitudinal axis;
  - c. a first sheath mounted over the post;
  - d. a second sheath mounted over the first sheath;
  - e. a pump housing top mounted on the pump housing bottom, wherein said pump housing top and bottom collectively form the pump housing, and comprising an inlet conduit centrally located in the pump housing;
  - f. an outlet conduit located in an outer radial region of the pump housing;
  - g. a rotatably mounted pump rotor comprising a central channel and positioned such that the second sheath protrudes through the central channel;
  - h. a first set of magnets, comprising an even number of magnets, embedded in the bottom of the rotor; and
  - i. a second set of magnets comprising the same number of magnets as the first set of magnets mounted outside the pump housing.
2. The centrifugal pump of claim 1, wherein the post is integrally formed with the pump housing bottom.
3. The centrifugal pump of claim 1, wherein the pump housing bottom is made from a biocompatible material.
4. The centrifugal pump of claim 1, wherein the first sheath is made from a fluorocarbon polymer.
5. The centrifugal pump of claim 1, wherein the second sheath is made from stainless steel.
6. The centrifugal pump of claim 1, wherein the inlet conduit is oriented in substantial alignment with the longitudinal axis
7. The centrifugal pump of claim 1, wherein the inlet conduit is centered over the post.
8. The centrifugal pump of claim 1, wherein the inlet conduit is circular.

9. The centrifugal pump of claim 1, wherein the outlet conduit is circular.
10. The centrifugal pump of claim 1, wherein the orientation of the inlet conduit is substantially perpendicular to the orientation of the outlet conduit.
11. The centrifugal pump of claim 1, wherein the outlet conduit extends beyond the outer radial edge of the pump housing top.
12. The centrifugal pump of claim 1, wherein the pump housing top is made from a biocompatible material.
13. The centrifugal pump of claim 1, wherein the inlet conduit and the outlet conduit are integrally formed in the pump housing top.
14. The centrifugal pump of claim 1, wherein the rotor comprises multiple disks stacked in a longitudinally aligned configuration.
15. The centrifugal pump of claim 14, wherein the rotor comprises four disks.
16. The centrifugal pump of claim 14, wherein the disks have diameters that are substantially equivalent to each other.
17. The centrifugal pump of claim 15, wherein the top disk has a smaller diameter than all discs below it.
18. The centrifugal pump of claim 17, wherein the second disk from the top has a smaller diameter than all disks below it.
19. The centrifugal pump of claim 18, wherein the outer edges of the top three disks are beveled.
20. The centrifugal pump of claim 13, wherein the pump housing top comprises a conically shaped interior.
21. The centrifugal pump of claim 13, wherein the top disk has at least two diametrically opposed studs protruding downward and each remaining disk comprises at least one hole aligned with and positioned to receive each stud, thereby aligning said disks
22. The centrifugal pump of claim 13, wherein each disk comprises at least three spacers each of said spacers being positioned in a separate third of said disk.

23. The centrifugal pump of claim 1, wherein the rotor is made from a polycarbonate material.
24. The centrifugal pump of claim 13, wherein the spacing between each disk is at least 0.02 inches.
25. The centrifugal pump of claim 13, wherein the disk thickness is at least 0.03 inches.
26. The centrifugal pump of claim 13, wherein the rotor is integrally formed as one piece of the pump.
27. The centrifugal pump of claim 1, wherein the rotor has an outer diameter that is less than 1.75 inches, and an inner diameter that is less than 1.25 inches.
28. The centrifugal pump of claim 1, wherein the magnets are embedded in the bottom of the rotor in a circular arrangement.
29. The centrifugal pump of claim 1, wherein the rotor comprises at least two washout fins.
30. The centrifugal pump of claim 1, wherein the second set of magnets are arranged in the same geometry as the first set of magnets.
31. The centrifugal pump of claim 1, further comprising a motor operatively coupled to the second set of magnets.
32. The centrifugal pump of claim 31, wherein the motor comprises a shaft that is coupled to the second set of magnets, such that rotation of the shaft causes rotation of the second set of magnets.
33. The centrifugal pump of claim 1, further comprising a multiplicity of washout fins mounted on the bottom of the rotor.

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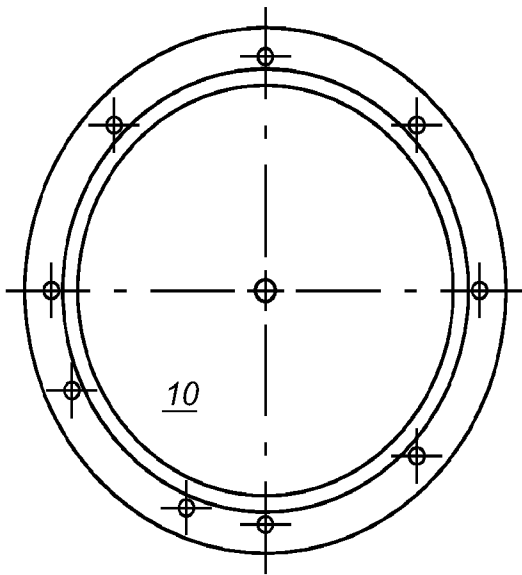


**FIG. 1a**

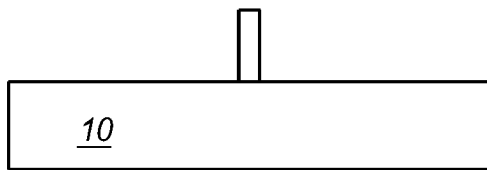


**FIG. 1b**

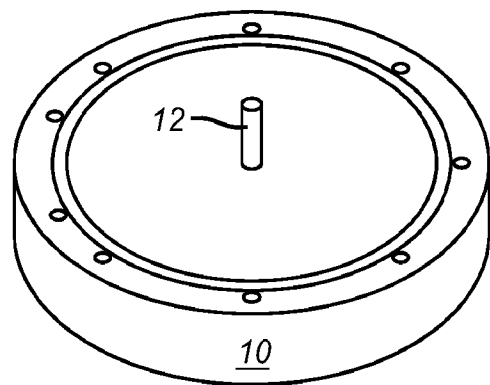


**FIG. 1d**

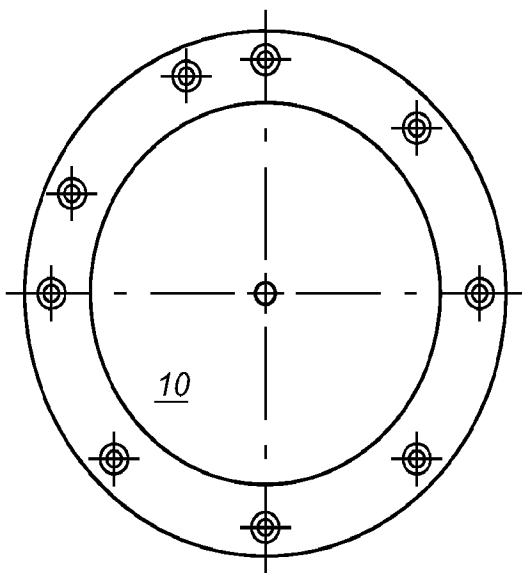


**FIG. 1c**

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2/8

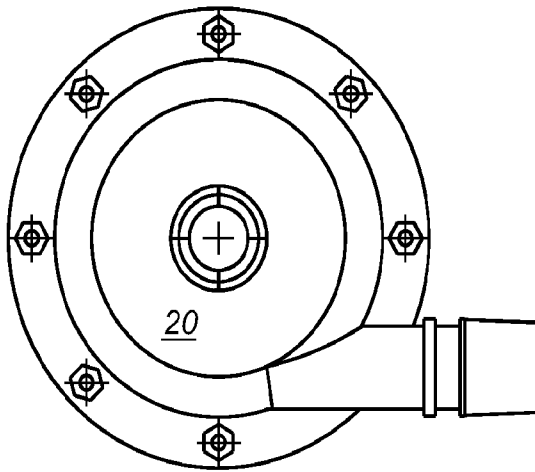


**FIG. 2a**

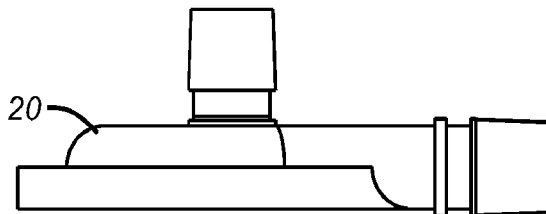


**FIG. 2b**

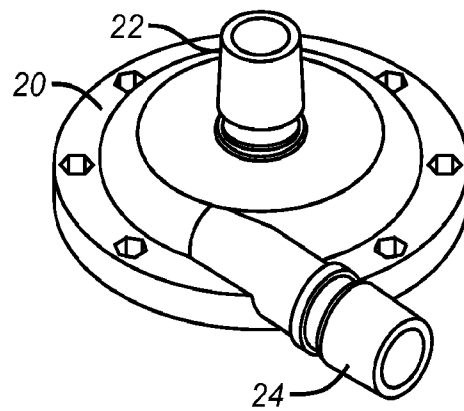


**FIG. 2d**

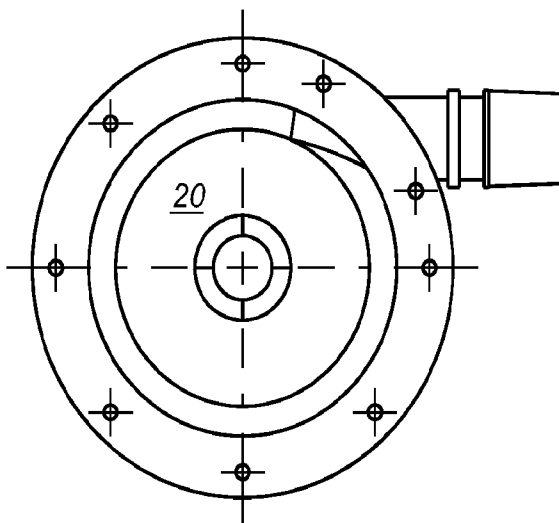


**FIG. 2c**

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3/8

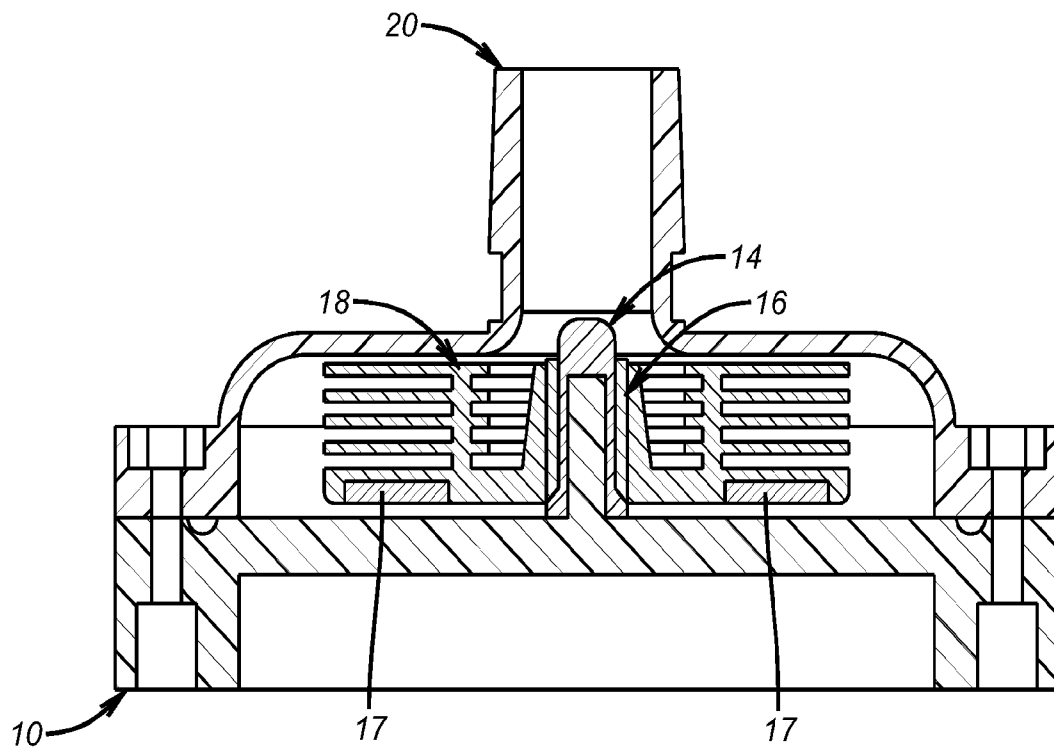


**FIG. 3**

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4/8

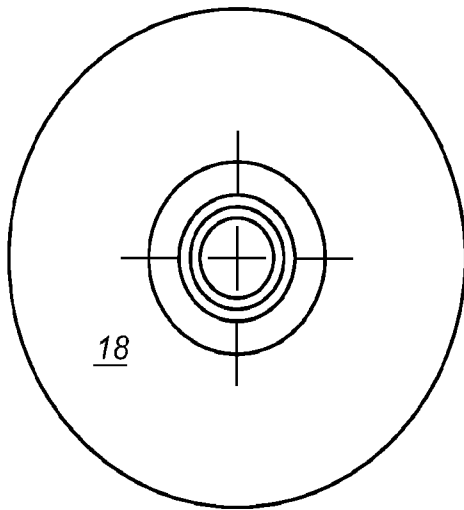


**FIG. 4a**

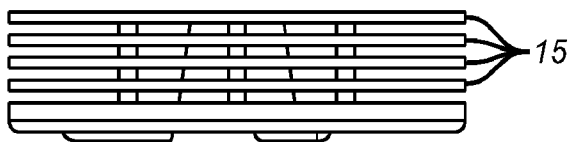


**FIG. 4b**

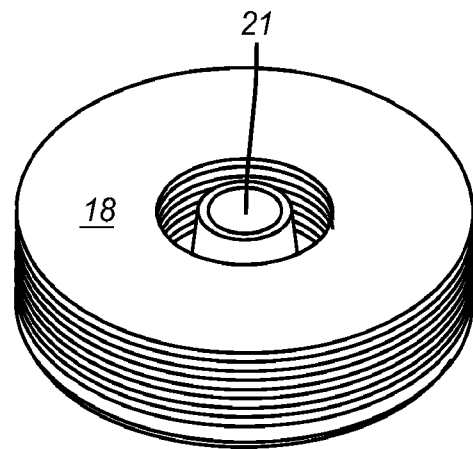


**FIG. 4d**

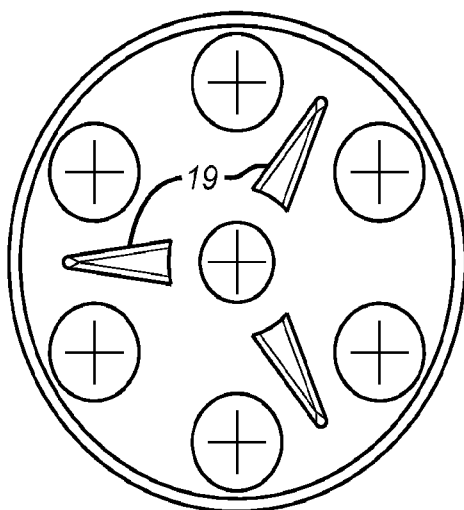


**FIG. 4c**

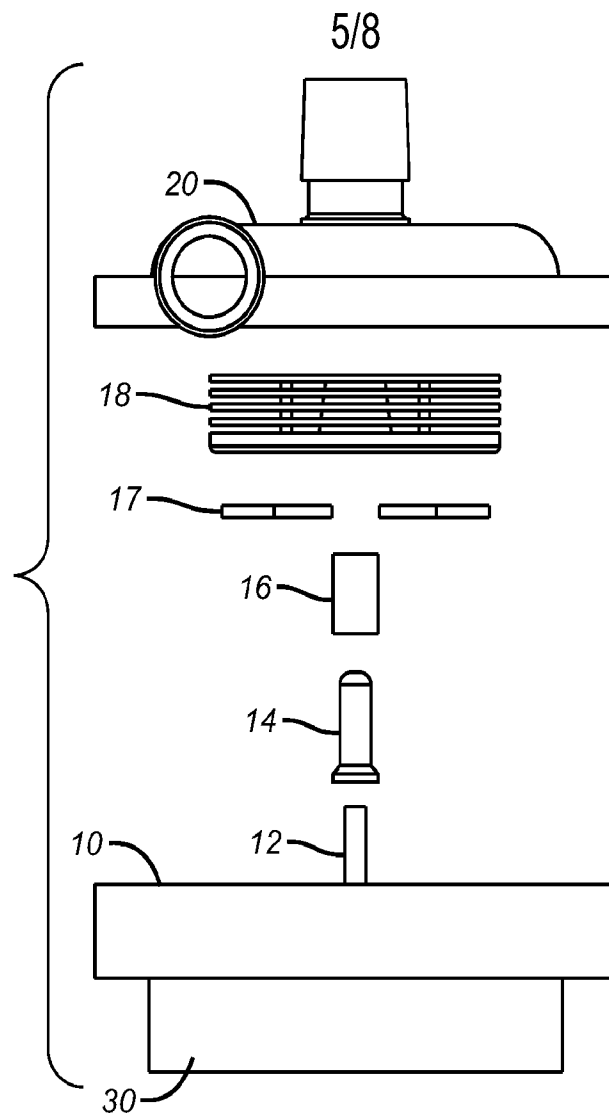


**FIG. 5**

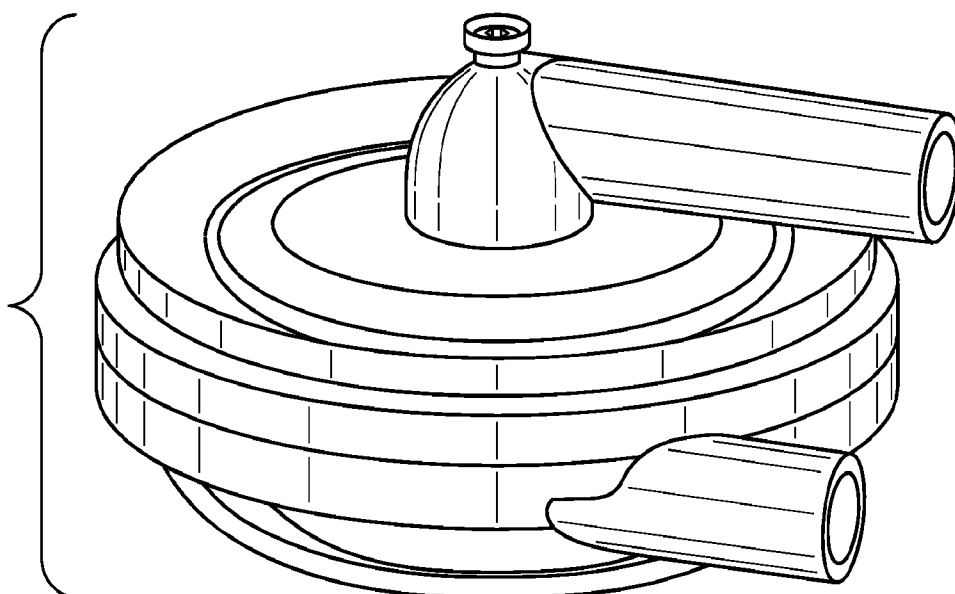


**FIG. 6**

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6/8

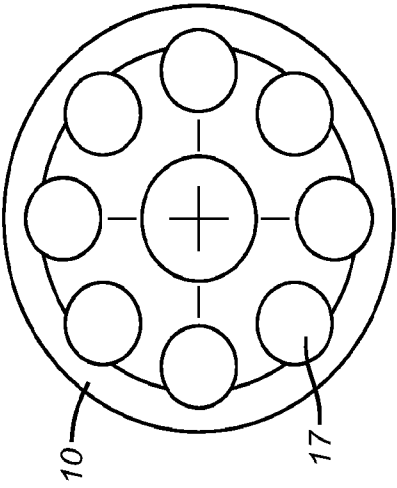


**FIG. 7b**

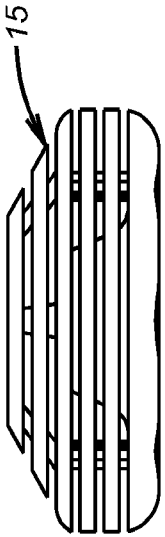


**FIG. 7a**

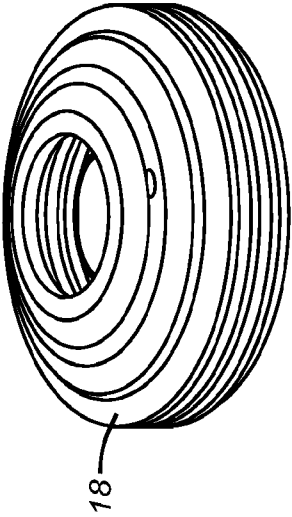


**FIG. 7c**



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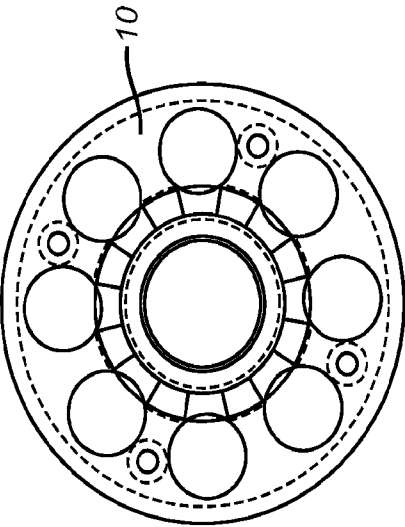


**FIG. 9a**

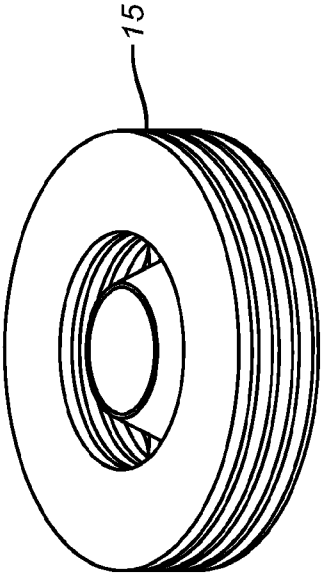


**FIG. 9b**

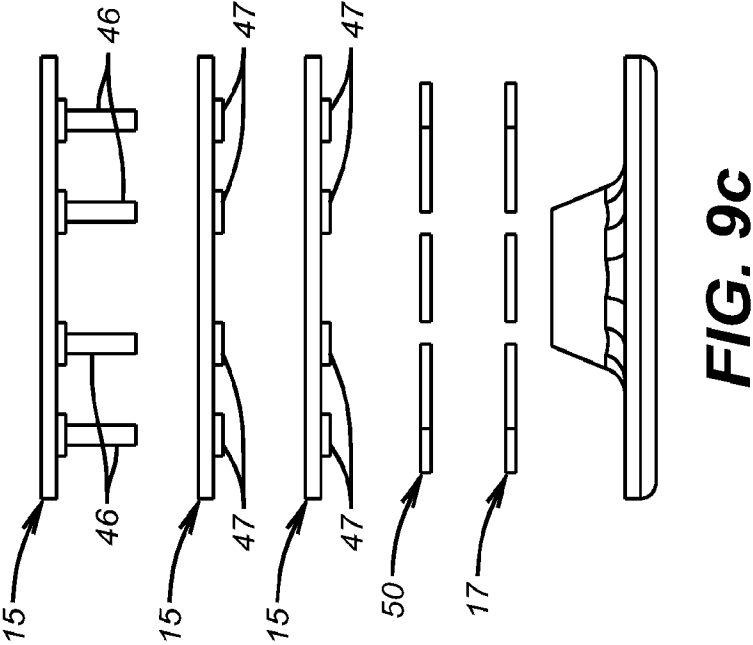


**FIG. 9c**

# INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2009/047320

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F04B 17/00 (2009.01)

USPC - 417/409

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)

IPC(8) - F04B 17/00 (2009.01)

USPC - 310/90.5; 415/90; 417/356, 405, 409, 410.1, 423.12

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)

PatBase

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|-----------|------------------------------------------------------------------------------------|-----------------------|
| Y         | US 2007/0280841 A1 (LAROSE et al) 06 December 2007 (06.12.2007) entire document    | 1-33                  |
| Y         | US 2003/0135086 A1 (KHAW et al) 17 July 2003 (17.07.2003) entire document          | 1-33                  |
| Y         | US 3,802,804 A (ZIMMERMANN) 09 April 1974 (09.04.1974) entire document             | 2                     |
| Y         | US 2,763,214 A (WHITE) 18 September 1956 (18.09.1956) entire document              | 5                     |
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☐ Further documents are listed in the continuation of Box C. ☐

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Date of the actual completion of the international search

27 July 2009

Date of mailing of the international search report

**06 AUG 2009**

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