



(86) Date de dépôt PCT/PCT Filing Date: 2003/05/30  
(87) Date publication PCT/PCT Publication Date: 2004/01/22  
(45) Date de délivrance/Issue Date: 2009/11/17  
(85) Entrée phase nationale/National Entry: 2004/11/17  
(86) N° demande PCT/PCT Application No.: US 2003/016894  
(87) N° publication PCT/PCT Publication No.: 2004/007048  
(30) Priorité/Priority: 2002/05/30 (US60/384,559)

(51) Cl.Int./Int.Cl. *B01D 65/08* (2006.01),  
*B01D 29/11* (2006.01), *B01D 29/86* (2006.01),  
*B01D 33/00* (2006.01), *B01D 33/68* (2006.01),  
*B01D 61/08* (2006.01), *B01D 61/10* (2006.01),  
*B01D 63/00* (2006.01), *B01D 63/16* (2006.01),  
*C02F 1/00* (2006.01), *C02F 1/38* (2006.01),  
*C02F 1/44* (2006.01)

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(54) Titre : DISPOSITIF ET PROCEDES DE FILTRATION AMELIOREE PAR VORTEX  
(54) Title: VORTEX ENHANCED FILTRATION DEVICE AND METHODS

(57) **Abrégé/Abstract:**

Preferred aspects of the present invention relate to advances in rotating, vortex-enhanced reverse osmosis filtration. More particularly, the filtration device and methods incorporate a rotational drive mechanism adapted to use the flow of pressurized process fluid to cause rotation of a rotor within a housing, thereby creating shear and Taylor vortices in the gap between the rotor and housing. The improvements disclosed herein facilitate continuous use of vortex-enhanced filtration for prolonged periods of time.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property  
Organization  
International Bureau



(43) International Publication Date  
22 January 2004 (22.01.2004)

PCT

(10) International Publication Number  
**WO 2004/007048 A1**

(51) International Patent Classification<sup>7</sup>: **B01D 29/00**,  
33/00, 61/00, 63/00, C02F 1/00, B04B 11/00

(21) International Application Number:  
PCT/US2003/016894

(22) International Filing Date: 30 May 2003 (30.05.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
60/384,559 30 May 2002 (30.05.2002) US

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(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ (utility model), CZ, DE (utility model), DE, DK (utility model), DK, DM, DZ, EC, EE (utility model), EE, ES, FI (utility model), FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK (utility model), SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Declaration under Rule 4.17:**  
— of inventorship (Rule 4.17(iv)) for US only

**Published:**  
— with international search report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: VORTEX ENHANCED FILTRATION DEVICE AND METHODS

(57) Abstract: Preferred aspects of the present invention relate to advances in rotating, vortex-enhanced reverse osmosis filtration. More particularly, the filtration device and methods incorporate a rotational drive mechanism adapted to use the flow of pressurized process fluid to cause rotation of a rotor within a housing, thereby creating shear and Taylor vortices in the gap between the rotor and housing. The improvements disclosed herein facilitate continuous use of vortex-enhanced filtration for prolonged periods of time.

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## VORTEX ENHANCED FILTRATION DEVICE AND METHODS

### Background of the Invention

#### Field of the Invention

5 Preferred aspects of the present invention relate to rotating reverse osmosis (RO) filtration, wherein filtrate flux is enhanced by creation of shear and Taylor vortices in the coaxial gap between a RO membrane and a cylindrical wall of the filtration device.

#### Description of the Related Art

10 One of the most limiting problems in filtration is filter clogging, scientifically described as “concentration polarization.” As a result of the selective permeability properties of the filter, the filtered material that cannot pass through the filter becomes concentrated on the surface of the filter. This phenomenon is clearly illustrated in the case of a “dead-end” filter, such as a coffee filter. During the course of the filtration process, the filtered material (coffee grounds) building up on the filter creates flow resistance to the  
15 filtrate, the fluid (coffee) which can pass through the filter. Consequently, filtrate flux is reduced and filtration performance diminishes.

Various solutions to the problem of concentration polarization have been suggested. These include: increasing the fluid velocity and/or pressure (see e.g., Merin *et al.*, (1980) *J. Food Proc. Pres.* 4(3):183-198); creating turbulence in the feed channels (Blatt *et al.*,  
20 Membrane Science and Technology, Plenum Press, New York, 1970, pp. 47-97); pulsing the feed flow over the filter (Kennedy *et al.*, (1974) *Chem. Eng. Sci.* 29:1927-1931); designing flow paths to create tangential flow and/or Dean vortices (Chung *et al.*, (1993) *J. Memb. Sci.* 81:151-162); and using rotating filtration to create Taylor vortices (see e.g., Lee and Lueptow (2001) *J. Memb. Sci.* 192:129-143 and U.S. Pat. Nos. 5,194,145, 4,675,106,  
25 4,753,729, 4,816,151, 5,034,135, 4,740,331, 4,670,176, and 5,738,792).

Taylor vortices are induced in the gap between coaxially arranged cylindrical members when the inner member is rotated relative to the outer member. Taylor-Couette filtration devices generate strong vorticity as a result of centrifugal flow instability (“Taylor instability”), which serves to mix the filtered material concentrated along the filter back  
30 into the fluid to be processed. Typically, a cylindrical filter is rotated within a stationary outer housing. It has been observed that membrane fouling due to concentration

polarization is very slow compared to dead-end or tangential filtration. Indeed, filtration performance may be improved by approximately one hundred fold.

The use of Taylor vortices in rotating filtration devices has been applied to separation of plasma from whole blood (see e.g., U.S. Pat. No. 5,034,135). For this application, the separator had to be inexpensive and disposable for one-time patient use. Further, these separators only had to operate for relatively short periods of time (e.g., about 45 minutes). Moreover, the separator was sized to accept the flow rate of blood that could reliably be collected from a donor (e.g., about 100 ml/minute). This technology provided a significant improvement to the blood processing industry. The advantages and improved filtration performance seen with rotating filtration systems (Taylor vortices) have not been widely exploited in other areas of commercial fluid separation.

In commercial blood separators, a fluid seal and mechanical bearings prevent the separated plasma from remixing with the concentrated blood cells. Pressure drives the plasma through the seal and mechanical bearings and into a tubing port that leads to a collection container. The rotor spins on an axis defined by two shaft bearings, one on either end. Spinning is induced by a rotating magnetic field and a magnetic coupling. A motor with permanent magnets fixed to its rotor generates the rotating magnetic field. While this design is appropriate for a disposable blood separator, it is not well adapted for long-term operation. First, the design adds a rotational drive motor to any filtration system, beyond the pump(s) needed for fluid feed and collection. Further, the seals are likely to wear out if the rotor is spun at 3600 rpm for prolonged periods. Likewise, the bearings that support the rotor are also likely to wear out. Use of seals and bearings adapted for continuous long-term use (like those used conventional pumps) are expensive and suffer from reliability concerns.

One other fluid separation technology, reverse osmosis (RO) membrane filtration, is well suited for removal of dissolved ions, proteins, and organic chemicals, which are difficult to remove using conventional filtration methods. Further, RO membrane systems are regenerable, thereby providing long term membrane service, requiring replacement only 1-2 times per year in commercial membrane plants. Moreover, because RO is an absolute filtration method, its treatment efficiency and performance are stable and predictable (Lee and Lueptow (2001) Reverse osmosis filtration for space mission wastewater: membrane

properties and operating conditions. *J. Memb. Sci.* 182:77-90). However, membrane fouling due to concentration polarization is still a problem in conventional RO filtration.

Lee and Lueptow recently published a study that suggests that rotating filtration devices that use Taylor vortices to reduce concentration polarization may be used to enhance filtrate flux through reverse osmosis (RO) membranes (Lee and Lueptow (2001) Rotating reverse osmosis: a dynamic model for flux and rejection. *J. Memb. Sci.* 192:129-143). Unfortunately, existing Taylor-Couette systems/devices, such as those discussed above with respect to blood separation, are poorly suited for large scale commercial applications where long-term continuous operation is desirable. Consequently, a need exists for energy efficient, rotating membrane filtration systems/devices, compatible with reverse osmosis membranes, adapted to long-term continuous use and scalable for commercial separation applications.

#### Summary of the Invention

Aspects of the present invention are directed to a device for rotational filtration. In one embodiment, the device comprises a housing having a bore with an inner wall. The housing has an inlet port for the flow of process fluid into the device and a filtrate port for the collection of filtrate. The housing may also have an outlet port for the flow of process fluid out of the device. The device also comprises a rotor having an outer wall. The rotor is adapted to rotate within the bore and has a rotational drive means adapted for driving the rotation of the rotor by the flow of process fluid. The device also comprises a filter attached to either the outer wall of the rotor or the inner wall of the bore.

In one preferred embodiment, the rotational drive means comprises a plurality of turbine vanes on the rotor. The turbine vanes are positioned at least partially within the flow path of the process fluid, to drive the rotation of the rotor. In one specific embodiment, the turbine vanes are positioned at the inlet port and the flow of process fluid into the device drives the rotation of the rotor.

According to another aspect of the present invention, the rotational filtration device also comprises a gap between the rotor and the housing, wherein the gap is configured so as to facilitate formation of Taylor vortices within the gap when the rotor is rotating within the bore. In one preferred embodiment the gap is sized so that the ratio of the gap to radius is

less than about 0.142. In other embodiments the gap is sized so that the ratio of the gap to radius is greater than about 0.142.

A filter is disposed within the gap. The filter is preferably provided in the form of a membrane for some embodiments. In one preferred embodiment, the membrane is attached  
5 to the inner wall of the bore. In another specific embodiment, the housing further comprises a layer of porous material located between the membrane and the inner wall.

According to yet another aspect of the present invention, the rotor further comprises surface modifications adapted to create wake turbulence. These surface modifications may include longitudinal grooves.

10 Preferably, the filter comprises a filtration membrane which is selected from the group including micro, macro, nano, dialysis and reverse osmosis membranes.

A method is disclosed in accordance with another embodiment of the present invention for filtering a solution and/or suspension to separate soluble and/or insoluble materials from a liquid filtrate. The method comprises the steps of: (1) providing a device  
15 comprising a cylindrical housing having at least one inlet port and at least one filtrate port, a cylindrical rotor adapted to rotate within the housing, the rotor having a rotational drive means comprising a plurality of turbine vanes, and a filtration membrane affixed to the rotor or the housing, between the at least one inlet port and the at least one filtrate port; (2) introducing the solution and/or suspension under pressure into the at least one inlet port,  
20 such that the solution and/or suspension flows across the turbine vanes causing the rotor to rotate within the housing; (3) allowing the rotor to rotate at a rate sufficient to generate Taylor vortices in a gap between the rotor and the housing, thereby reducing concentration polarization along the filtration membrane; and (4) collecting the filtrate from the at least one filtrate port after passing through the filtration membrane.

25 In accordance with another preferred embodiment, a filtration device is disclosed. The device comprises: a housing having a bore; an inlet port on the housing; a filtrate port on the housing; a rotor adapted to rotate within the bore, the rotor comprising a turbine vane configured to convert a flow of pressurized process fluid from the inlet port into rotational energy; a gap between an inner surface of the bore and the rotor; and a filter  
30 within the gap, between the inlet port and the filtrate port.

### Brief Description of the Drawings

Figure 1 is a sectional view of the rotational filtration device according to one embodiment of the present invention.

Figure 2 is an enlarged view of the circled area in Figure 1 to show the gap between  
5 the outer wall of the rotor and the inner wall of the housing.

Figure 3 illustrates the end of the housing viewed along the central axis of the rotational filtration device.

Figure 4 is a cross sectional view of the rotational filtration device at line A-A' of Figure 1.

10 Figure 5a is a sectional view of the rotor taken along line B-B' of Figure 5b.

Figure 5b is cross sectional view of the rotor showing the turbine vanes.

Figure 6a is a sectional view of the rotor taken along line C-C' of Figure 6b.

Figure 6b is a cross sectional view of the rotor and turbine vanes.

Figure 7 illustrates a rotational filtration device according to another embodiment of  
15 the present invention, having one or more inner cylindrical sections added to the rotor.

Figure 8 illustrates an end view of a rotational filtration device having two inlet ports.

### Detailed Description of the Preferred Embodiments

20 Figure 1 is a sectional view of the rotational filtration device 100 according to one embodiment of the present invention. The sectional view shows the housing 150 of the rotational filtration device bisected along line A-A', but the rotor 110 is shown intact. The rotational filtration device 100 comprises a rotor 110 arranged coaxially within the bore of a housing 150. In the illustrated embodiment both the rotor 110 and the bore are  
25 cylindrical. In one embodiment the rotor 110 is mounted on two posts 152 within the housing 150 along the central axis 102 of the rotational filtration device 100. These posts limit both the axial and the radial motion of the rotor 110. There is a gap 104 between the outer wall 112 of the rotor 110 and the inner wall 154 of the housing 150. The gap 104 extends evenly around the rotor 110. In another embodiment the posts 152 are not used and  
30 the rotor 110 is suspended within the housing 150 solely by the flow of process fluid through the gap 104.

The housing 150 comprises an inlet port 156 and one or more filtrate ports 158. The process fluid flows into the rotational filtration device 100 via the inlet port 156. The filtrate (filtered process fluid) flows out of the rotational filtration device 100 via the filtrate ports 158. Additionally, the housing 150 may comprise an outlet port (not shown), through which the process fluid flows out of the rotational filtration device 100. The outlet port allows the flow of process fluid through the rotational filtration device 100 at a greater rate than the flow of filtrate out of the rotational filtration device 100. The number of each port may be adjusted to modify the flow of the process fluid.

The rotor 110 comprises a rotational drive means 114 which is positioned at least partially within the flow path of the process fluid to drive the rotation of the rotor 110. In the illustrated embodiment, the rotational drive means 114 comprises a plurality of turbine vanes. These turbine vanes are positioned at the inlet port 156 and the flow of process fluid into the rotational filtration device 100 via the inlet port 156 drives the rotation of the rotor 110.

A filter 106 is disposed within the gap 104. In the illustrated embodiment, the filter 106 is mounted on the inner wall 154 of the housing 150. In another embodiment, the filter 106 may be mounted on the outer wall 112 of the rotor 110. For this embodiment, the inlet port 156 is relocated to direct the flow of the process fluid into the interior of the rotor 110 to accommodate the mounting of the filter 106 on the outer wall 112 of the rotor 110.

According to some embodiments, the filter comprises of a filtration membrane which is selected from the group including micro, macro, nano, dialysis and reverse osmosis membranes.

Figure 2 is an enlarged view of the circled area in Figure 1 to clarify the gap 104 between the outer wall 112 of the rotor 110 and the inner wall 154 of the housing 150. As discussed above with reference to Figure 1, the filter 106 is mounted on the inner wall 154 of the housing 150. Referring to Figure 2, the filter 106 may be supported by a sintered porous bed 160 or any other porous structure known in the art. In one embodiment the porous bed may be made of stainless steel. The porous bed 160 provides a foundation for the filter 106 to withstand the high pressure within the housing 150 (e.g. 1000 psi), while its porosity adds little resistance to the flow of the filtrate out of the filtrate port 158.

The gap 104 is sized to provide optimal shear and vorticity to the process fluid as it flows through the gap 104. In one embodiment, the rotor is 1" in diameter, 5" long, and the

gap 104 is 0.020". The rotor 110 spins at a rate of 3600 rpm in this embodiment. Rotor and housing configurations and gap dimension can be modified as described in Lee and Leuptow (2001) in order to optimize filtrate flux.

5 The dimensions of the various components of the rotational filtration device 100 described above can be scaled up and down depending on the application. For example, the rotational filtration device disclosed in Lee and Lueptow (2001) employs a relatively large gap (0.142") on a rotor 110 radius of 1", or a gap to rotor radius ratio of 0.142. Some embodiments may employ a much smaller gap to increase shear. Other embodiments may employ a larger gap to increase Taylor vorticity. Increasing the gap increases Taylor  
10 vorticity but reduces shear. Those of skill in the art can readily determine the optimal balance between Taylor vorticity and shear depending on the application. For example, excessive shear is preferably avoided in blood separators to minimize damage red blood cells or other desired blood components. However, for water treatment (e.g., desalination), shear damage is of less or no concern.

15 It is known from tangential filtration that the higher the shear the better the membrane filter performs, because shear reduces membrane clogging by diminishing concentration polarization. In tangential filtration, however, there is a limit to the effectiveness of shear in improving filtrate flux because the tangential flow is generated by pumping pressure, which can be limiting. The Taylor-Couette devices as modified in the  
20 present invention allow increased shear without increased pressure, because the shear is created by the rotation of the rotor 110 within the housing 150 and varies as discussed above with the size of the gap 104. In one preferred embodiment, the gap to radius ratio is about 0.040, or about 1/3 that taught by the Lueptow reference (about 0.142) cited above.

Figure 3 illustrates the end of the housing 150 viewed along the central axis 102 of  
25 the rotational filtration device 100. As discussed above with reference to Figure 1, the housing 150 comprises an inlet port 156 and one or more filtrate ports 158. Referring to Figure 3, an outlet port 162 is also shown.

Figure 4 is a cross sectional view of the rotational filtration device 100 at line A-A' of Figure 1. As discussed above with reference to Figure 1, the rotor 110 comprises a  
30 rotational drive means 114 which is positioned at least partially within the flow path of the process fluid to drive the rotation of the rotor 110. Referring to Figure 4, the rotational drive means 114 comprises a plurality of turbine vanes 116. These turbine vanes 116 are

positioned at the inlet port 156 and sculpted to capture the flow of process fluid into the rotational filtration device 100 via the inlet port 156, which drives the rotation of the rotor 110. Preferably, the process fluid is pumped at a relatively high flow rate and pressure (e.g., about 100-1000 mL/min for the dimensions discussed above with reference to Figure 5 2).

Figure 5a is a sectional view of the rotor 110 taken along line B-B' of Figure 5b, which is cross sectional view of the rotor 110 similar to that in Figure 4. Figure 6a is a sectional view of the rotor 110 taken along line C-C' of Figure 6b, which is a cross sectional view of the rotor 110 similar to that in Figure 5b, except the rotor 110 is rotated 10 clockwise about one sixth of a rotation. Figure 6a illustrates the semicircular cut-out shape 164 of the vanes.

In accordance with one preferred embodiment, the rotor is preferably freely supported. There may be center limit posts extending from the housing on the axis of rotation. These limit posts restrict both axial and radial motion of the rotor until it reaches 15 its optimal self-centering speed.

A rotor surrounded by a viscous fluid and constrained to rotate within a bearing surface will self-center itself. Fluid tends to follow the rotor, and thus the rotor is in a sense totally submerged as it spins. Pressure increases where the gap is small, and the pressure tends to push the rotor away from the case and increase the gap.

20 There are preferred ranges of rotational speed (RPM) where the self-centering effect becomes optimal. That RPM range depends on viscosity and density of the fluid, gap, rotor geometry, and possibly other variables. The center limit posts help keep the rotor reasonably centered during spin-up of the system.

In one preferred embodiment, as shown in Figures 5-6, the rotor includes a section 25 of turbine vanes, centrally located under the tangential inlet port. Preferably, process fluid (salt water for example) is pumped at a relatively high flow rate for the system dimensions described above (e.g., about 100-1000 mL/min) and at high pressures. Figures 4-6 show some detail on the vanes. The inlet port is preferably positioned so that inlet flow hits the rotor tangentially in the form of a jet. The vanes are preferably sculptured to capture this 30 inlet flow and convert it into rotational energy.

The self-centering forces described above with respect to a rotor surrounded by a viscous fluid operate to cause radial centering. Design features of the turbine vanes that

function to keep the rotor axially centered are illustrated in Figures 6a and 6b (see e.g., the semicircular cut-out shape 164 in Figure 6a, corresponding to the section C-C' in Figure 6b). The curvature of the vanes can be shaped to divert the forces of the inlet flow to move the rotor to a stable equilibrium position directly under the inlet port. Inlet flow against the semicircular shape of the vane will tend to split, with some going left and some going right. When the device is horizontal, as shown in Figure 6a and 6b, if the rotor moves to the right under the inlet port, the left wall of the vane 163 will accept more force than the right wall 165, and this will tend to move the rotor back to center it under the inlet port. This is an axial self-centering design feature. The vanes can be modified, as known to those of skill in the art, to stabilize the rotor so it levitates, in a sense, and does not contact either center limit post. For example, if axial flow of the feed fluid tends to push the rotor towards the outlet port, the curvature of the vane can be modified, making the curvature on the left side steeper than on the right. This will add a force to oppose that pushing the rotor to the outlet port.

In some embodiments the rotor 110 is solid. In other embodiments the rotor 110 is hollow. In some of these other embodiments the hollow rotor 110 is permeable to the process fluid to reduce the buoyancy of the rotor 110 within the housing 150.

Referring to Figures 1 and 2, the surfaces of the outer wall 112 of the rotor 110 and the inner wall 154 of the housing 150 may be modified to increase turbulence and enhance the formation of Taylor vortices. For example, texture may be added to either or both surfaces. More particularly, longitudinal grooves on the outer wall 112 of the rotor 110 will cast trailing wakes that will increase Taylor vorticity and should improve filtrate flux. Further, the addition of surface modifications such as longitudinal grooves may be used to create an exit path for the inlet flow, which is diverted to the right by the turbine vanes as illustrated in Figure 4. The exit path could be along deep longitudinal grooves that direct flow from the right side of the housing 150 back into the gap 104 and then out through an outlet port 162.

Referring to Figure 4, the rotation of the rotor 110 coaxially within the housing 150 generates a self-centering effect. The rotor 110 behaves like a spinning shaft within a journal bearing, with the process fluid serving as a lubricant. The process fluid forms a sheet within the gap 104 between the rotor 110 and the housing 150. The rotation of the rotor 110 induces motion in the process fluid which produces a hydrodynamic pressure in the sheet. The hydrodynamic pressure is a function of the width of the gap 104, the

diameter of the rotor 110, its rate of rotation, the density and viscosity of the process fluid. Above a threshold rate of rotation, this hydrodynamic pressure tends to keep the width of the gap 104 even, causing the rotor 110 to self-center within the housing 150. Referring to Figure 1, the posts 152 keeps the rotor 110 reasonably centered along the central axis 102  
5 before it reaches the discussed threshold rate of rotation. A more detailed discussion of the radial self-centering effect is given in the Standard Handbook for Mechanical Engineers, 7th Edition (1967), Baumeister and Marks, pages 156-157.

As discussed immediately above and earlier with reference to Figure 2, the width of the gap 104 affects shear, Taylor vorticity, and the hydrodynamic pressure which generates  
10 self-centering effect of the rotor 110. The optimization of any one of these factors may reduce the effect of the other two. One possible solution is discussed with reference to Figure 7.

Figure 7 illustrates a rotational filtration device built according to another embodiment of the present invention. One or more inner cylindrical sections 118 are added  
15 to the rotor 110 in the illustrated embodiment. In other embodiments these inner cylindrical sections 118 may be arranged within the length of the rotor 110. These inner cylindrical sections 118 cooperate with outer cylindrical sections 166 added to inner wall 154 of the housing 150, forming a gap 108 between them. The gaps 104 and 108 have different widths, allowing the gap 104 to be optimized for filtration (e.g., shear and Taylor vorticity)  
20 and the gap 108 to be optimized for self-centering the rotor 110 (e.g., hydrodynamic pressure).

While the inner cylindrical sections 118 have a smaller diameter than the rotor 110, and the outer cylindrical sections 166 are implemented as protrusions in the illustrated embodiment, another embodiment may implement the inner cylindrical sections 118 with a  
25 greater diameter than the rotor 110, and the outer cylindrical sections 166 as cooperating depressions. Further, the length of the rotor 110 and the cooperating inner cylindrical sections 118 and outer cylindrical sections 166 may be adjusted to modify the optimization effects.

Forces which tend to cause the rotor 110 to move off-center from the central axis  
30 102 (see e.g., Figure 1) include the flow of the process fluid into and out of the housing 150 via the inlet port 156 as well as the flow of filtrate out of the housing 150 via the filtrate ports 158, and in some embodiments, via an outlet port 162, shown in Figure 8. The outlet

port may be used in some embodiments to re-circulate unfiltered process fluid that was used to drive the turbine, but could not be filtered without unduly increasing the filtration pressure. In one embodiment, the outlet port may include a valve, adapted to maintain a constant filtration pressure within the device, while providing sufficient fluid flow to drive the rotor at a desired RPM. To minimize the off-centering forces, the number of these ports (inlet, filtrate and outlet) may be adjusted.

Figure 8 illustrates a rotational filtration device similar to that discussed above with reference to Figures 1-6, but with two inlet ports 156. Generally, a rotational filtration device having a plurality of ports serving the same function (e.g., a plurality of inlet ports) will have those ports arranged evenly around the circumference of the housing 150. In the illustrated embodiment, the two inlet ports 156 are opposed such that their respective effect on the rotor 110 (not shown) is offset or balanced. In some embodiments, the respective flow of the process fluid into the housing 150 via each inlet port 156 may be individually adjusted to further tune the use of the two opposed inlet ports 156. In other embodiments, the number of outlet ports and filtrate ports may also be adjusted. The minimization of off-centering forces may reduce the necessary gap hydrodynamic pressure for the rotor 110 to self-center.

Table 1 summarizes the experimental results obtained using a motor-driven RO prototype system. The prototype rotational filtration device used a Hydranautics ESNA membrane (Oceanside, CA). Hydranautics calls this a nanofilter. The rotor was 1" in diameter, 5" long, and the gap was 0.020". Each housing half contained a 1.4" by 3.5" sheet of membrane ( $4.9 \text{ in}^2$  or  $32 \text{ cm}^2$ ) covering a filtrate port. The reduction in active membrane area from its mounting on a porous bead diminished the active surface area by about 50%.

The rotor used in developing the data presented in Table 1 did not include the turbine drive vanes described above with reference to Figures 1-6. Instead, it was rotated via magnetic drive. Rotor speeds varied from 3000 to 4600 RPM. The test solution was NaCl (ordinary table salt) in tap water. Trans-membrane pressure ran between 50 and 160 psi.

| Date of Experiment | Salt content<br>Input (ppm) | RPM  | Pump used      | Input flow<br>(mL/min) | Pressure (psi) | Top half filter |              |             | Bottom half filter |              |             | Comments                                      |
|--------------------|-----------------------------|------|----------------|------------------------|----------------|-----------------|--------------|-------------|--------------------|--------------|-------------|-----------------------------------------------|
|                    |                             |      |                |                        |                | Drip rate       | Salt content | % rejection | Drip rate          | Salt content | % rejection |                                               |
| 4/4/2002           | 0                           | 3000 | Teel 1P777     |                        | 100            | 10              | 0            | NA          | 13                 | 0            | NA          | running fresh water                           |
|                    |                             |      |                |                        |                | 10              | 0            | NA          | 14                 | 0            | NA          |                                               |
|                    |                             |      |                |                        |                | 12              | 0            | NA          | 17                 | 0            | NA          |                                               |
|                    |                             |      |                |                        |                | 17              | 0            | NA          | 22                 | 0            | NA          |                                               |
|                    |                             |      |                |                        |                | 18              | 0            | NA          | 24                 | 0            | NA          |                                               |
|                    |                             |      |                |                        |                | 21              | 0            | NA          | 29                 | 0            | NA          |                                               |
| 4/4/2002           | 0                           | 4000 | "              |                        | 90             | 10              | 0            | NA          | 14                 | 0            | NA          | running fresh water                           |
|                    |                             |      |                |                        |                | 13.5            | 0            | NA          | 18.5               | 0            | NA          |                                               |
|                    |                             |      |                |                        |                | 21              | 0            | NA          | 29                 | 0            | NA          |                                               |
| 4/5/2002           | 500                         | 3000 | "              | 30                     | 90             | 8               | 200          | 60          | 13                 | 0            | 100         | New rotor and magnetic drive                  |
| 4/8/2002           |                             |      |                |                        |                |                 |              |             |                    |              |             |                                               |
| 4/8/2002           | 0                           | 3000 | "              |                        | 90             | 6               | 0            | NA          | 12                 | 0            | NA          | running fresh water                           |
|                    |                             |      |                |                        |                | 7               | 0            | NA          | 13.5               | 0            | NA          |                                               |
|                    |                             |      |                |                        |                | 8               | 0            | NA          | 16                 | 0            | NA          |                                               |
|                    |                             |      |                |                        |                | 10              | 0            | NA          | 18.5               | 0            | NA          |                                               |
|                    |                             |      |                |                        |                | 12              | 0            | NA          | 21.5               | 0            | NA          |                                               |
| 4/8/2002           | 750                         | 3000 | "              |                        | 90             | 7               | 200          | 73          | 11.5               | 0            | 100         |                                               |
|                    |                             |      |                |                        |                | 8               |              |             | 11.5               |              |             |                                               |
|                    |                             |      |                |                        |                | 10              | 300          | 60          | 15.5               | 100          | 97          |                                               |
| 4/9/2002           | 1250                        | 3000 | "              |                        | 95             | 7               | 700          | 44          |                    |              |             |                                               |
|                    |                             |      |                |                        |                | 8               | 700          | 44          | 16                 | 500          | 60          |                                               |
|                    |                             |      |                |                        |                | 9               | 600          | 44          | 16                 | 400          | 66          |                                               |
| 4/10/2002          | 2500                        | 3000 | "              | 5 (?)                  | 95             | 11              |              |             | 21                 |              |             |                                               |
|                    |                             |      |                |                        |                | 12              |              |             | 22                 |              |             |                                               |
|                    |                             |      |                |                        |                | 10              | 1300         | 48          | 20.5               | 1000         | 60          |                                               |
| 4/12/2002          | 5000                        | 3000 | "              | 5 (?)                  | 95             | 10.5            |              |             | 21.5               |              |             |                                               |
|                    |                             |      |                |                        |                | 15              |              |             | 29                 |              |             |                                               |
|                    |                             |      |                |                        |                | 14              | 5000         | 0           | 24.5               | 2500         | 58          |                                               |
| 4/12/2002          | 10000                       | 3000 | "              |                        | 95             | 14              | 5000         | 50          | 24                 | 4000         | 60          | By this time Top leaks significantly          |
|                    |                             |      |                |                        |                | 15              | 10000        | 0           | 29                 | 3500         | 65          |                                               |
| 4/20/2002          | 0                           |      | Haldex 4F 649A | 100                    | 95             | 14              | 0            | NA          | 21.5               | 0            | NA          | Switched to new pump & running fresh water    |
|                    |                             |      |                |                        |                | 10              | 0            | NA          | 17                 | 0            | NA          |                                               |
| 4/20/2002          | 10000                       | 3000 | "              | 100                    | 100            | 25              |              |             | 60                 |              |             |                                               |
|                    |                             |      |                |                        |                | 12              |              |             | 28                 |              |             |                                               |
|                    |                             |      |                |                        |                | 10              | 10000        | 0           | 23                 | 4500         | 55          |                                               |
|                    |                             |      |                |                        |                |                 |              |             |                    |              |             |                                               |
| 4/21/2002          | 10000                       | 4600 | "              | 100                    | 120            | 9               |              |             | 23                 |              |             |                                               |
|                    |                             |      |                |                        |                | 7               |              |             | 18                 |              |             |                                               |
|                    |                             |      |                |                        |                | 6               |              |             | 16.5               |              |             |                                               |
|                    |                             |      |                |                        |                | 6               |              |             | 16                 |              |             |                                               |
|                    |                             |      |                |                        |                |                 |              |             |                    |              |             |                                               |
| 4/21/2002          | 0                           | "    | "              | 100                    | 160            | 6               |              |             | 16                 |              |             | Filtrate flow rate same with rotor stationary |

Table 1

Table 1 shows that up to 100% of the salt contaminating the feed solution was rejected. These results clearly suggest that placing the membrane on the housing is acceptable, and that salt can be removed from water at relatively low pressures and rpm.

In variations to the embodiment illustrated in Figures 1-8, this invention can be applied to a vast number of applications. In a general sense, embodiments of this invention can be useful in any application where filters lose performance due to clogging or concentration polarization. These applications include: removal of salt from water, processing sea water for human consumption, processing sea water for agricultural uses, reprocessing waste water for agricultural uses, reprocessing waste water for human consumption, concentrating sugar or other desired components from sap from plants, such as sugar cane sap or maple sap, concentrating latex from the sap of rubber plants, removing impurities from water for industrial applications, such as needed in the pharmaceutical or electronic industries, recycling cooking oil, recycling motor oil or lubricating oils, and producing sterile water for intravenous injection.

Further, where molecular exclusion or sieving membranes are employed, the device can be used for large scale cell and biotechnology separation applications, such as purifying cell supernatants and/or lysates from cellular material in a bioprocessor or fermentor. The advantages discussed above with regard to energy efficiency (flow-driven turbine) and high  
5 flux rates (vortex-scrubbed membranes) would be applicable to the large scale filtration needs of the biotechnology industry. Similarly, some embodiments of the present turbine-driven device may be well suited for energy-efficient filtration of fermented beverages, to remove for example, yeast and particulate material (grains, vegetable matter, fruit, etc.) in the production of wines and beers.

10 The various materials, methods and techniques described above provide a number of ways to carry out the invention. Of course, it is to be understood that not necessarily all objectives or advantages described may be achieved in accordance with any particular embodiment described herein. Thus, for example, those skilled in the art will recognize that the components of the system may be made and the methods may be performed in a  
15 manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other objectives or advantages as may be taught or suggested herein.

Although the present invention has been described in terms of certain preferred embodiments, other embodiments of the invention including variations in dimensions,  
20 configuration and materials will be apparent to those of skill in the art in view of the disclosure herein. In addition, all features discussed in connection with any one embodiment herein can be readily adapted for use in other embodiments herein. The use of different terms or reference numerals for similar features in different embodiments does not imply differences other than those which may be expressly set forth. Accordingly, the  
25 present invention is intended to be described solely by reference to the appended claims, and not limited to the preferred embodiments disclosed herein.

**CLAIMS:**

1. A device for rotational filtration of a flow of pressurized process fluid, comprising:
  - a housing having a bore with an inner wall;
  - a rotor having an outer wall, and being adapted to rotate within said bore, said rotor also having a rotational drive means for converting said flow of pressurized process fluid into rotational energy;
  - a gap between said rotor and said housing; and
  - a filtration membrane attached to either said outer wall of said rotor or said inner wall of said bore;wherein said housing has an inlet port for directing said flow of pressurized process fluid into said gap and a filtrate port for collecting a filtrate.
2. The device of claim 1, wherein said rotational drive means comprises a plurality of turbine vanes on said rotor, said turbine vanes being positioned at least partially within a flow path of the pressurized process fluid.
3. The device of claim 1, wherein said gap is configured so as to facilitate formation of Taylor vortices within the gap when said rotor is turning within said bore.
4. The device of claim 3, wherein said gap is sized so that the ratio of gap to radius is less than about 0.142.
5. The device of claim 1, wherein said filtration membrane is attached to said inner wall of said bore.
6. The device of claim 5, further comprising a layer of porous material located between said filtration membrane and said inner wall.
7. The device of claim 1, wherein said rotor further comprises surface modifications adapted to create wake turbulence.
8. The device of claim 7, wherein said surface modifications are longitudinal grooves.

9. The device of claim 1, wherein said filtration membrane is selected from the group consisting of micro, macro, nano, dialysis and reverse osmosis membranes.

10. The device of claim 1, wherein said rotor is radially self-centering.

11. The device of claim 2, further comprising at least two inlet ports arranged at equal circumferential distances from one another, wherein the flow of pressurized process fluid against the turbine vanes on said rotor improves radially self-centering at a lower RPM.

12. The device of claim 2, wherein said turbine vanes are shaped so as to allow said rotor to axially self-center within the flow path.

13. A method for filtering a solution and/or suspension to separate soluble and/or insoluble materials from a liquid filtrate, comprising:

providing a device comprising a cylindrical housing having at least one inlet port and at least one filtrate port, a cylindrical rotor adapted to rotate within said housing, said rotor having a rotational drive means comprising a plurality of turbine vanes, and a filtration membrane affixed to said rotor or said housing, between said at least one inlet port and said at least one filtrate port;

introducing the solution and/or suspension under pressure into said at least one inlet port, such that the solution and/or suspension flows into a gap between the rotor and the housing and across the turbine vanes causing the rotor to rotate within the housing;

allowing said rotor to rotate at a rate sufficient to generate Taylor vortices in a gap between said rotor and said housing, thereby reducing concentration polarization along the filtration membrane; and

collecting the filtrate from the at least one filtrate port after passing through the filtration membrane.

14. A filtration device for filtering a flow of pressurized process fluid, comprising:

a housing having a bore;

an inlet port on said housing;

a filtrate port on said housing;

a rotor adapted to rotate within said bore, said rotor comprising a turbine vane configured to convert a flow of pressurized process fluid from said inlet port into rotational energy;

a gap between an inner surface of said bore and said rotor; and

a filter within said gap, between the inlet port and the filtrate port;  
wherein said inlet port is configured to direct said flow of pressurized process fluid into said gap.

15. The filtration device of claim 14, further comprising an outlet port.

16. The filtration device of claim 15, wherein said outlet port comprises a valve adapted to maintain a constant filtration pressure.

17. The filtration device of claim 14, wherein a ratio of said gap to a diameter of said rotor is less than about 0.142.

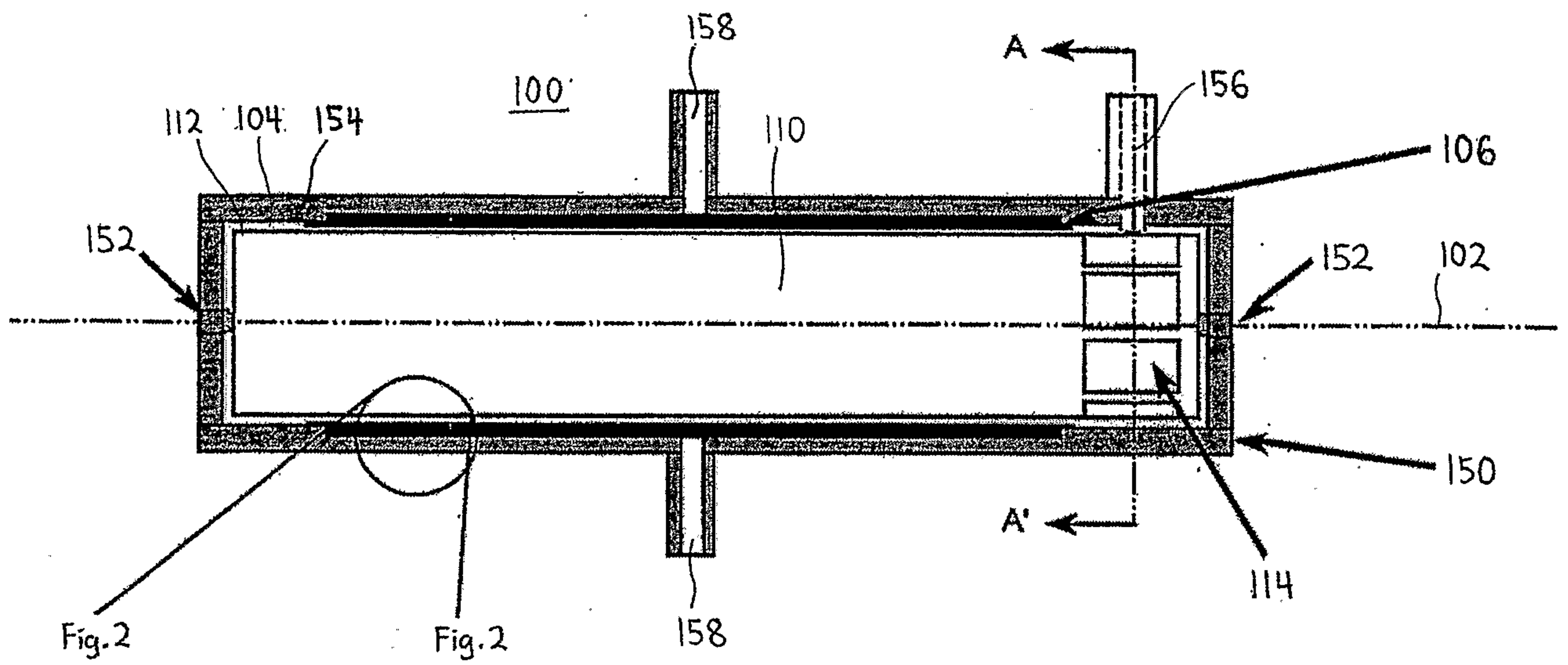
18. The filtration device of claim 14, wherein a ratio of said gap to a diameter of said rotor is about 0.04.

19. The filtration device of claim 14, wherein a ratio of said gap to a diameter of said rotor is about 0.02.

20. The filtration device of claim 14, wherein an external surface of said rotor additionally comprises a plurality of longitudinal groove.

21. The filtration device of claim 14, wherein said filter comprises a reverse osmosis membrane.

22. The filtration device of claim 14, wherein a diameter of said rotor varies along a length of said rotor such that said gap varies in width.



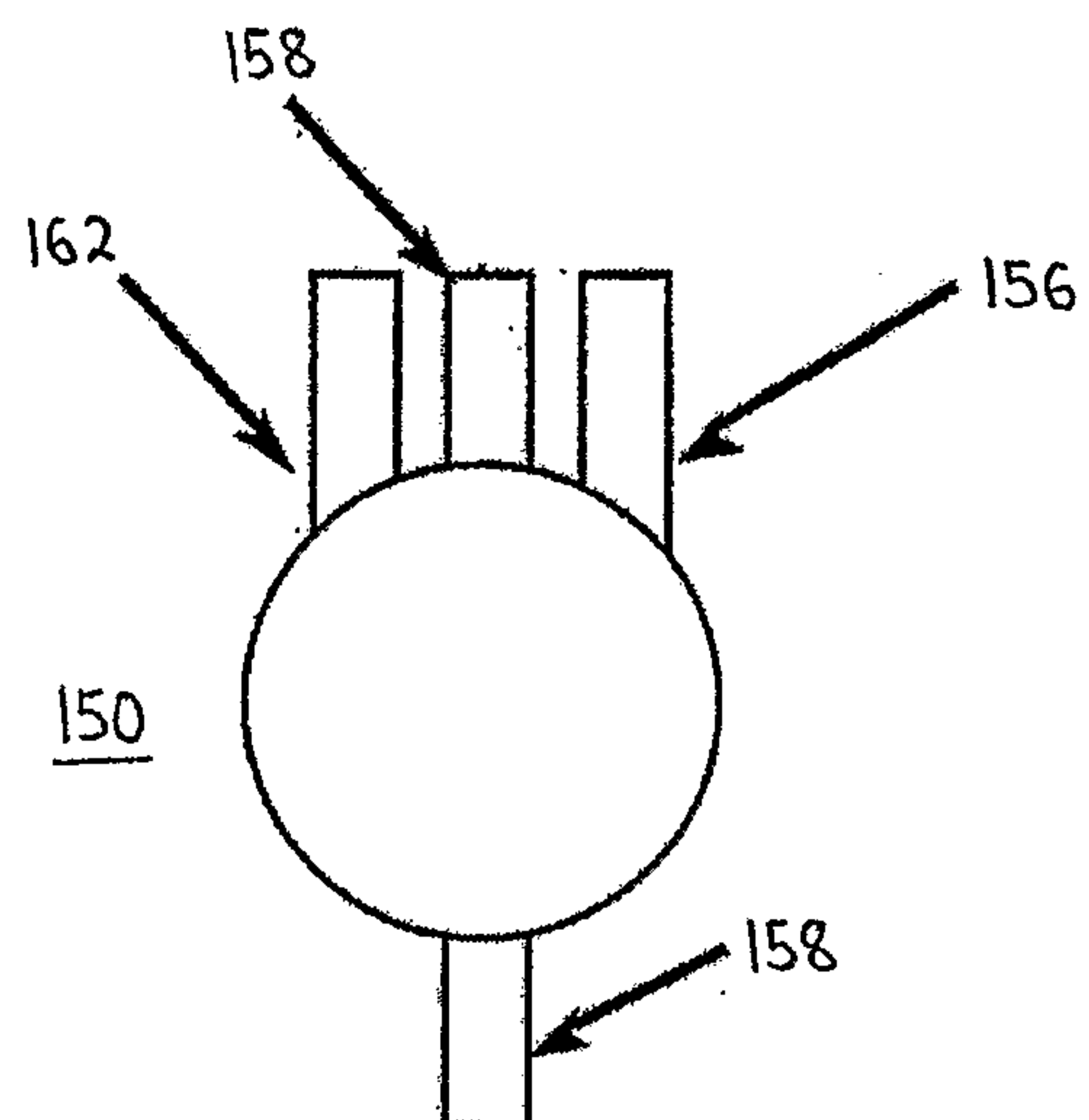


Fig. 3

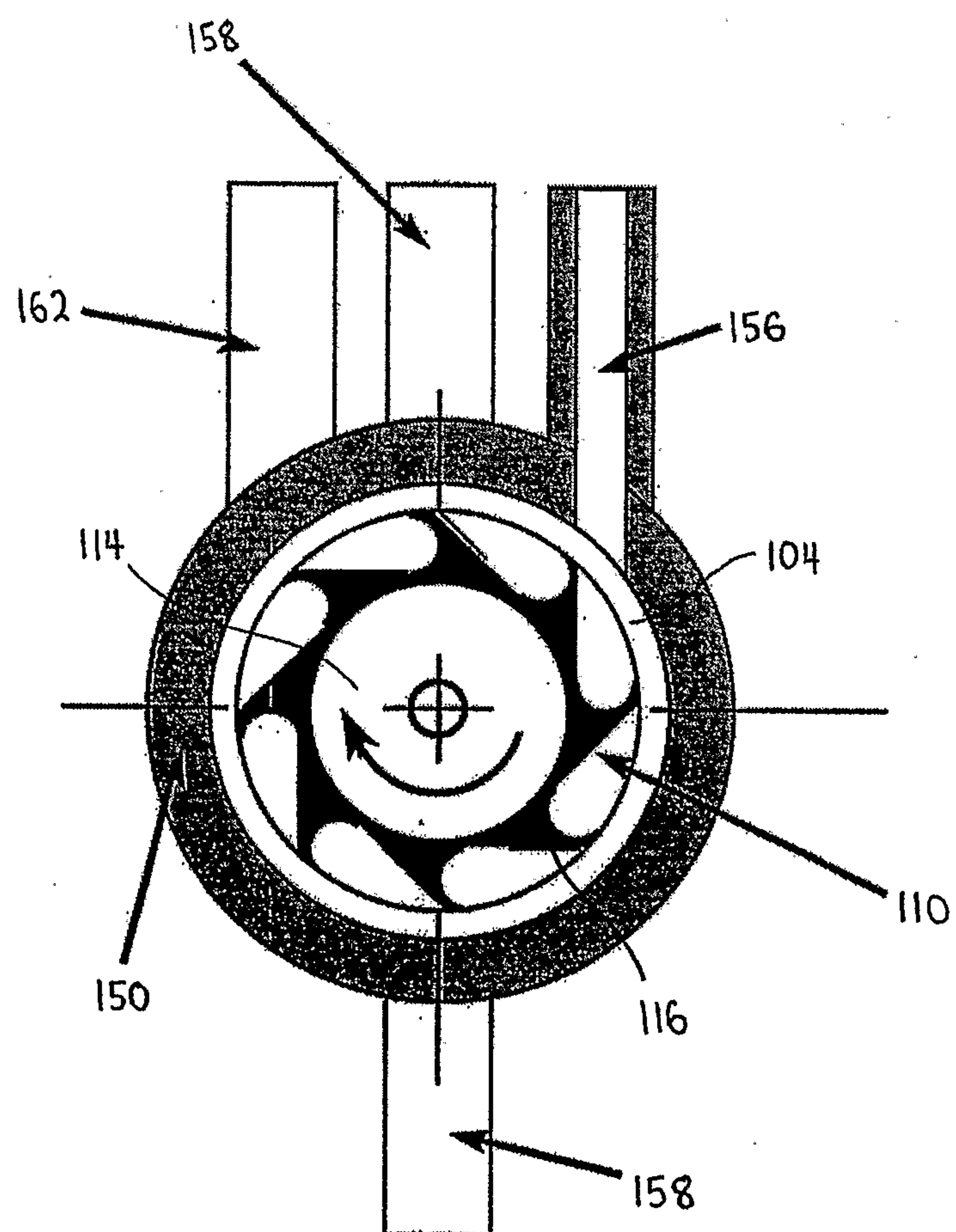


Fig. 4

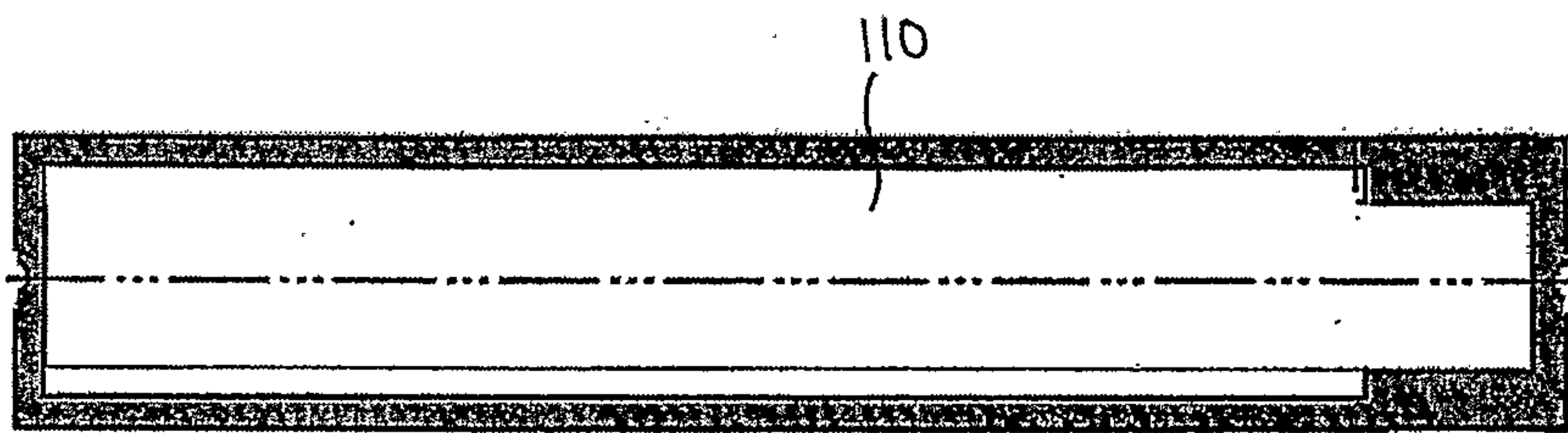


Fig. 5a

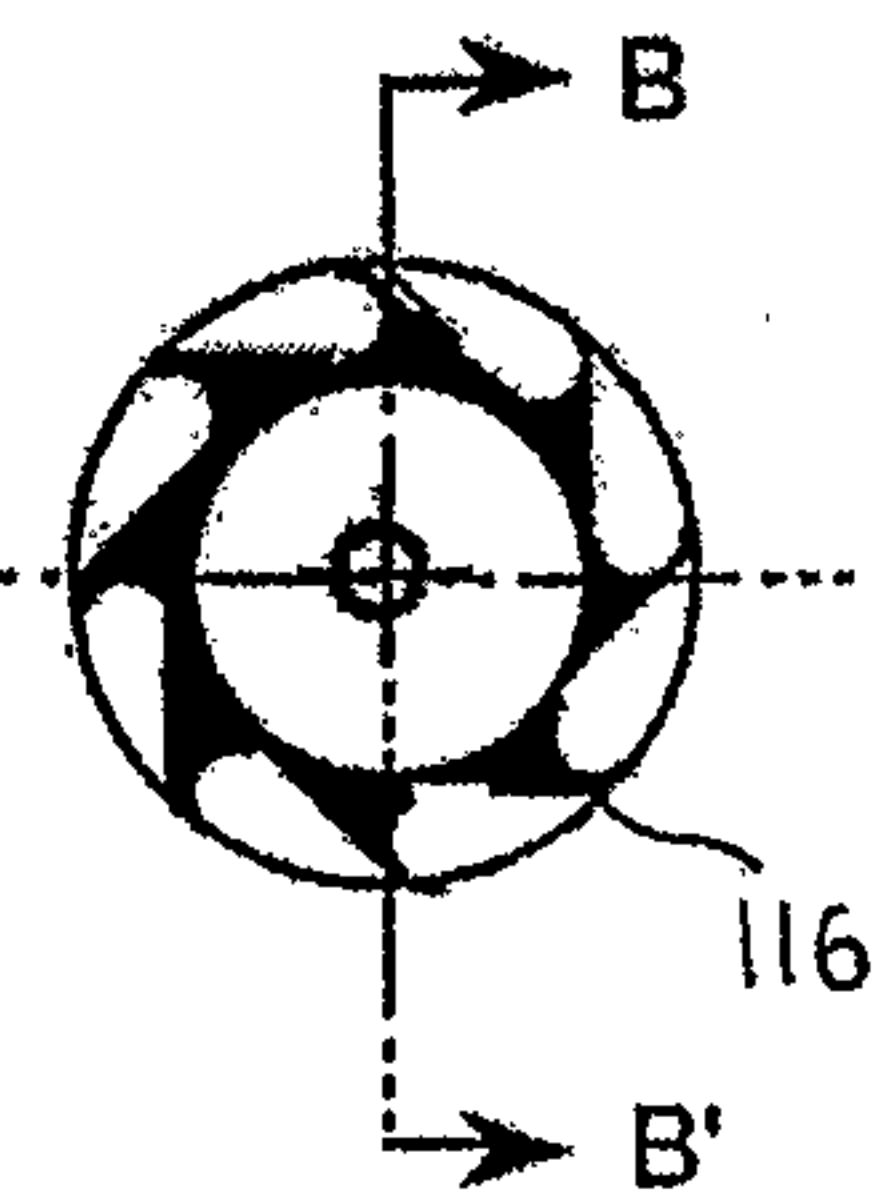


Fig. 5b

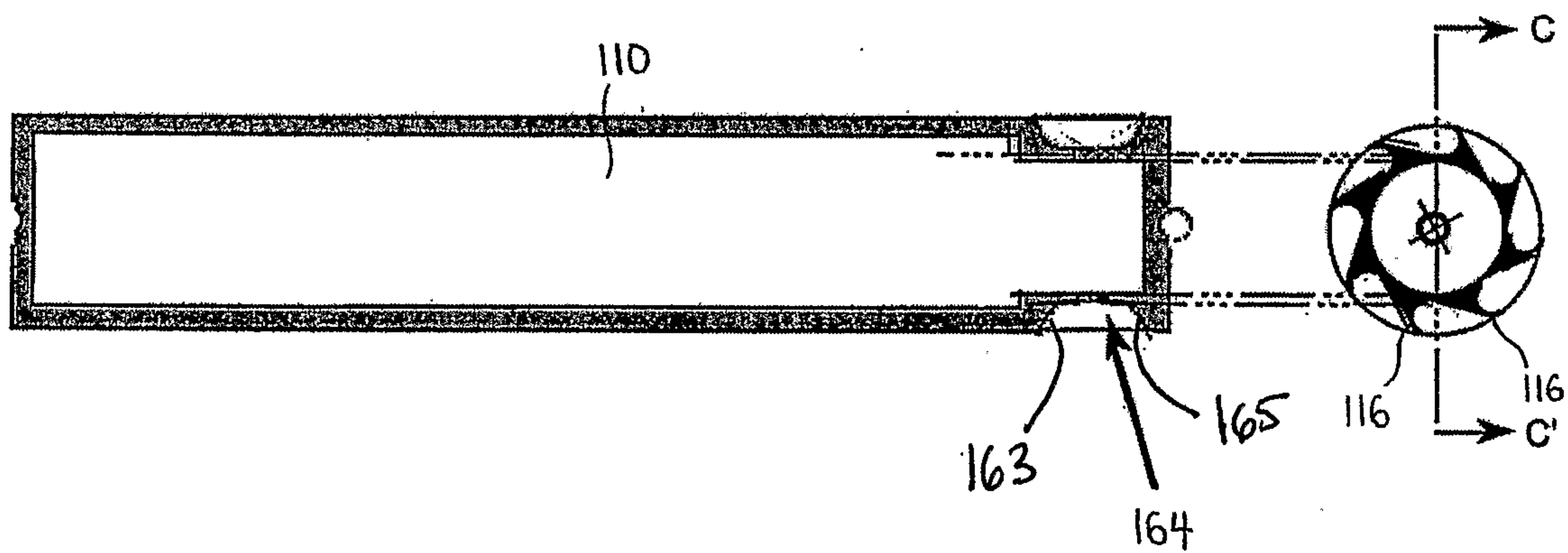


Fig. 6a

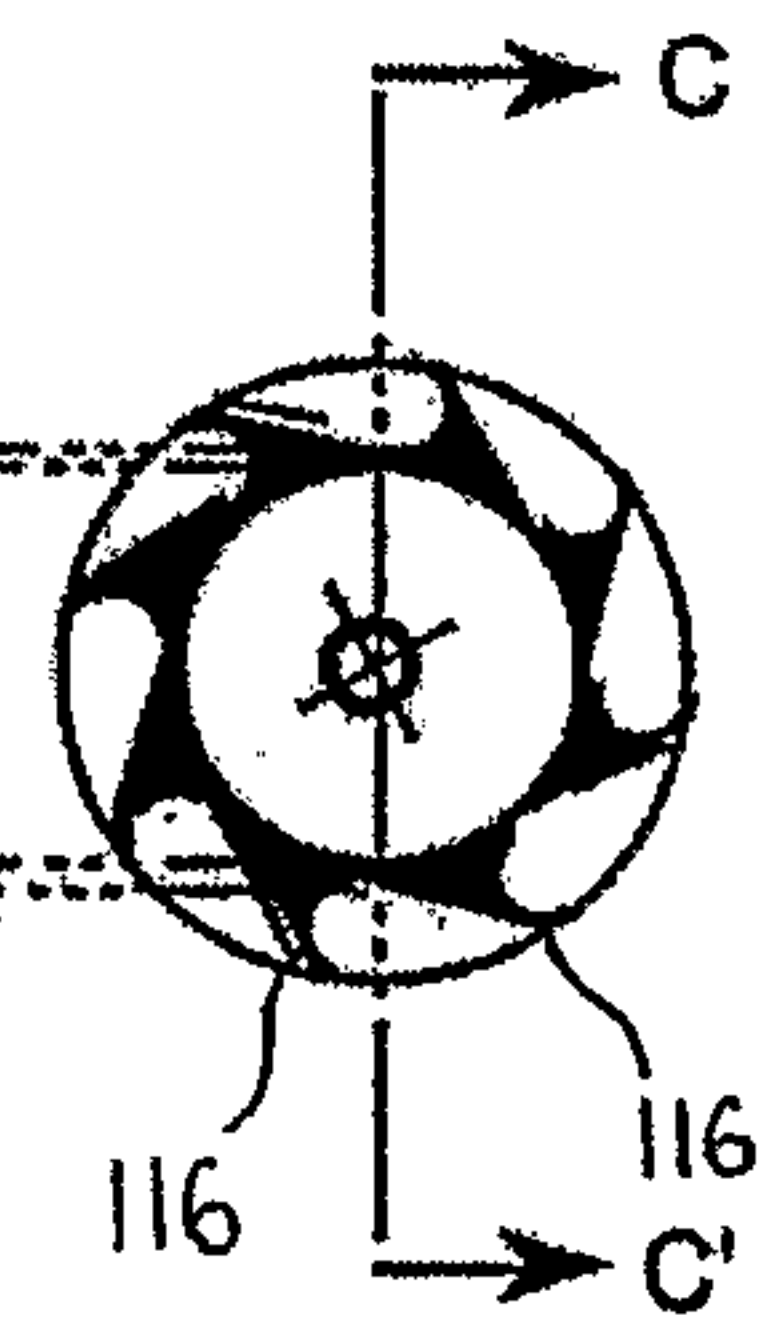
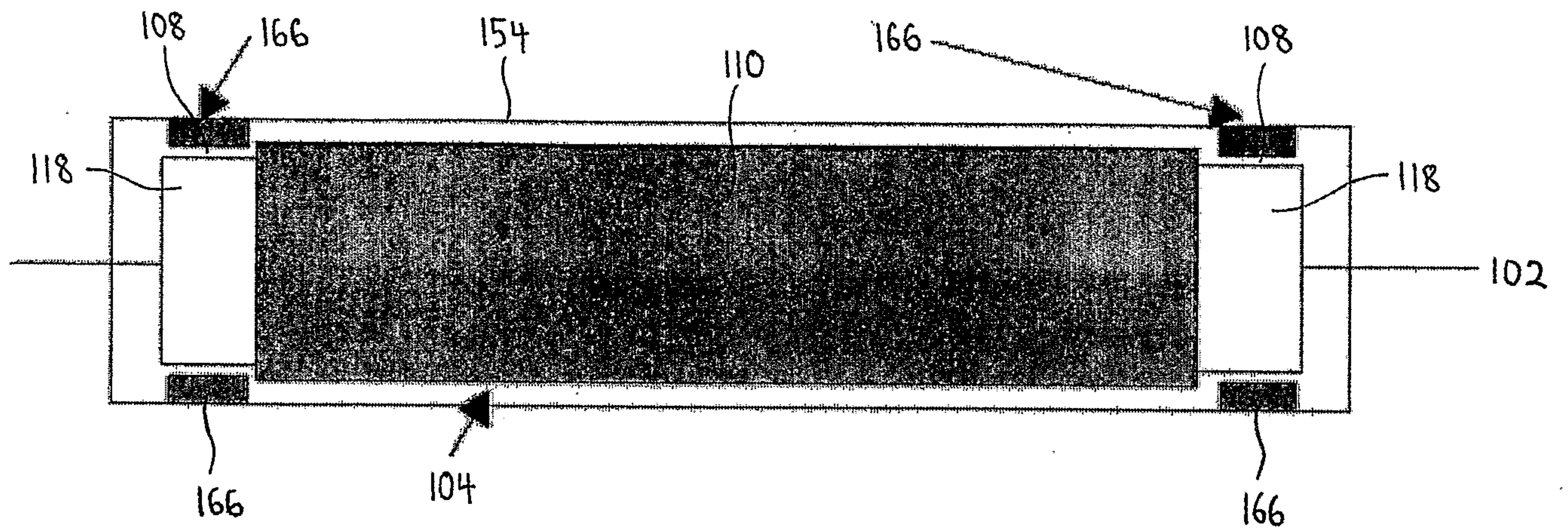
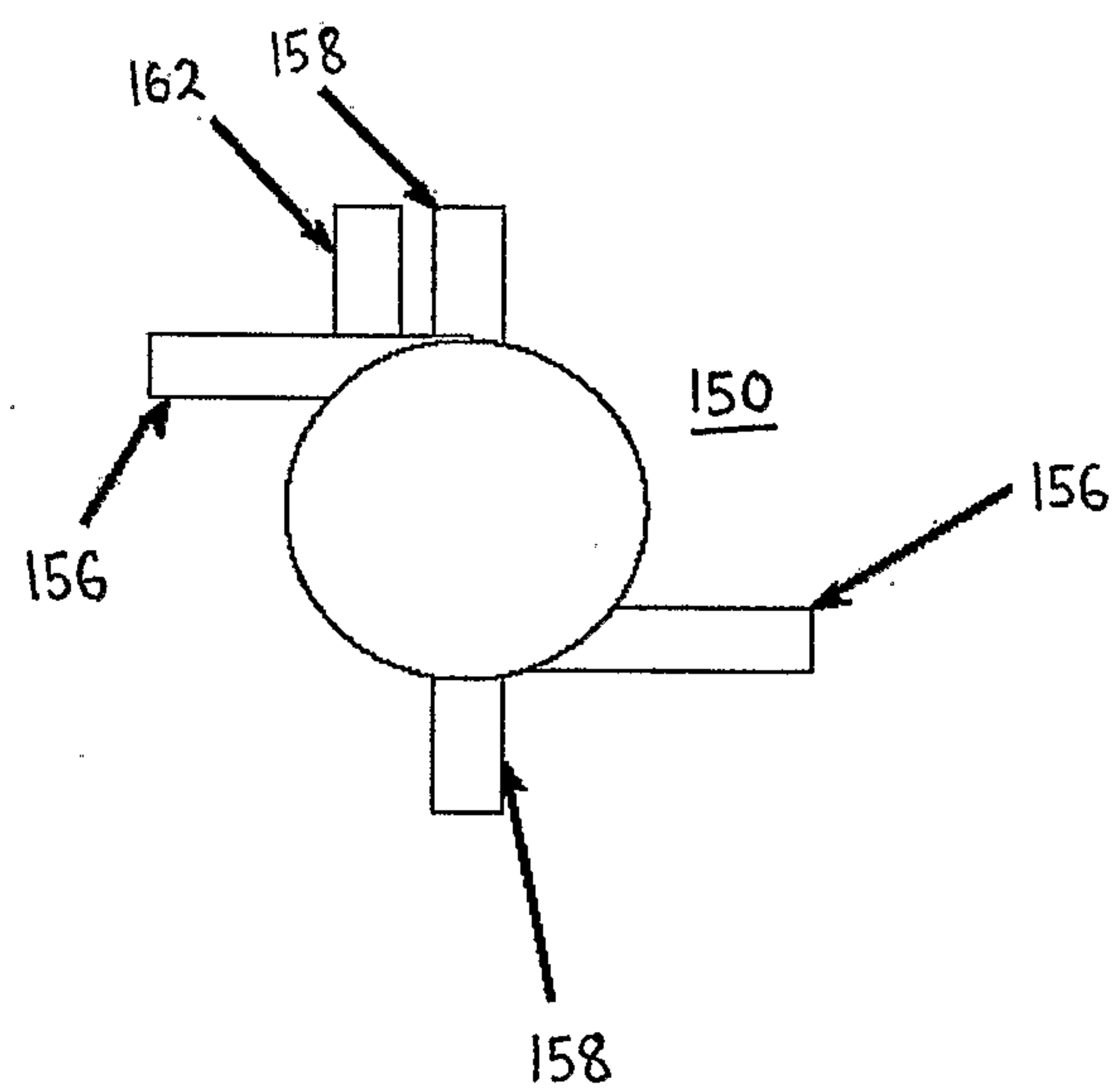


Fig. 6b

**Fig. 7****Fig. 8**