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(12) **United States Patent**
Montie et al.

(10) **Patent No.: US 11,815,094 B2**
(45) **Date of Patent: Nov. 14, 2023**

(54) **FIXED-ECCENTRICITY HELICAL TROCHOIDAL ROTARY MACHINES**

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(73) Assignee: **Rotoliptic Technologies Incorporated**, Squamish (CA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(22) Filed: **Mar. 10, 2021**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
F04C 2/107 (2006.01)
F04C 2/08 (2006.01)

(52) **U.S. Cl.**
CPC .... ***F04C 2/1076*** (2013.01); ***F04C 2/084*** (2013.01); *F04C 2240/10* (2013.01); (Continued)

(58) **Field of Classification Search**
CPC .. F04C 2/084; F04C 2240/10; F04C 2240/20; F04C 2250/20; F04C 2250/30
See application file for complete search history.

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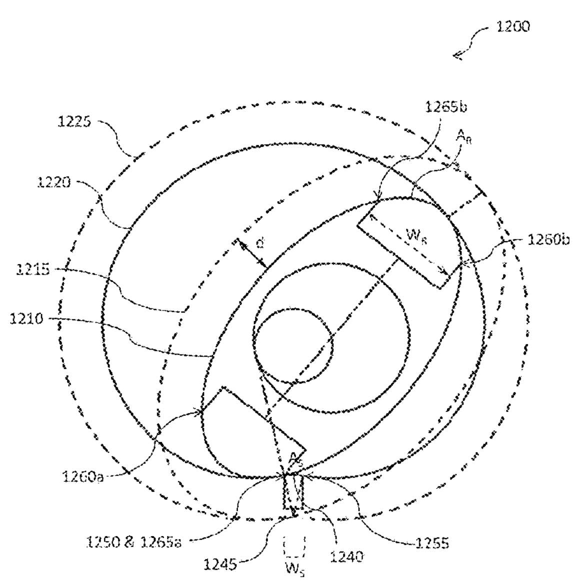
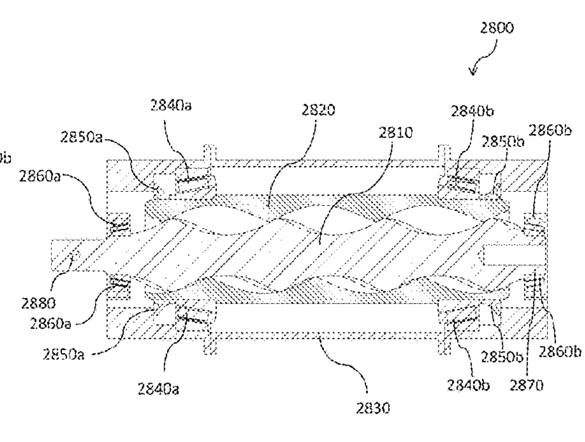
Primary Examiner — Mary Davis
(74) *Attorney, Agent, or Firm* — Cook Alex Ltd.

(57) **ABSTRACT**

Rotary positive displacement machines based on trochoidal geometry that includes a helical rotor that undergoes planetary motion relative to a helical stator are described. The rotor can have a hypotrochoidal-based cross-sectional shape, with the corresponding stator cavity cross-sectional shape being the outer envelope of the rotor cross-sectional shape as it undergoes planetary motion, or the stator cavity can have an epitrochoidal-based cross-sectional shape with the corresponding rotor cross-sectional shape being the inner envelope of the stator cross-sectional shape as it undergoes planetary motion. Such machines can be configured so that the stator axis is spaced from the rotor axis, the rotor is configured to spin about its axis and the stator is configured to spin about its axis, and/or the rotor and the stator are held at a fixed eccentricity so that the rotor undergoes planetary motion relative to the stator, but does not orbit.

6 Claims, 32 Drawing Sheets





(52) **U.S. Cl.**
CPC *F04C 2240/20* (2013.01); *F04C 2250/20* (2013.01); *F04C 2250/30* (2013.01)

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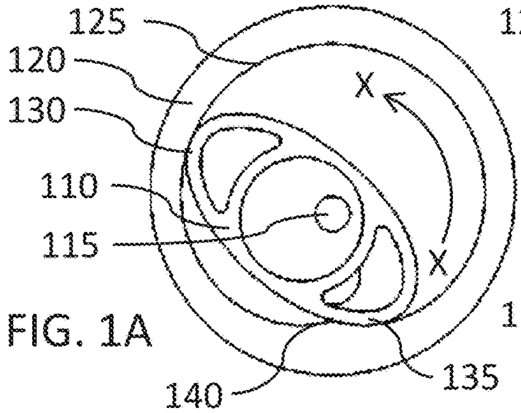


FIG. 1A

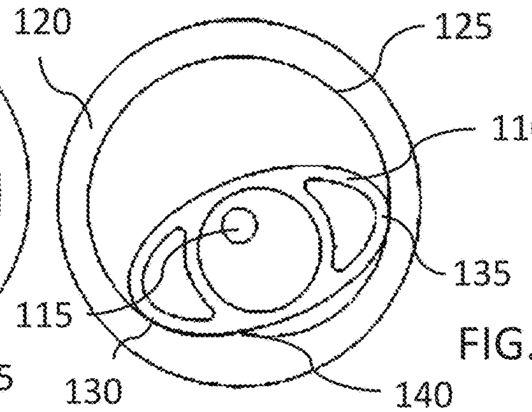


FIG. 1B

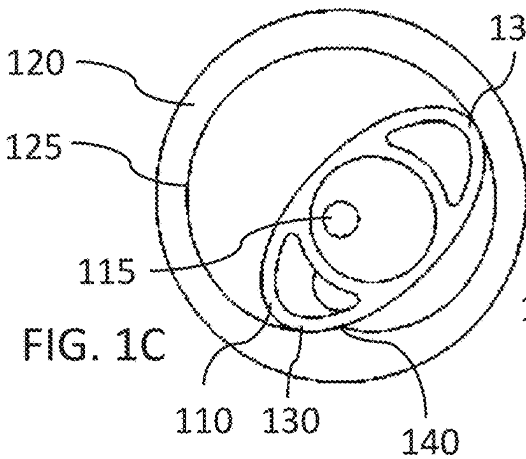


FIG. 1C

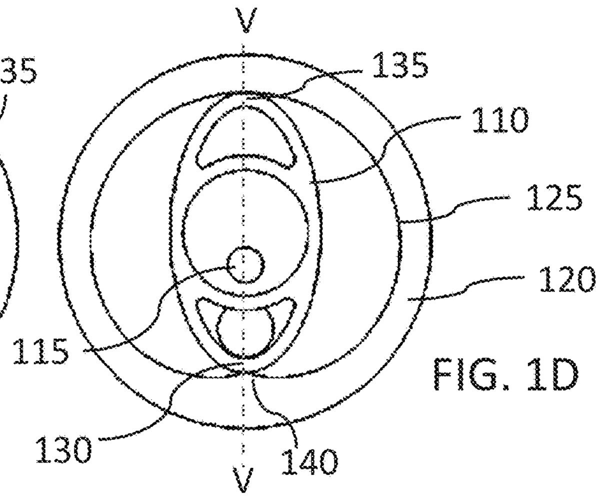


FIG. 1D

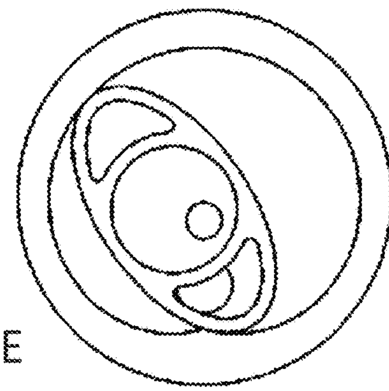


FIG. 1E

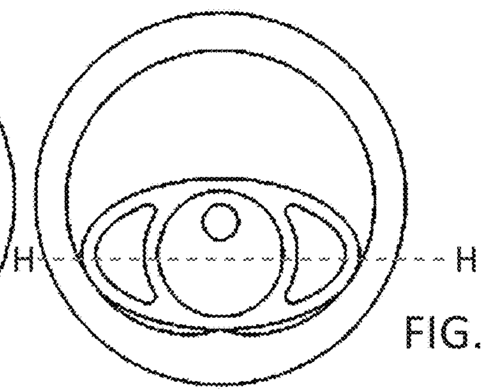


FIG. 1F

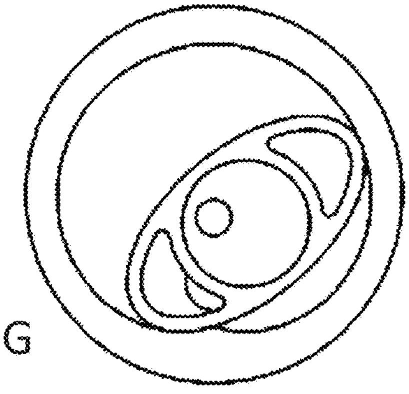


FIG. 1G

PRIOR ART

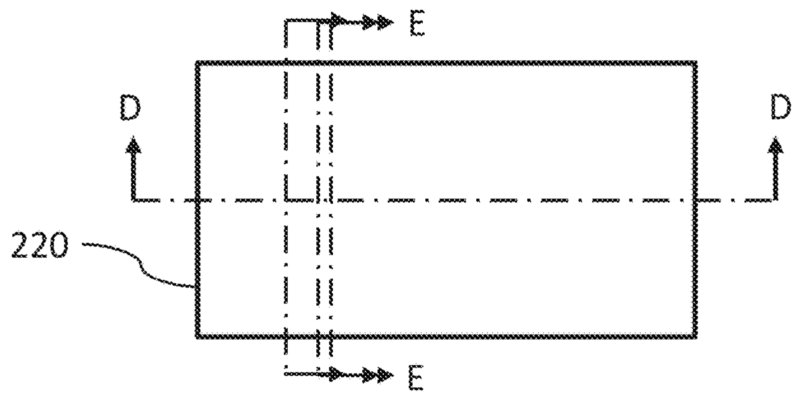


FIG. 2A

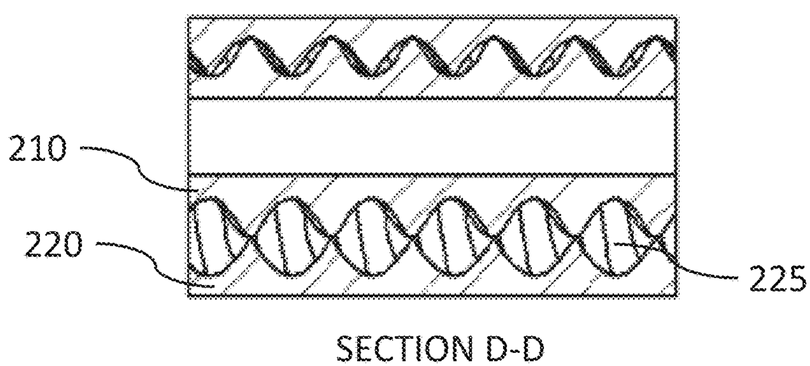


FIG. 2B

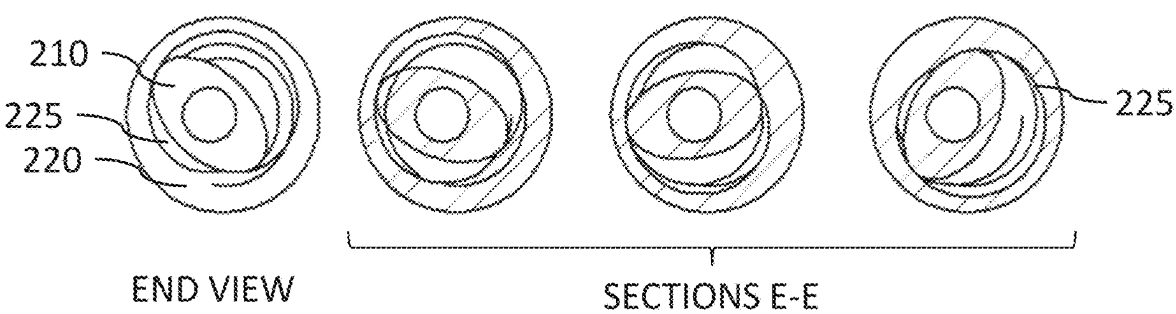


FIG. 2C

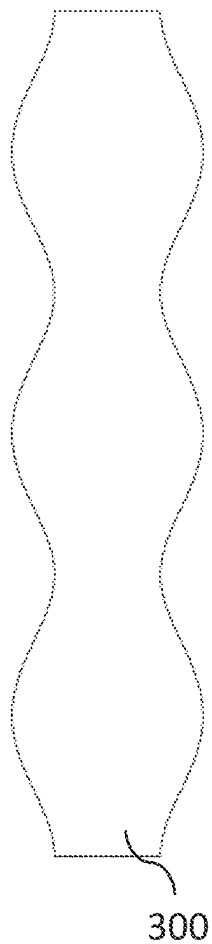


FIG. 3A

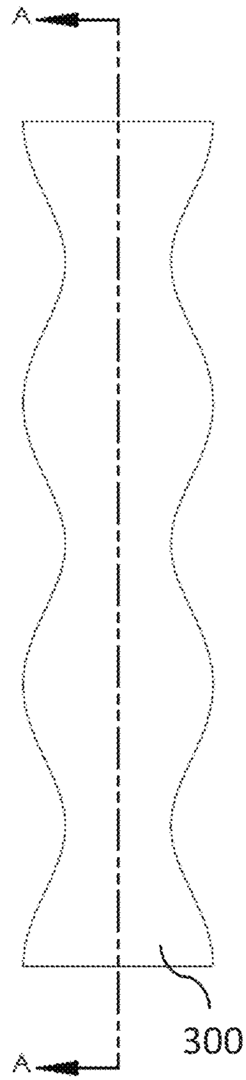


FIG. 3B

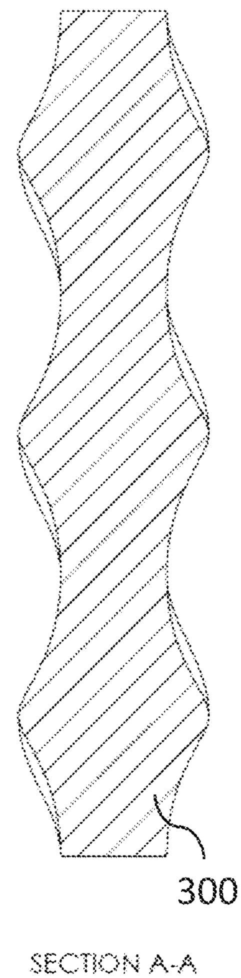


FIG. 3C

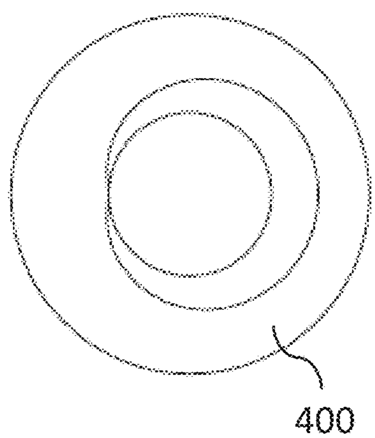


FIG. 4A

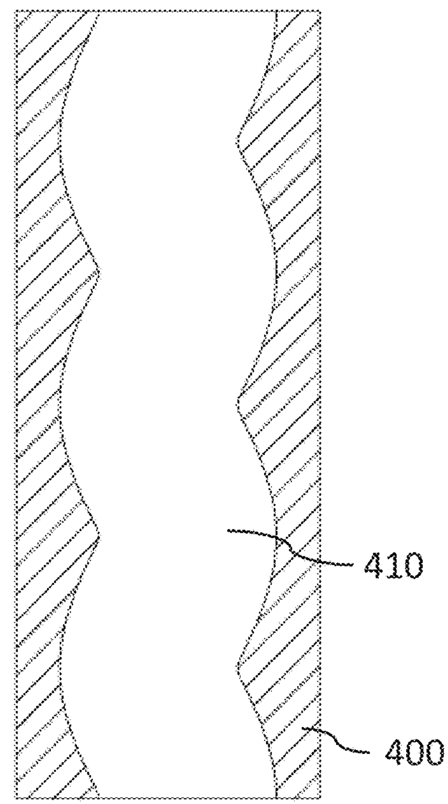


FIG. 4B

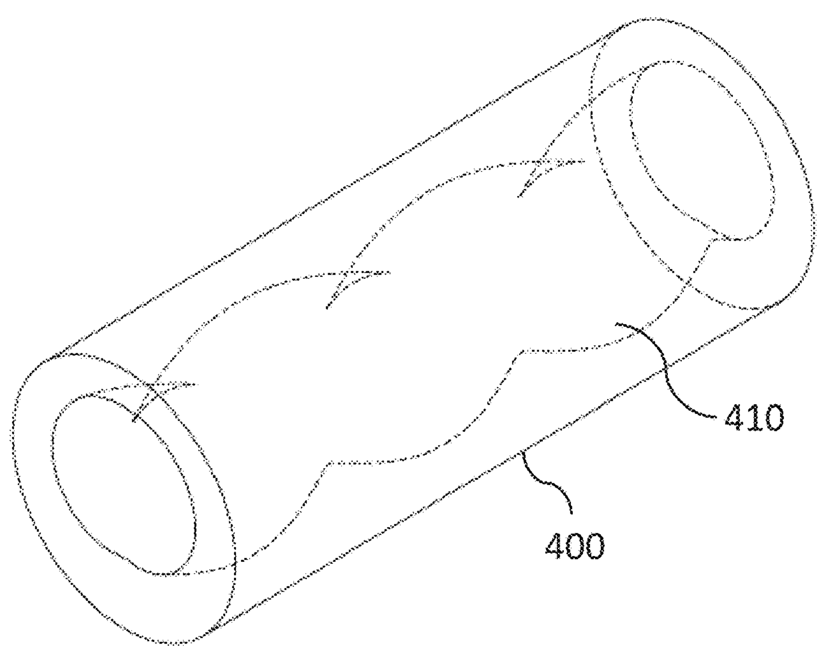


FIG. 4C

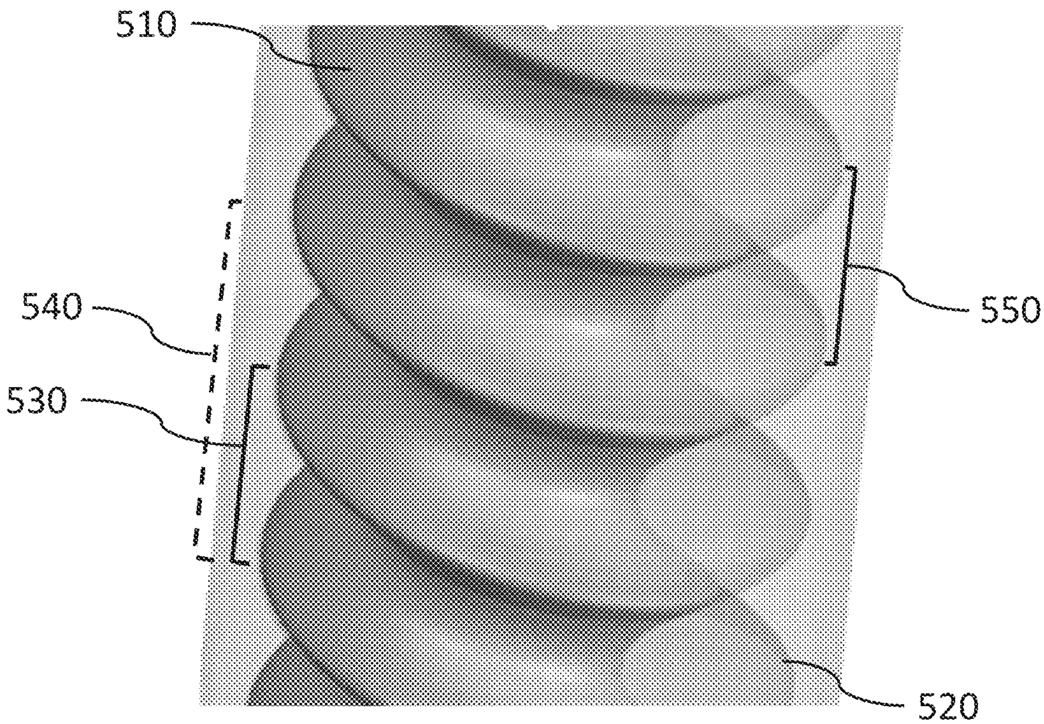


FIG. 5

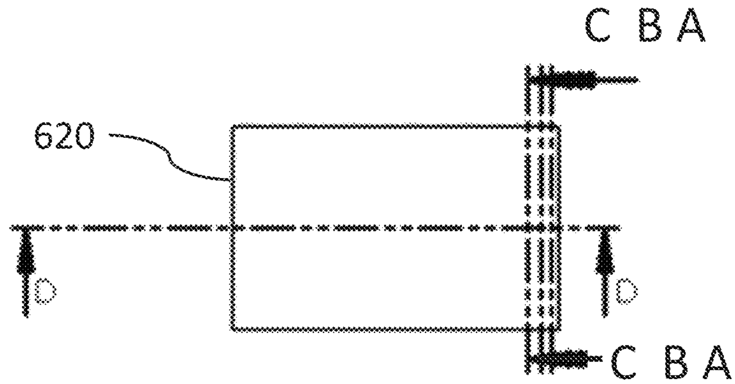


FIG. 6A

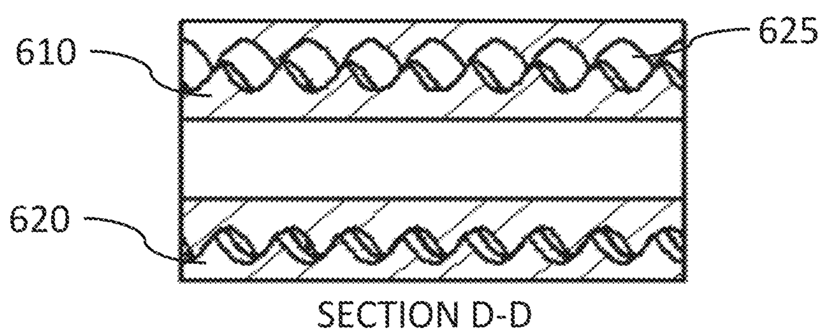
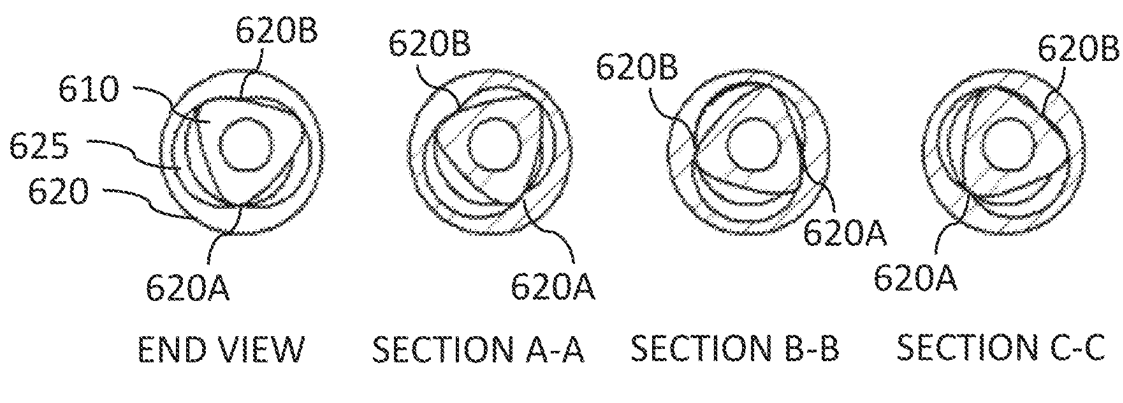


FIG. 6B



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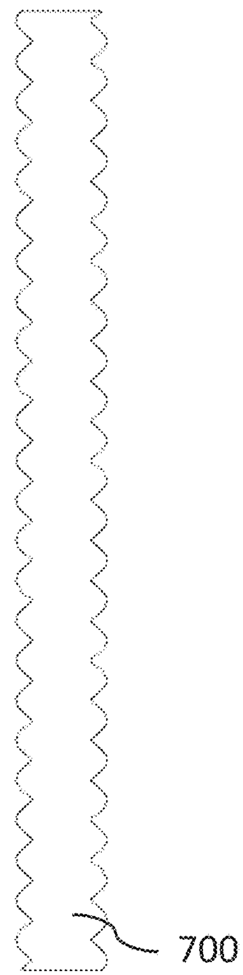


FIG. 7A

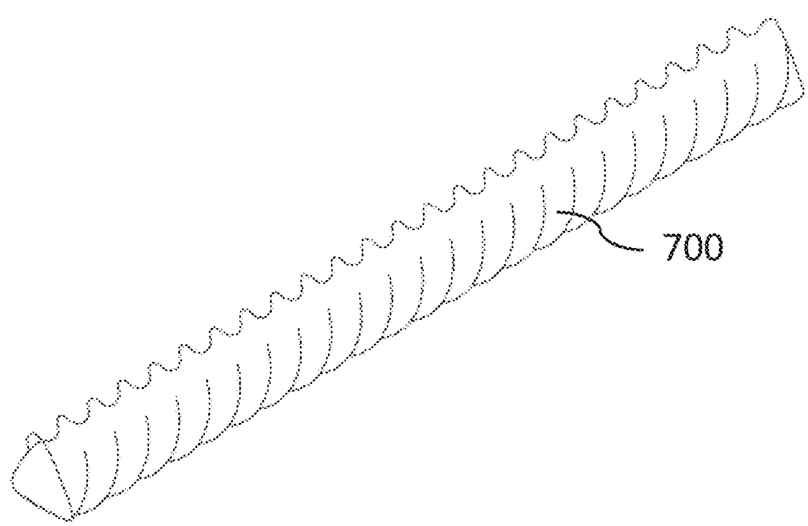


FIG. 7B

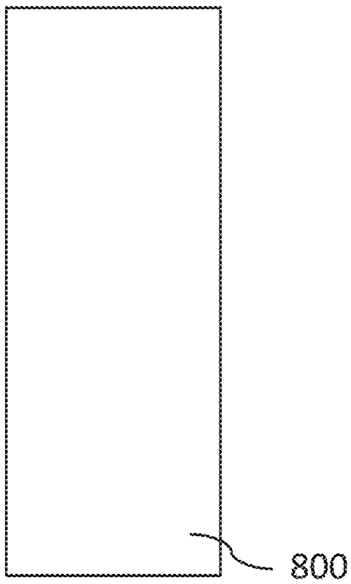


FIG. 8A

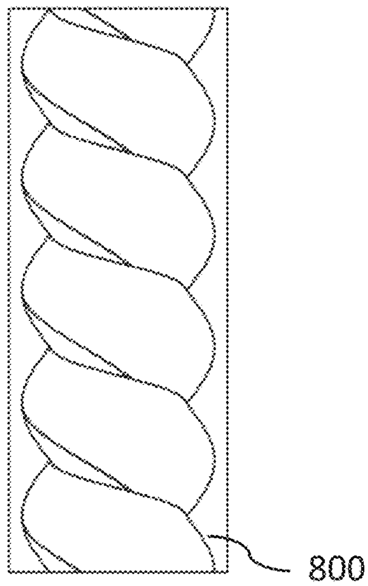


FIG. 8B

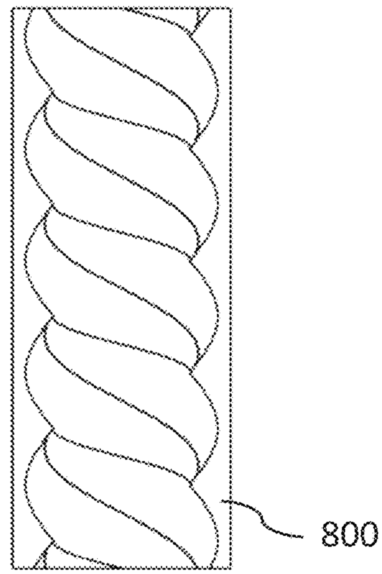


FIG. 8C

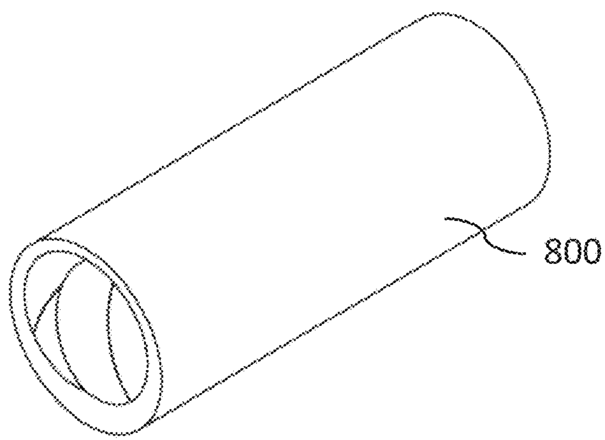


FIG. 8D

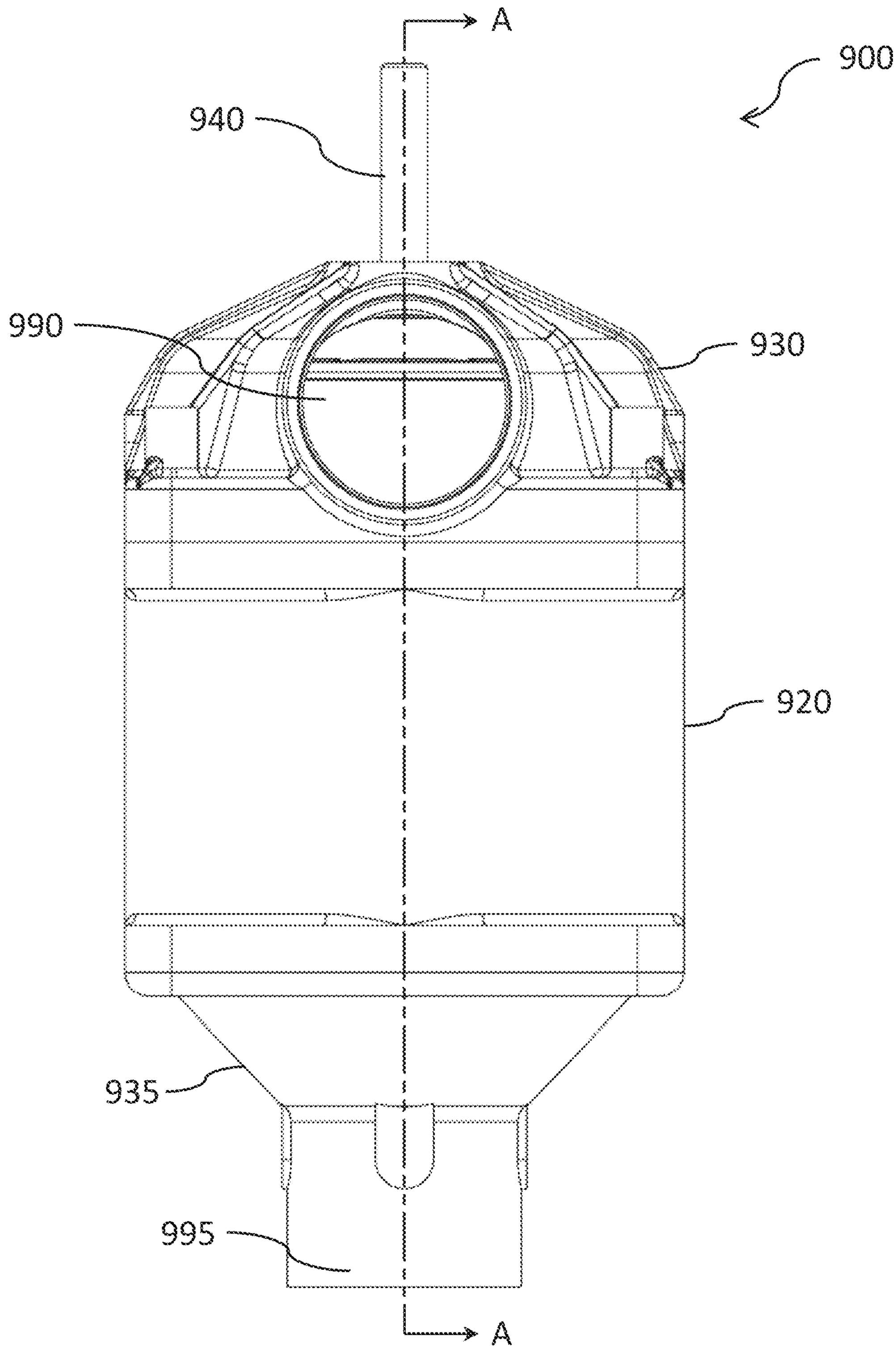


FIG. 9A

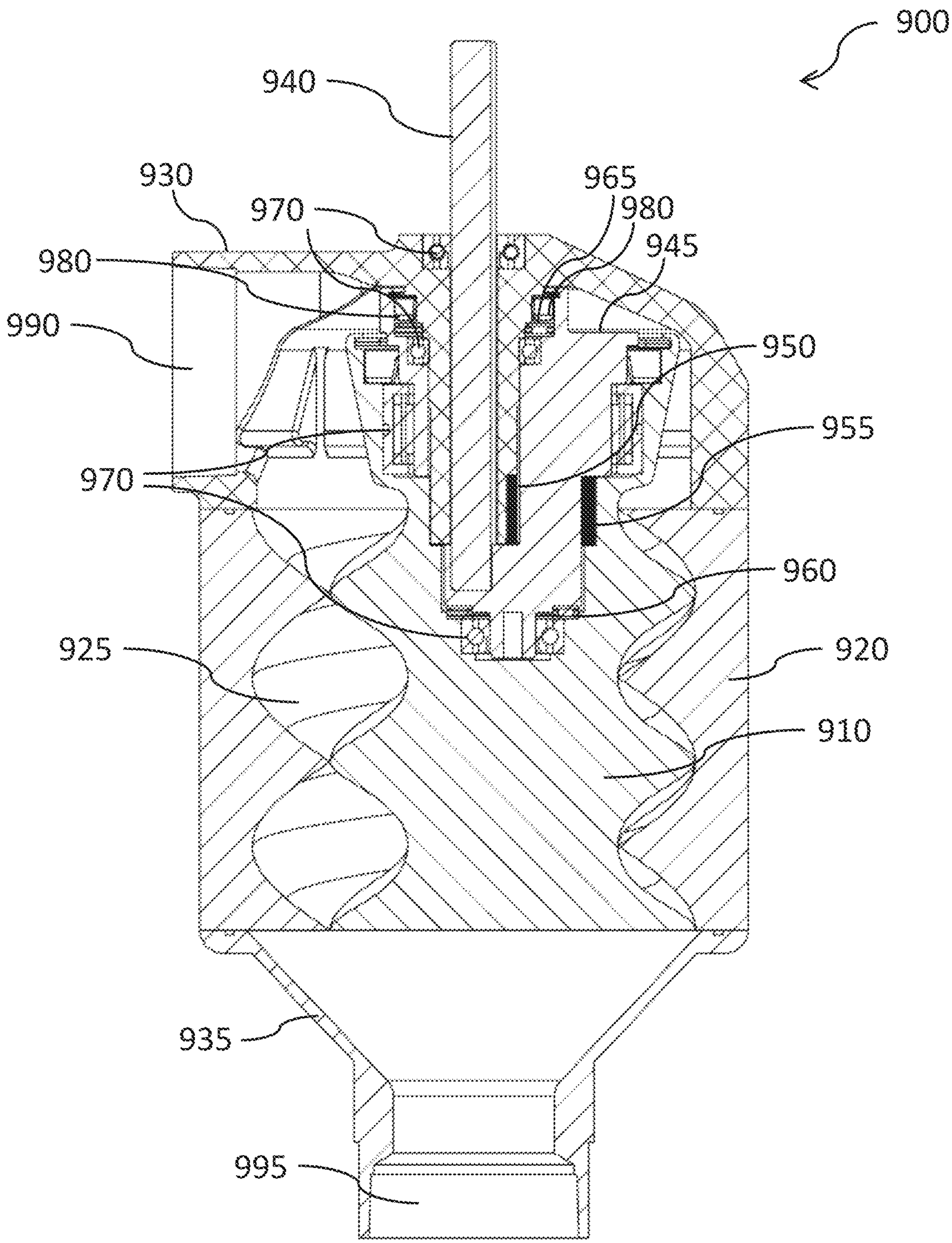

900
940
930
970
965
980
980
945
990
950
955
970
960
925
920
910
935
995

FIG. 9B

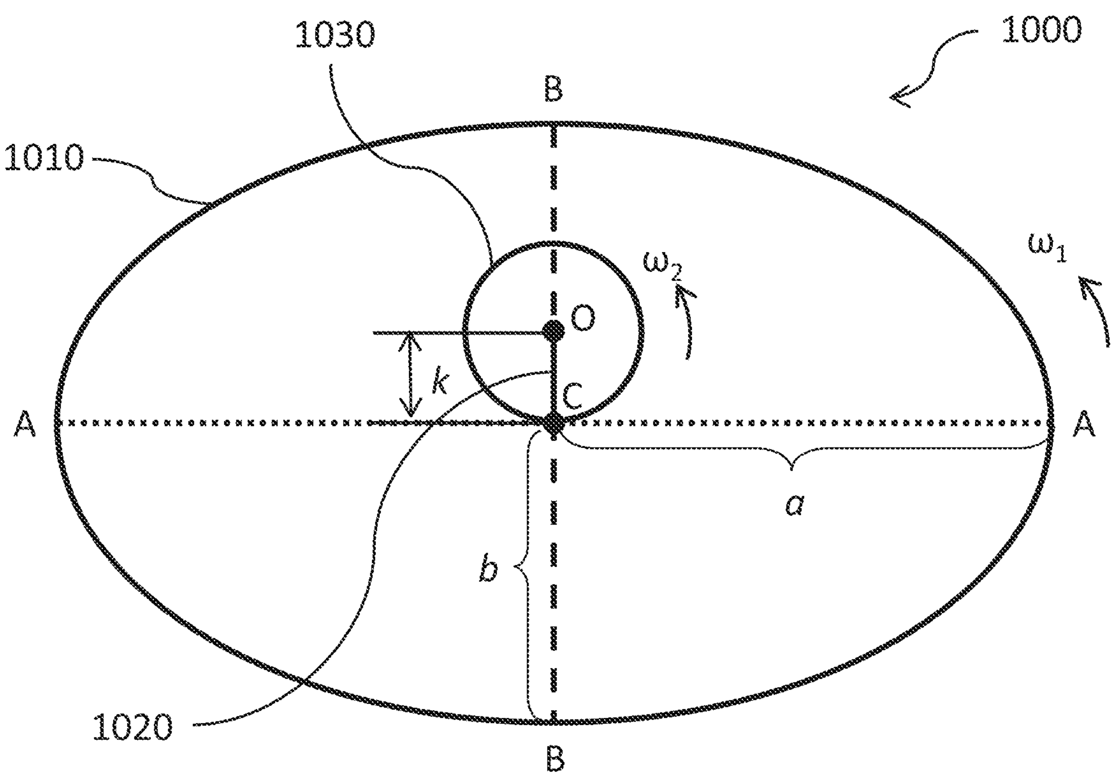


FIG. 10

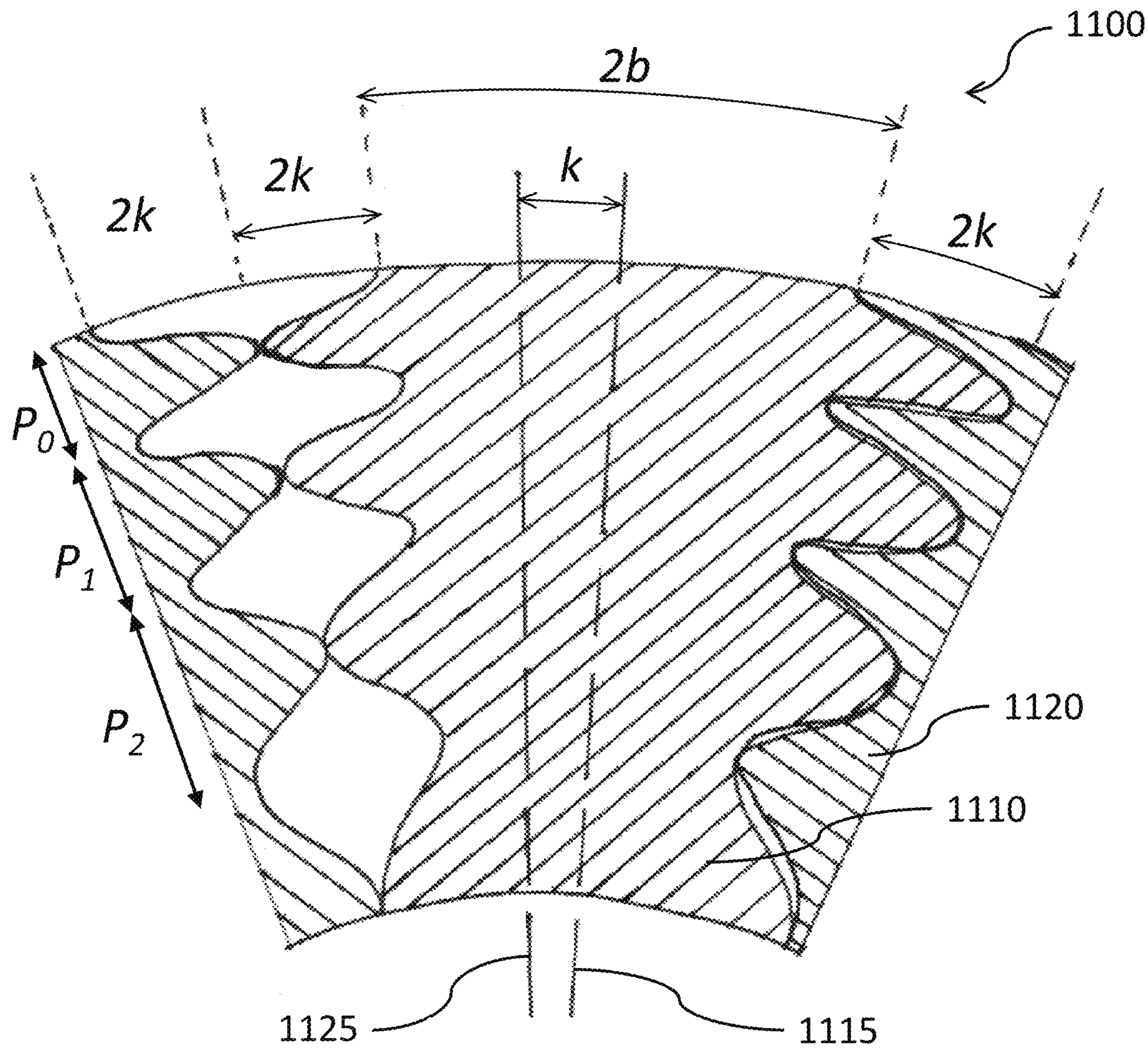


FIG. 11

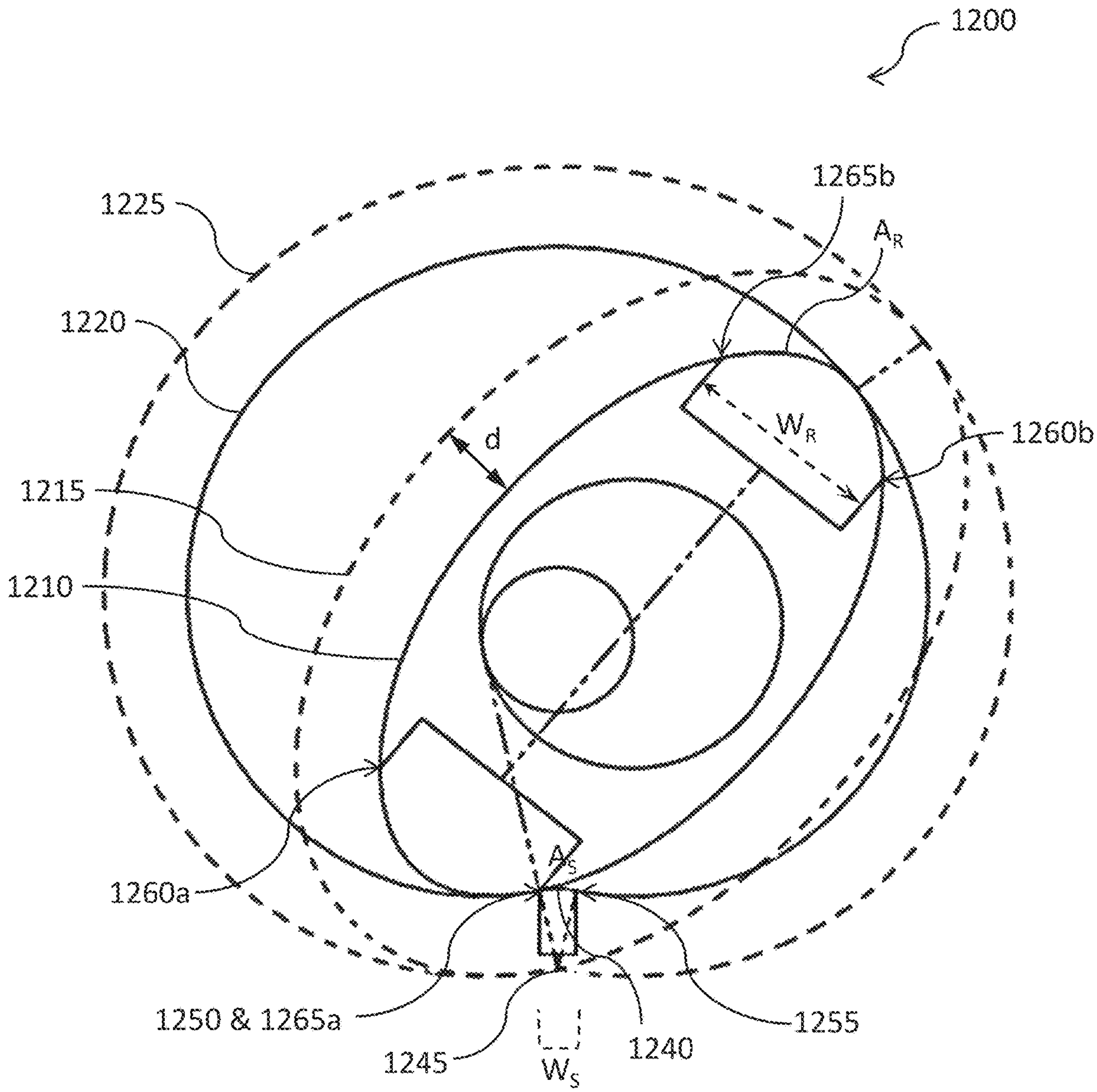

1200
1225
1265b
A_R
1220
W_R
1260b
d
1215
1210
1260a
A_S
1250 & 1265a
1245
W_S
1240
1255

FIG. 12

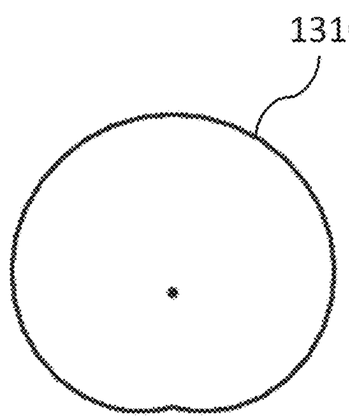


FIG. 13A

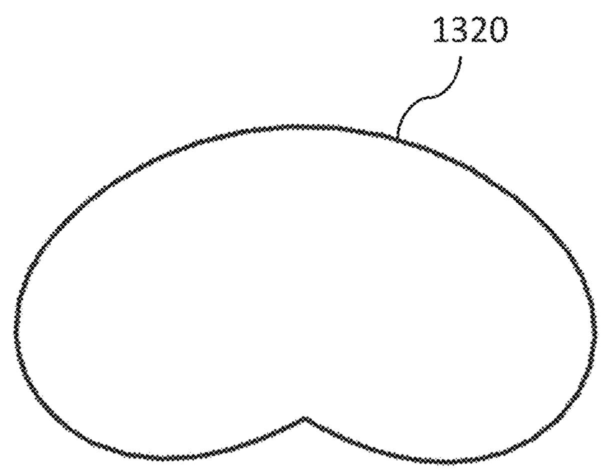


FIG. 13C

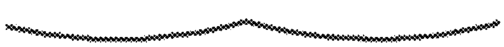


FIG. 13B

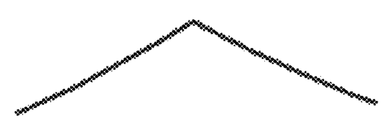


FIG. 13D

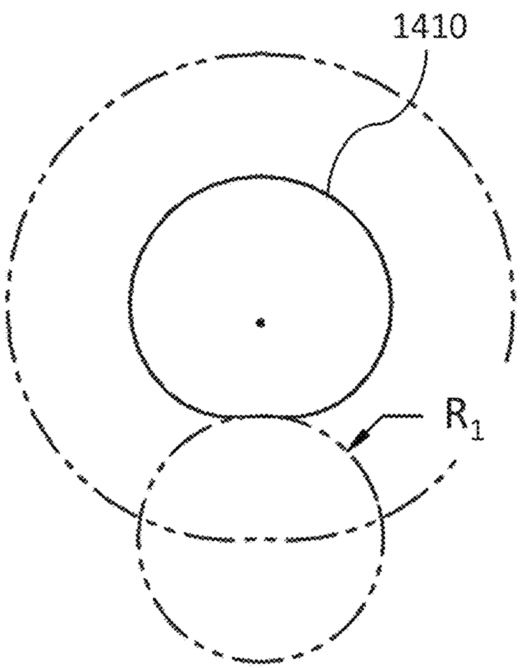


FIG. 14A

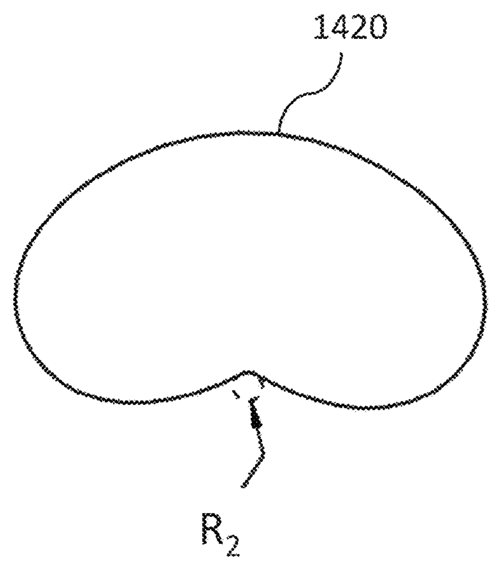


FIG. 14C

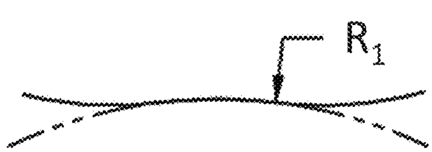


FIG. 14B

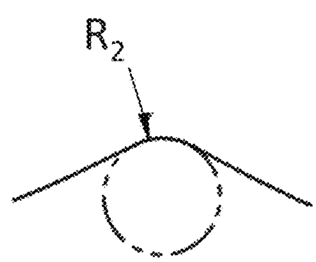


FIG. 14D

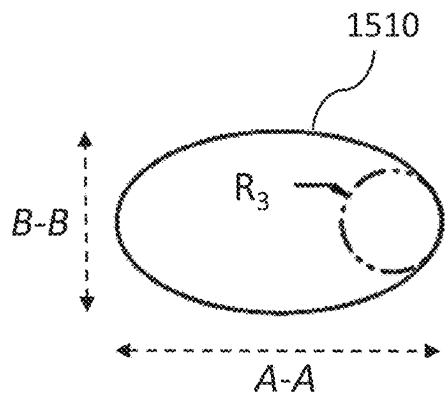


FIG. 15A

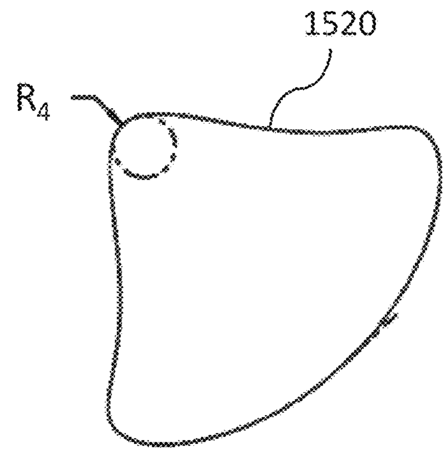


FIG. 15B

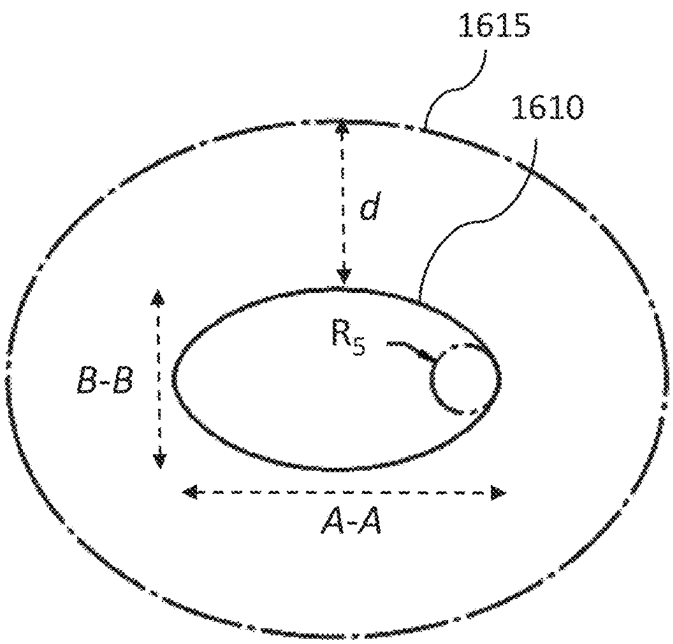


FIG. 16A

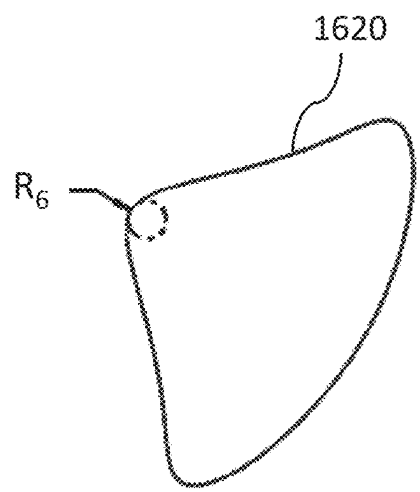


FIG. 16B

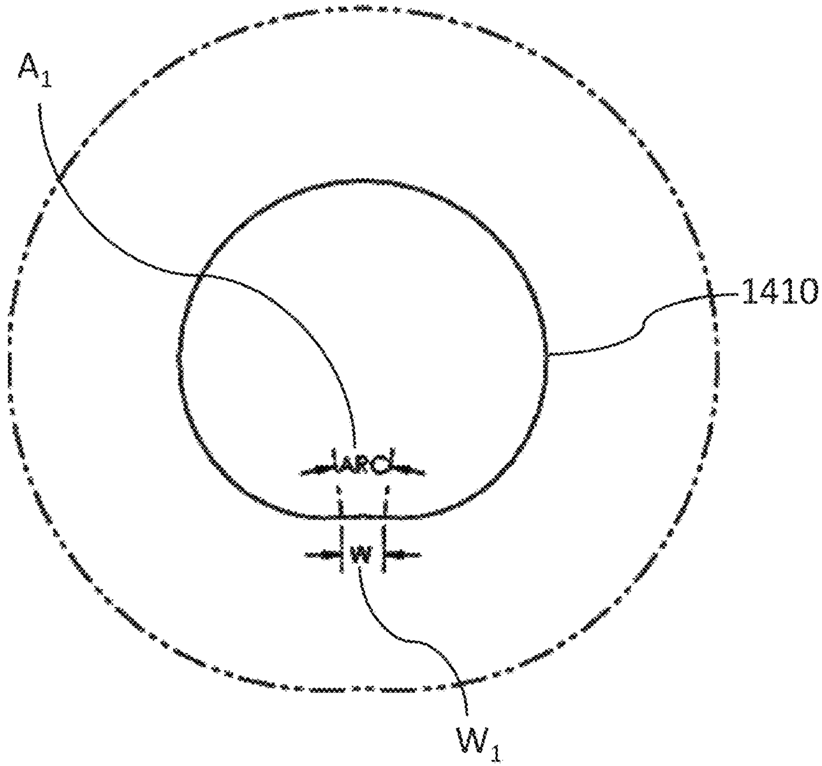


FIG. 17A

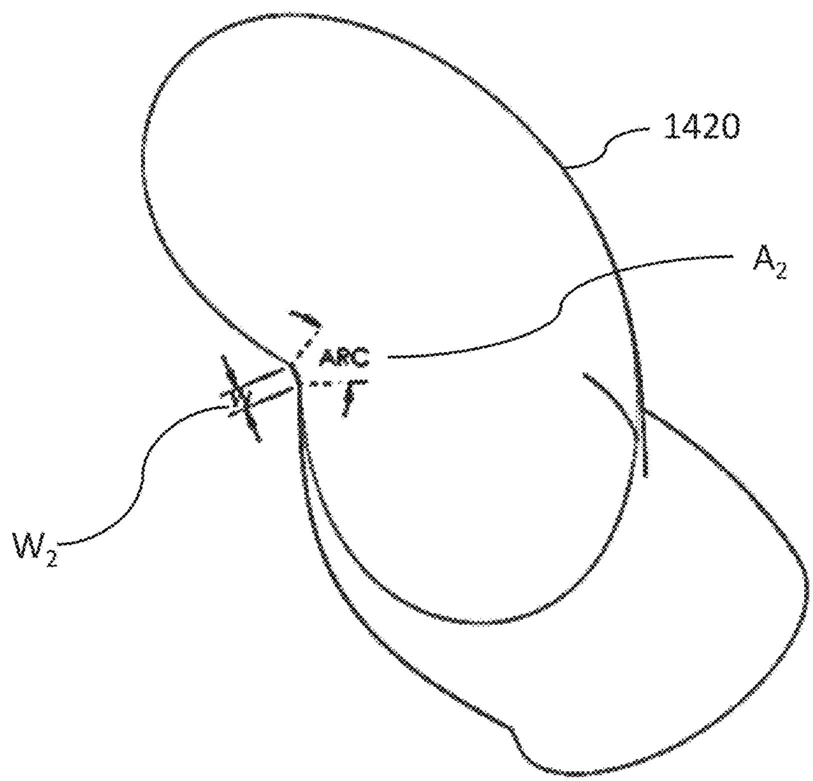


FIG. 17B

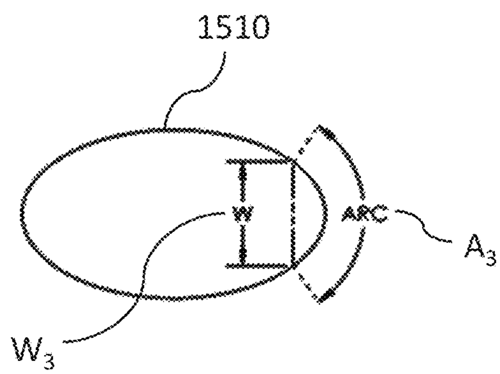


FIG. 18A

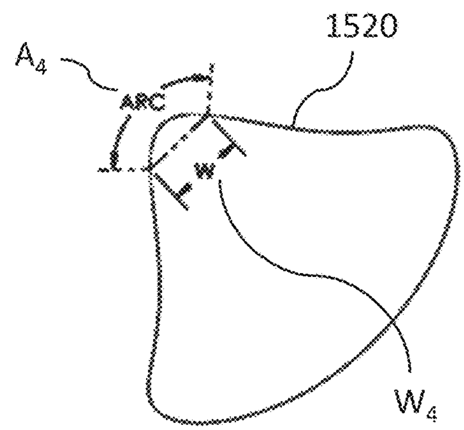


FIG. 18B

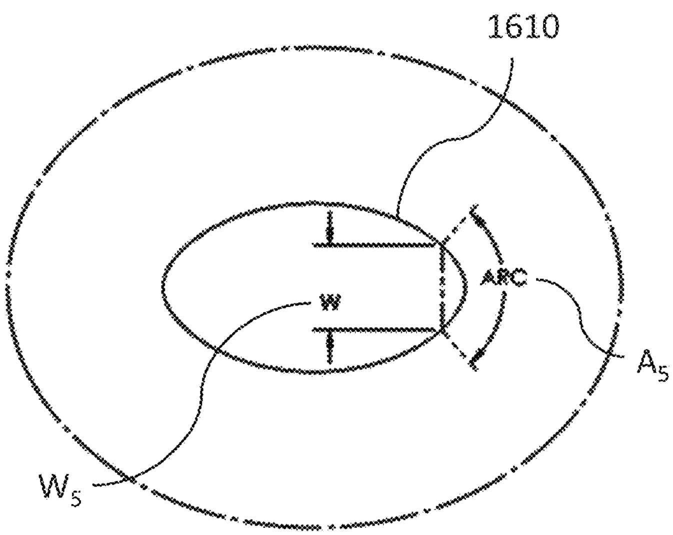


FIG. 19A

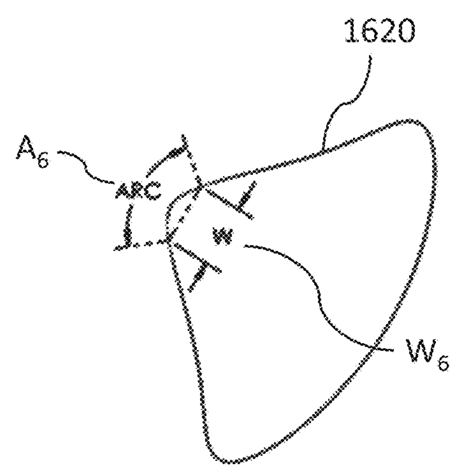


FIG. 19B

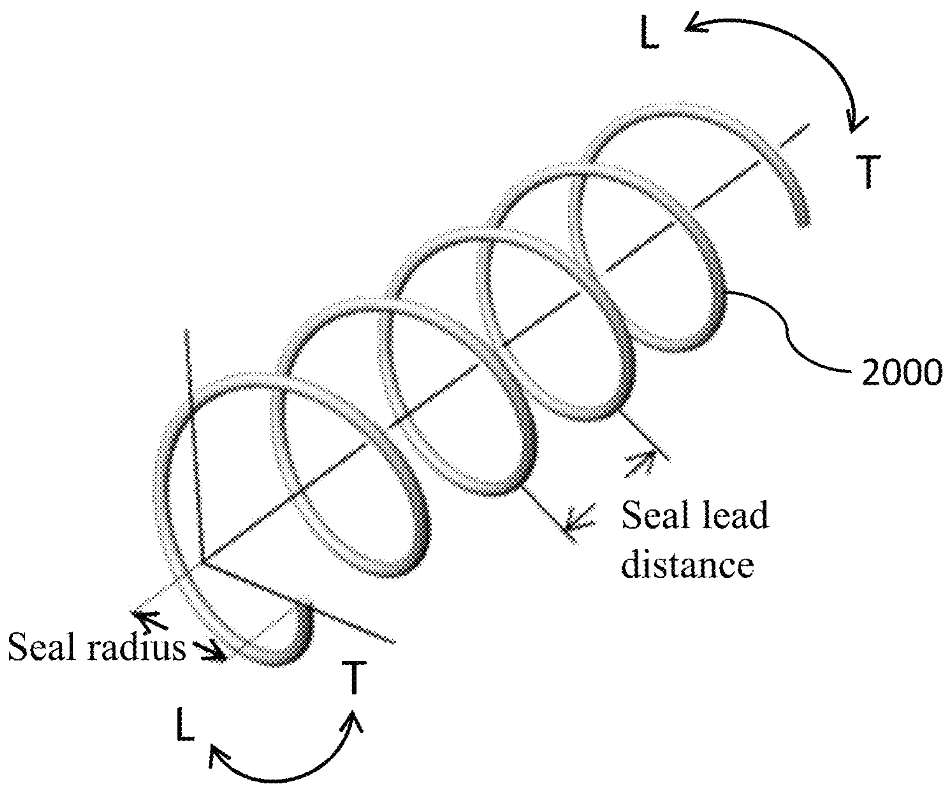


FIG. 20

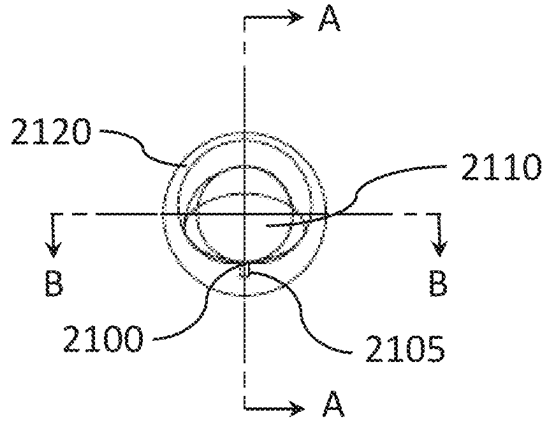
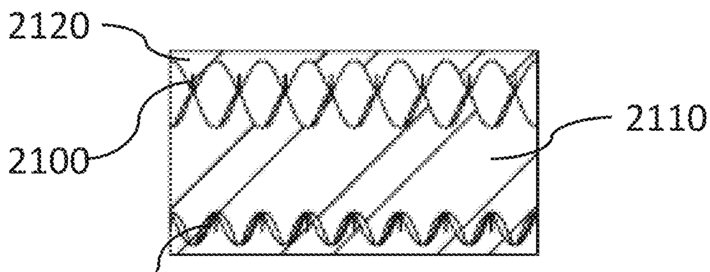
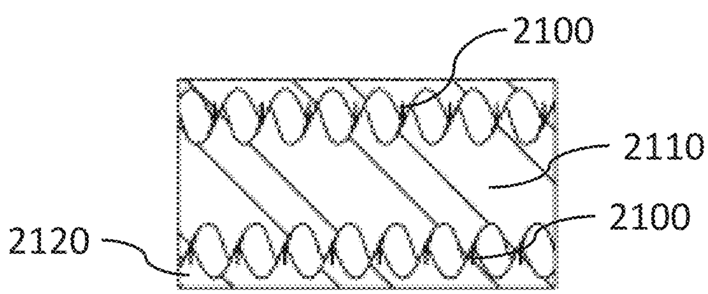


FIG. 21A



SECTION A-A

FIG. 21B



SECTION B-B

FIG. 21C

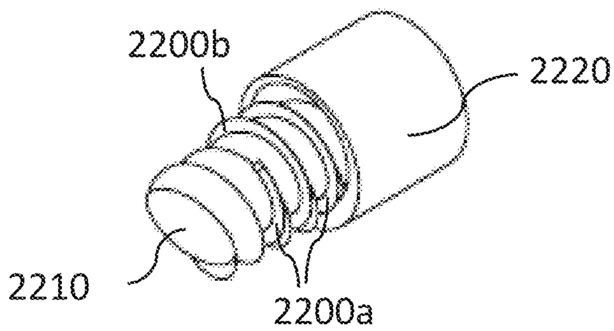


FIG. 22A

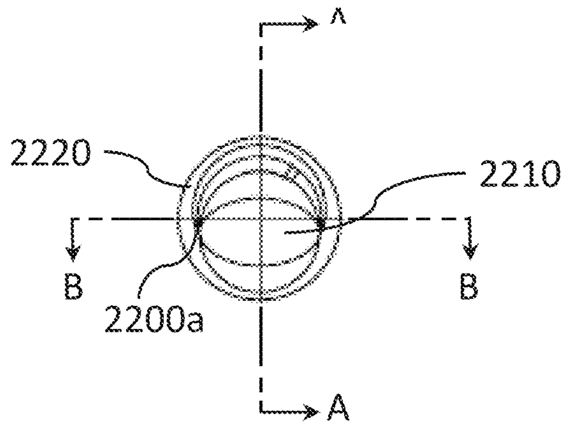


FIG. 22B

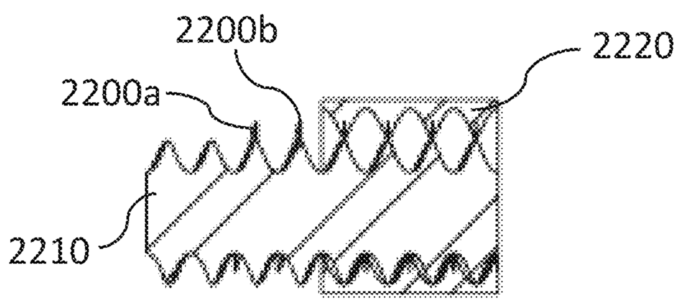


FIG. 22C

SECTION A-A

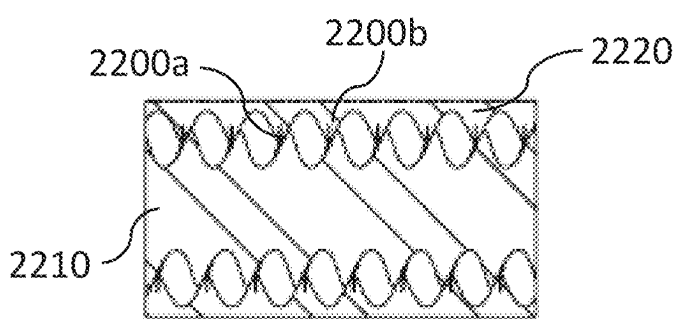


FIG. 22D

SECTION B-B

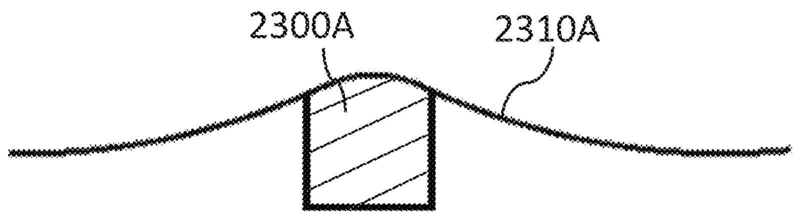


FIG. 23A

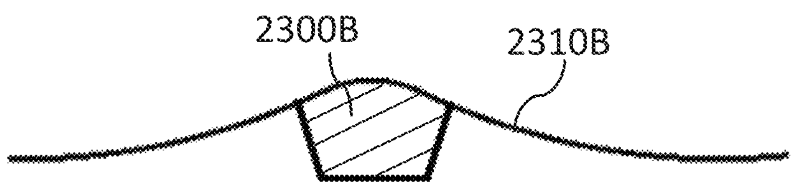


FIG. 23B

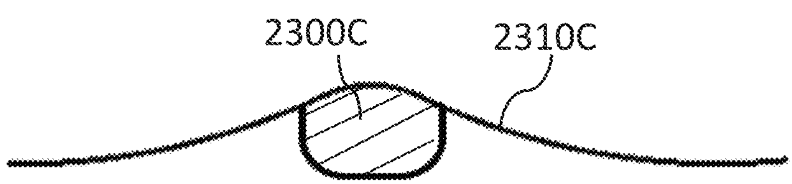


FIG. 23C

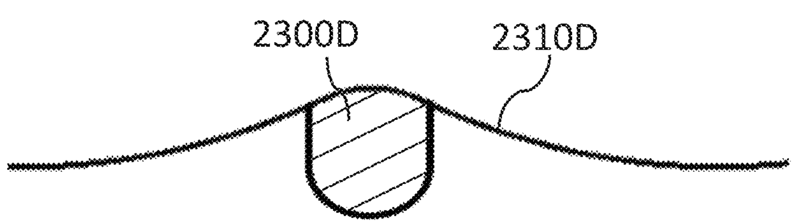


FIG. 23D

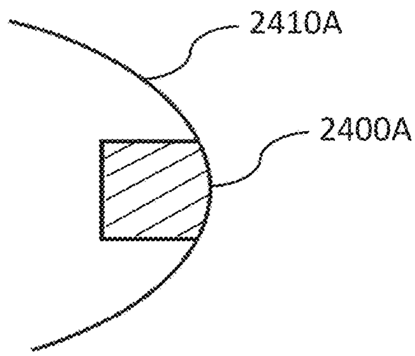


FIG. 24A

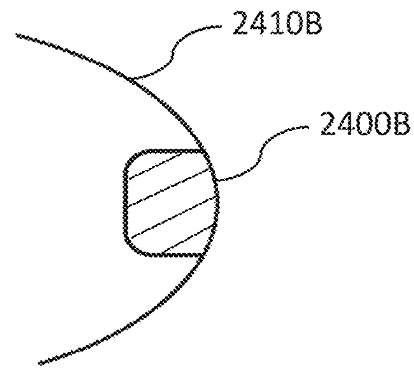


FIG. 24B

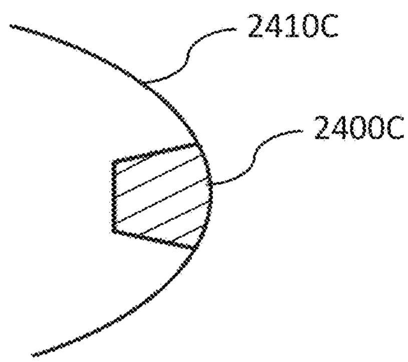


FIG. 24C

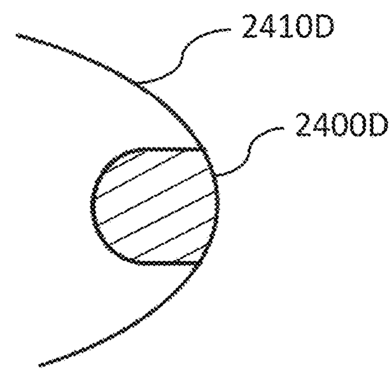


FIG. 24D

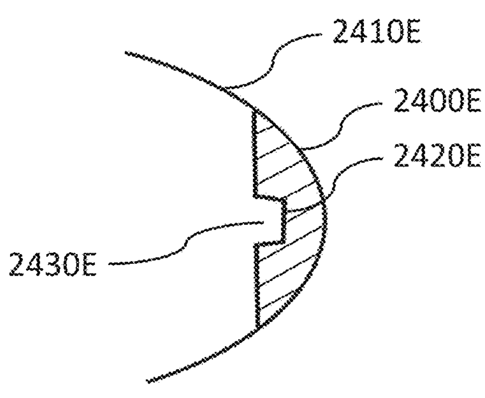


FIG. 24E

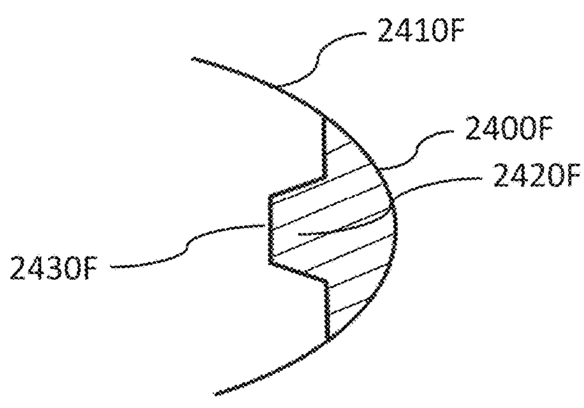


FIG. 24F

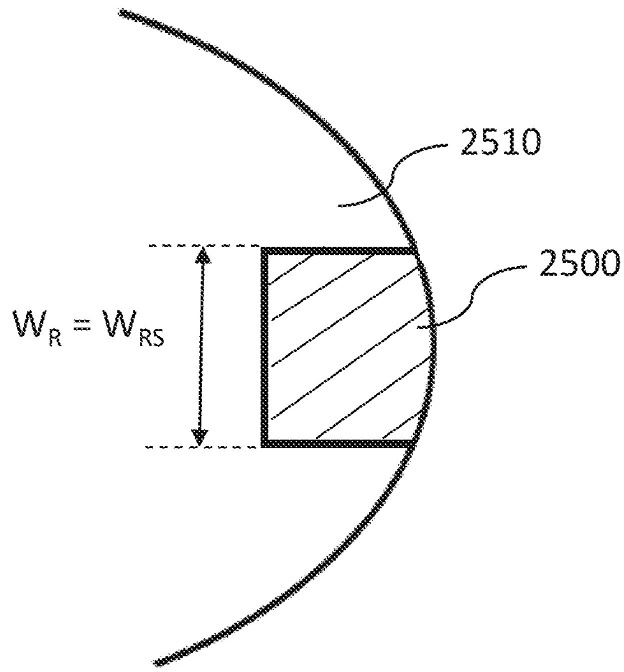


FIG. 25

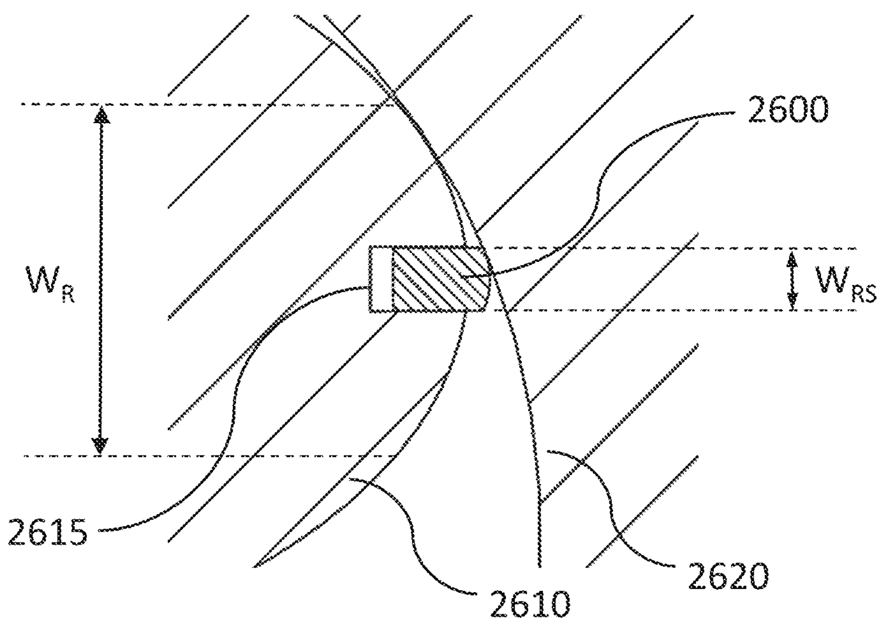


FIG. 26

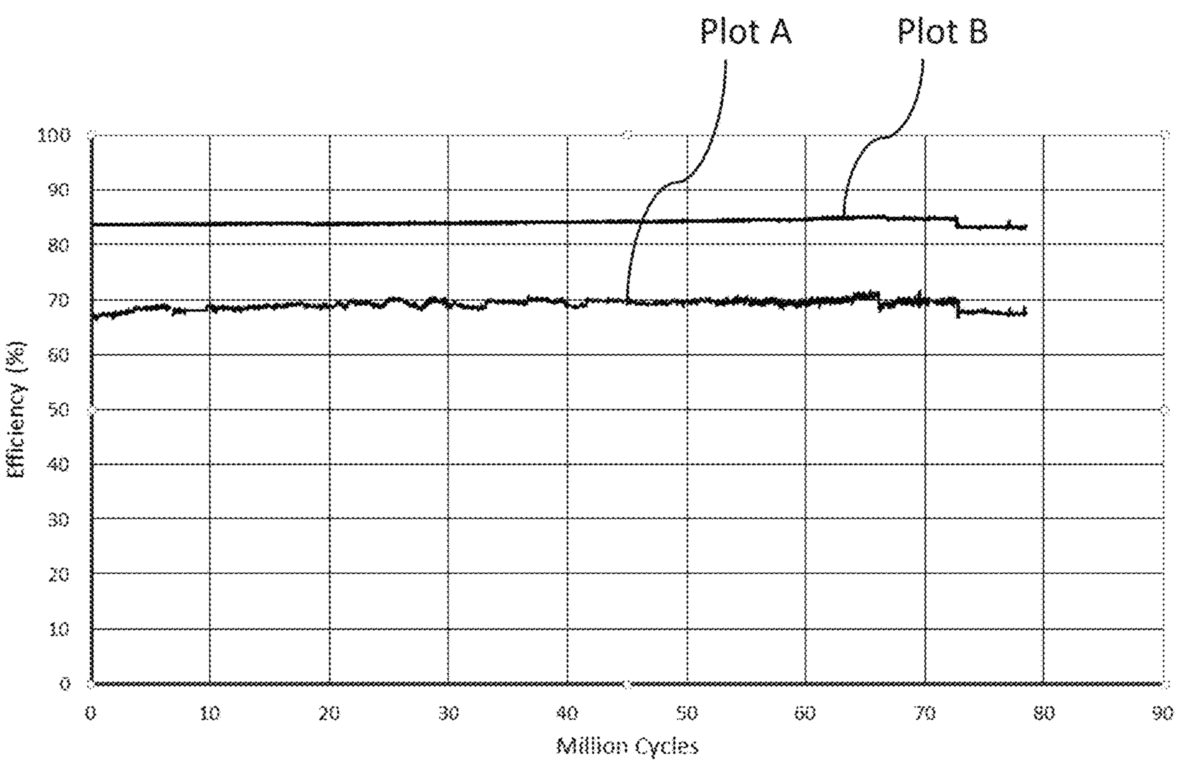

Plot A
Plot B
100
90
80
70
60
50
40
30
20
10
0
Efficiency (%)
0
10
20
30
40
50
60
70
80
90
Million Cycles

FIG. 27

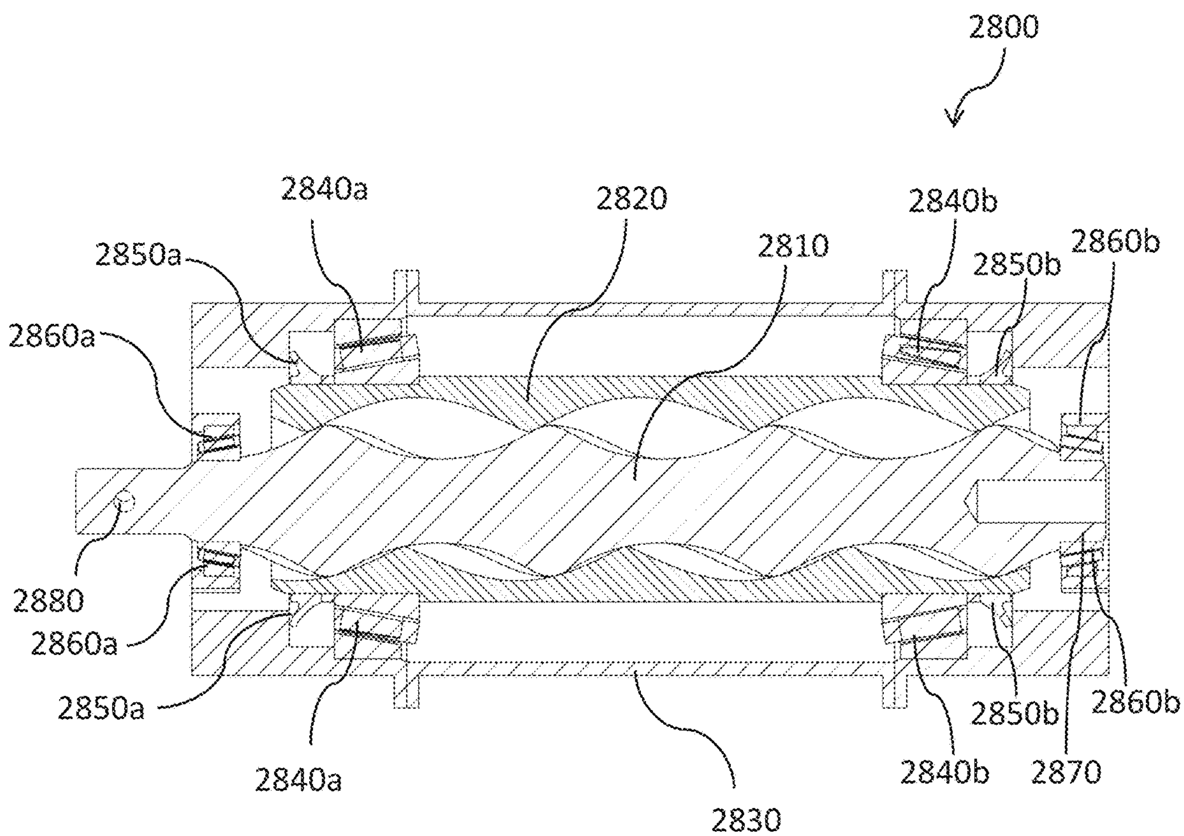

2800
2840a
2820
2810
2840b
2850a
2850b
2860b
2860a
2880
2860a
2850a
2840a
2830
2840b
2850b
2860b
2870

FIG. 28

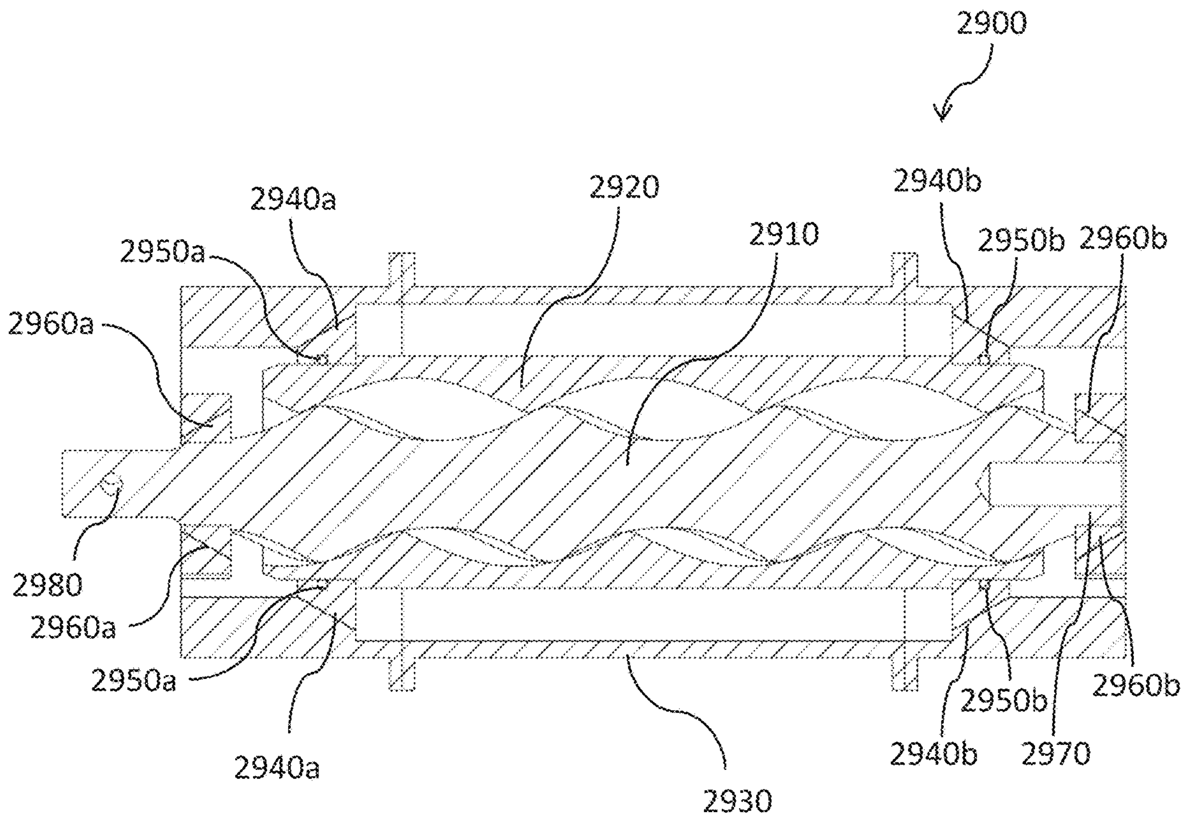

2900
2940a
2920
2940b
2910
2950b
2960b
2950a
2960a
2980
2960a
2950a
2940a
2930
2940b
2950b
2960b
2970

FIG. 29

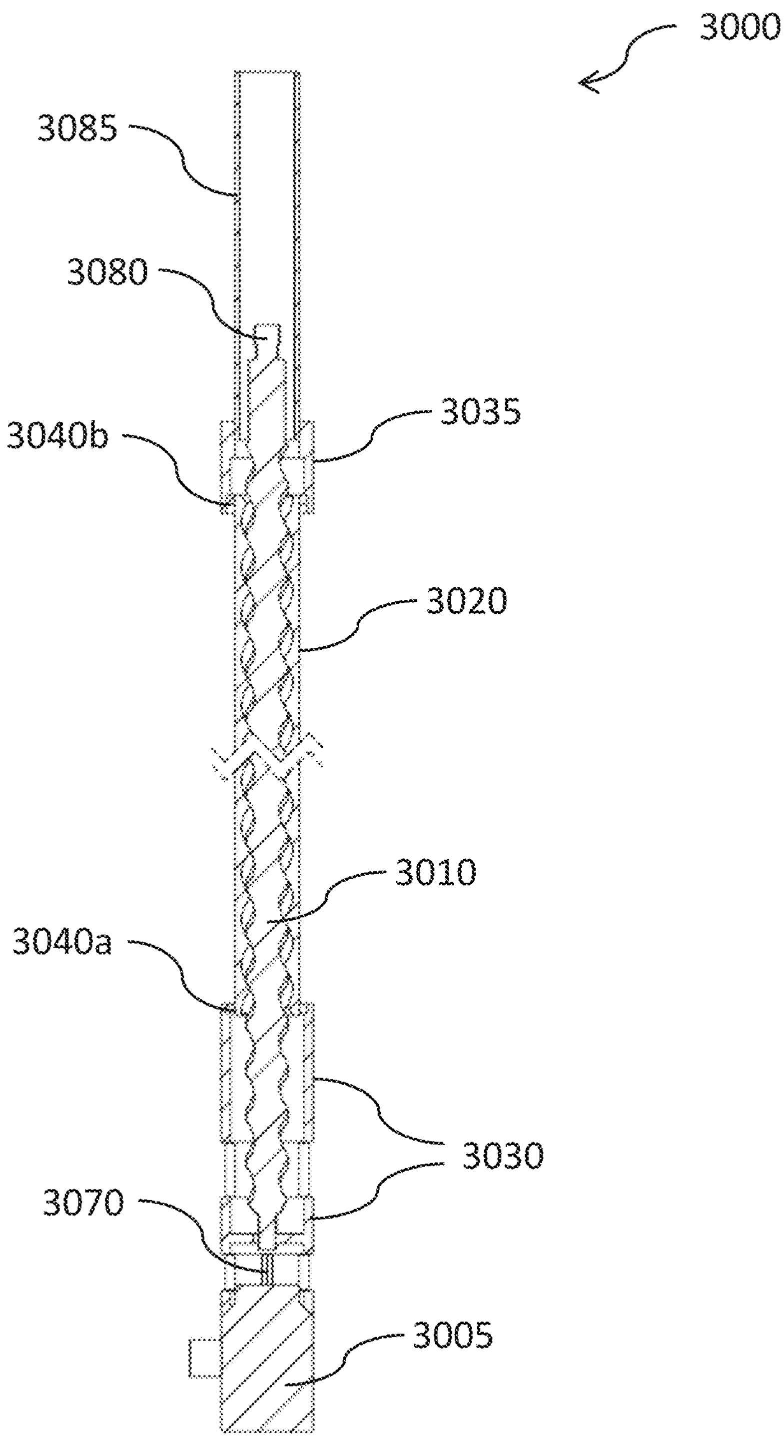


FIG. 30

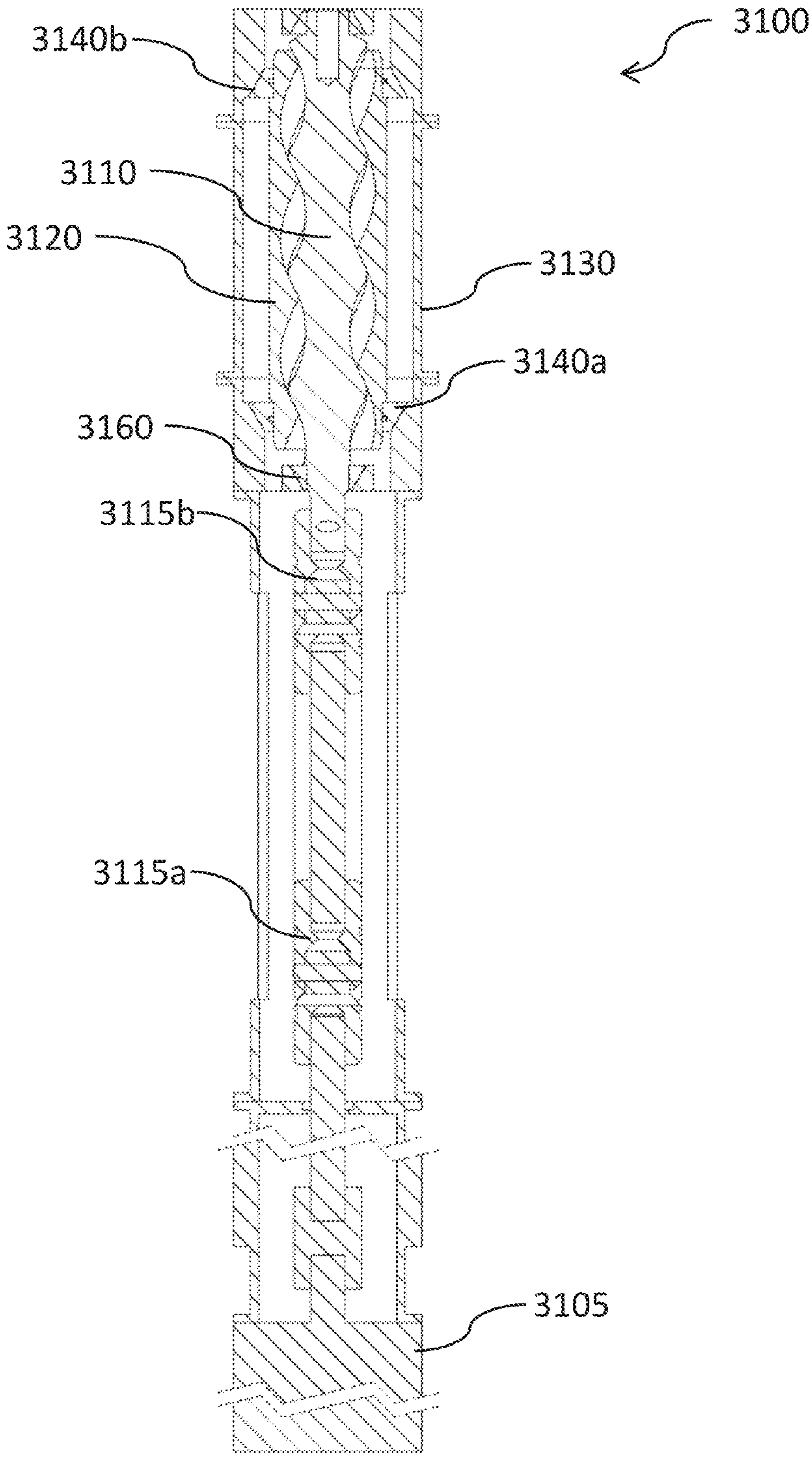


FIG. 31

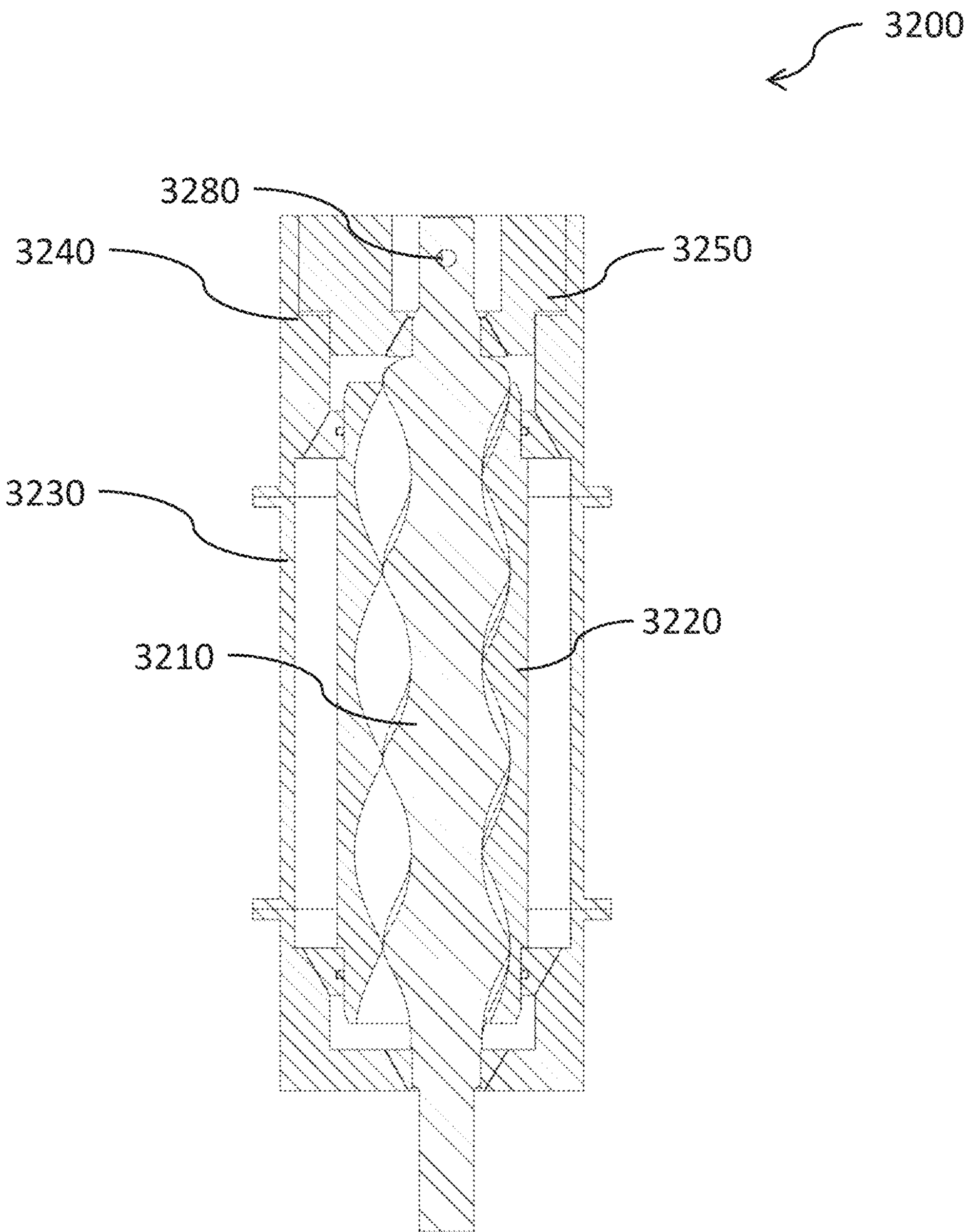


FIG. 32

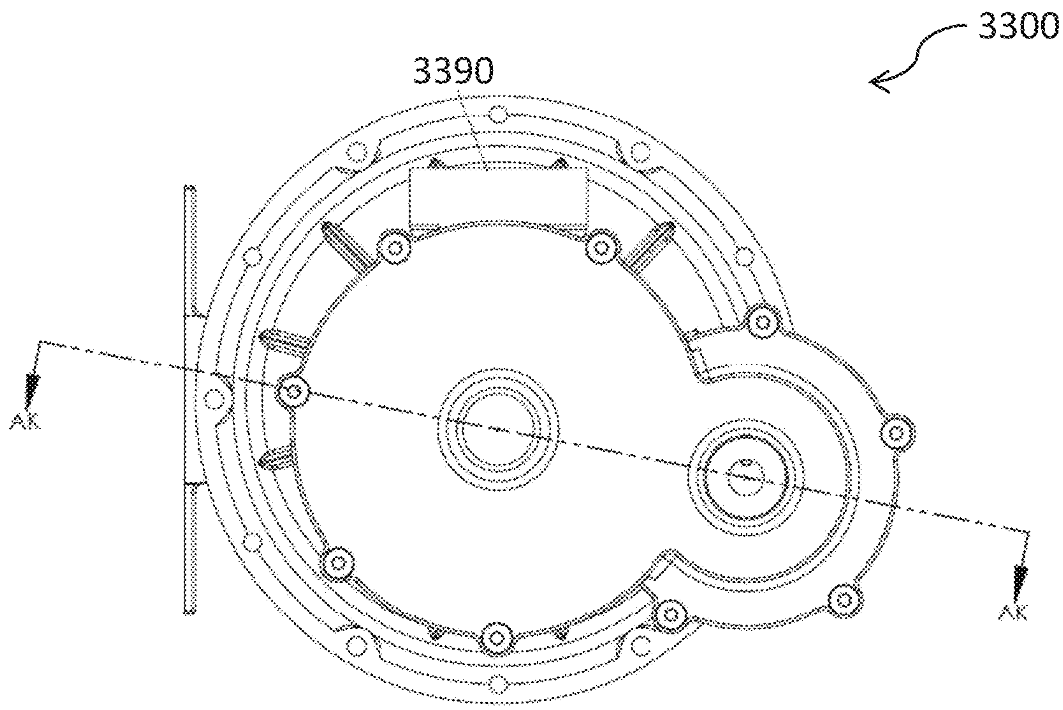


FIG. 33A

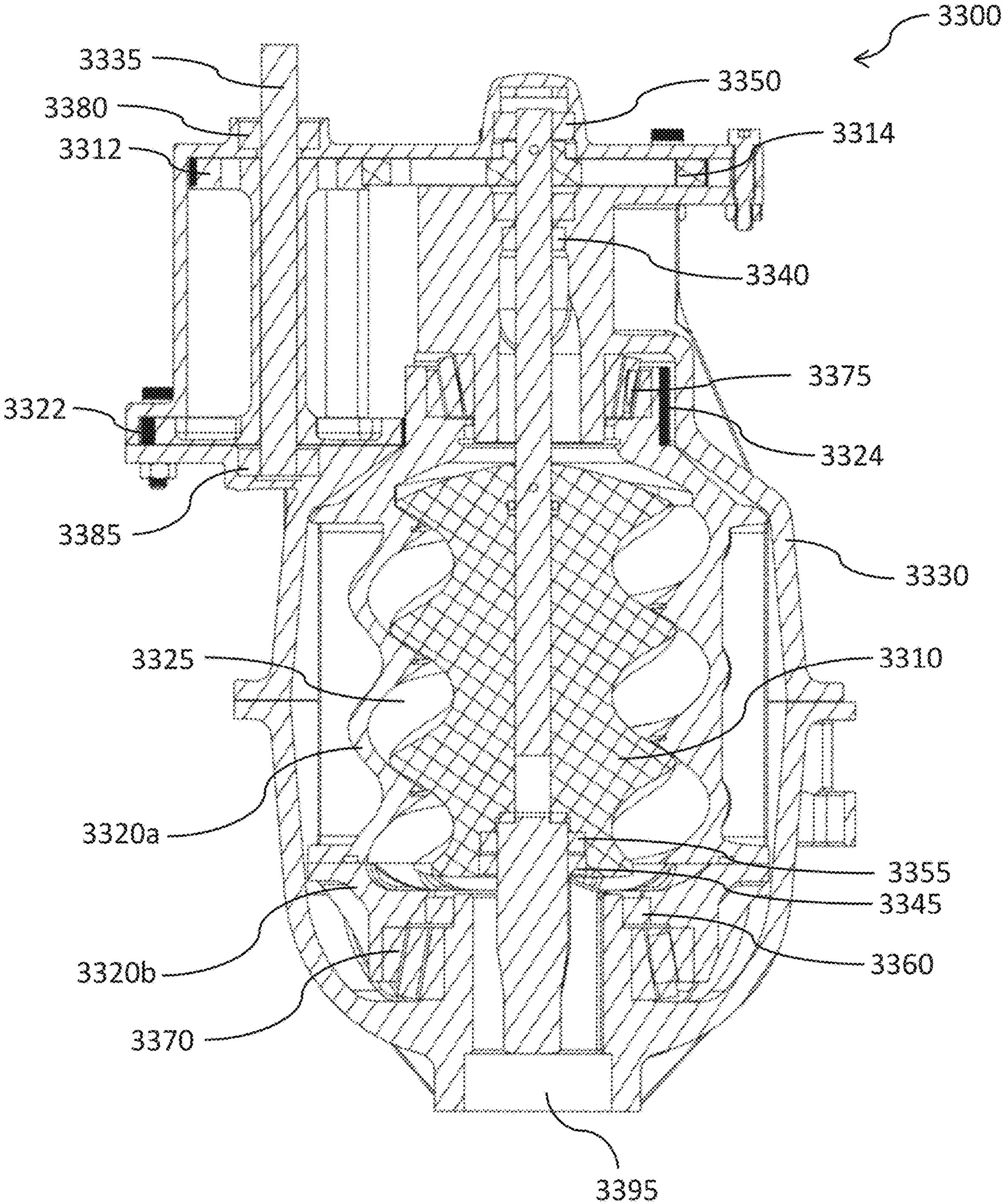

3300
3335
3380
3312
3350
3314
3340
3375
3322
3324
3385
3330
3325
3310
3320a
3355
3345
3320b
3360
3370
3395

FIG. 33B

FIXED-ECCENTRICITY HELICAL TROCHOIDAL ROTARY MACHINES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to and claims priority benefits from U.S. Provisional Patent Application Ser. No. 62/987,817 filed Mar. 10, 2020, entitled "Helical Trochoidal Rotary Machines". The '817 application is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

The present invention relates to rotary positive displacement machines, particularly rotary machines based on trochoidal geometry, the machines including a helical rotor that undergoes planetary motion relative to a helical stator.

Rotary machines, in which at least one rotor has planetary motion within a stator or housing, can be employed, for example, as positive displacement pumps, rotary compressors, vacuum pumps, expansion engines, and the like.

Pumps are devices that can move a working fluid from one place to another. There is a wide range of end uses for various types of pumps, including irrigation, fire-fighting, flood control, water supply, gasoline supply, refrigeration, chemical movement and sewage transfer. Rotary pumps are typically positive displacement pumps with a fixed housing, gears, cams, rotors, vanes and similar elements. Rotary pumps usually have close running clearances (only a small distance or gap between their moving and stationary parts), do not require suction or discharge valves, and are often lubricated only by the fluid being pumped.

A positive displacement pump moves fluid by trapping a volume of fluid in a chamber and forcing the trapped volume into a discharge pipe. Some positive displacement pumps employ an expanding chamber on the suction side and a decreasing chamber on the discharge side. Fluid flows into the pump intake as the chamber on the suction side expands, and the fluid flows out of the discharge pipe as the chamber collapses. The output volume is the same for each cycle of operation. An ideal positive displacement pump can produce the same flow rate at a given pump speed regardless of the discharge pressure.

Various classes of rotary machines based on trochoidal geometries are known. Such rotary machines comprise a rotor or stator whose cross-section is bounded by a certain family of curves, known as trochoids or trochoidal shapes. These include machines with the following configurations:

(1) rotary machines in which the rotor is hypotrochoidal in cross-section, and undergoes planetary motion (spins about its axis and orbits eccentrically) within a stator that is shaped as an outer envelope of that rotor (with the rotor having one more apex or lobe than the stator cavity);

(2) rotary machines in which the stator cavity is hypotrochoidal in cross-section, and the rotor undergoes planetary motion within the stator and is shaped as the inner envelope of that stator (with the rotor having one less apex or lobe than the stator cavity);

(3) rotary machines in which the rotor is epitrochoidal in cross-section, and undergoes planetary motion within a stator that is shaped as an outer envelope of that rotor (with the rotor having one less apex or lobe than the stator cavity); and

(4) rotary machines in which the stator cavity is epitrochoidal in cross-section, and the rotor undergoes planetary motion within the stator and is shaped as the inner envelope of that stator (with the rotor having one more apex or lobe than the stator cavity).

Thus, in all of these configurations, the rotor or stator is a trochoidal component, meaning it has a cross-sectional shape that is a trochoid.

Generally, as used herein, an object is said to undergo "planetary motion" when it spins about one axis and orbits about another axis.

Rotary machines, such as those described above, can be designed for various applications including, for example, pumps, compressors, and expansion engines. The design, configuration and operation of different rotary machines can offer particular advantages for certain applications.

Progressive cavity pumps (PCPs) are another type of rotary positive displacement machine that can offer advantages for certain applications. In PCPs, a rotor is disposed and rotates eccentrically within a helical stator cavity. The material to be pumped (typically a fluid) follows a helical path along the pump axis. The rotor is typically formed of rigid material and the stator (or stator lining) of resilient or elastomeric material. The rotor is typically helical with a circular transverse cross-section displaced from the axis of the helix, and defines a single-start thread. The corresponding stator cavity is a double helix (two-start thread) with the same thread direction as the rotor, and in transverse cross-section has an outline defined by a pair of spaced apart semi-circular ends joined by a pair of parallel sides. The pitch (the axial distance between adjacent threads) of the stator is the same as the pitch of the rotor, and the lead of the stator (the axial distance or advance for one complete turn) is twice that of the rotor.

In PCPs, the rotor generally seals tightly against the elastomeric stator as it rotates within it, forming a series of discrete fixed-shape, constant-volume chambers between the rotor and the stator. The fluid is moved along the length of the pump within the chambers as the rotor turns relative to the stator. The volumetric flow rate is proportional to the rotation rate. The discrete chambers taper down toward their ends and overlap with their neighbors, so that the flow area is substantially constant and in general, there is little or no flow pulsation caused by the arrival of chambers at the outlet. The shear rates are also typically low in PCPs in comparison to those in other types of pumps. In PCPs, where the rotor touches the stator, the contacting surfaces are generally traveling transversely relative to one another, so small areas of sliding contact occur.

SUMMARY OF THE INVENTION

Rotary positive displacement machines based on trochoidal geometry can include a helical rotor that undergoes planetary motion relative to a helical stator. Some such machines can be configured so that the axis of the rotor is spaced from the axis of the rotor axis, and the rotor and stator are held at a fixed eccentricity. The rotor can be configured to spin about its axis and the stator can be configured to spin about its axis. With the rotor and stator held at a fixed eccentricity, the rotor can undergo planetary motion relative to the stator without orbiting.

In a first aspect, a rotary machine comprises a stator and a rotor disposed within the stator. In some embodiments, the rotor has a helical profile, and a rotor axis, and has a hypotrochoidal shape at any cross-section transverse to the rotor axis along at least a portion of a length of the rotor. In some embodiments, the stator has a helical profile, a stator axis, and has a shape at any cross-section transverse to the stator axis along at least a portion of a length of the stator that is an outer envelope formed when the hypotrochoidal shape of the rotor undergoes planetary motion. In some embodiments, the stator axis is offset relative to the rotor axis. In some embodiments, the rotor is configured to spin about its axis, the stator is configured to spin about its axis, and the rotor and the stator are held at a fixed eccentricity (their longitudinal axes are offset or spaced from one another) so that the rotor undergoes planetary motion relative to the stator but does not orbit.

In some embodiments of a rotary machine in accordance with a first aspect described above, the hypotrochoidal shape has n lobes, where n is an integer, the outer envelope shape has (n−1) lobes, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is n:(n−1). In some such embodiments, the hypotrochoidal shape is an ellipse, n=2, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1.

In some embodiments of a rotary machine in accordance with a first aspect described above, the rotor has a double-start helical profile having a first rotor thread and a second rotor thread, the stator has a single-start helical profile. In some embodiments, the rotary machine further comprises at least one helical seal mounted on the rotor and/or at least one helical seal mounted on the stator. In some embodiments, the at least one helical seal comprises two rotor seals mounted on the rotor and/or a stator seal mounted on the stator.

In a second aspect, a rotary machine comprises a stator and a rotor disposed within the stator. The rotor has a rotor axis and a helical profile, and the rotor has a rotor shape that is inwardly offset from a hypotrochoidal shape at any cross-section transverse to the rotor axis along at least a portion of a length of the rotor. The stator has a stator axis and a helical profile, and the stator has a stator shape at any cross-section transverse to the stator axis along at least a portion of a length of the stator that is an outer envelope formed when the rotor shape undergoes planetary motion. In some embodiments, the stator axis is offset relative to the rotor axis. In some embodiments, the rotor is configured to spin about its axis, the stator is configured to spin about its axis, and the rotor and the stator are held at a fixed eccentricity so that the rotor undergoes planetary motion relative to the stator but does not orbit.

In some embodiments of a rotary machine in accordance with a second aspect described above, the hypotrochoidal shape has n lobes, where n is an integer, the outer envelope shape has (n−1) lobes, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is n:(n−1). In some such embodiments, the hypotrochoidal shape is an ellipse, n=2, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1.

In some embodiments of a rotary machine in accordance with a second aspect described above, the rotor has a double-start helical profile having a first rotor thread and a second rotor thread and the stator has a single-start helical profile. In some embodiments, the rotary machine further comprises at least one helical seal mounted on the rotor and/or at least one helical seal mounted on the stator.

In a third aspect, a rotary machine comprises a stator and a rotor disposed within the stator. The stator has a helical profile, a stator axis, and has an epitrochoidal shape at any cross-section transverse to the stator axis along at least a portion of a length of the stator. The rotor has a helical profile, a rotor axis, and has a shape at any cross-section transverse to the rotor axis along at least a portion of a length of the rotor, that is an inner envelope formed when the epitrochoidal shape of the stator undergoes planetary motion. In some embodiments, the stator axis is offset relative to the rotor axis. In some embodiments, the rotor is configured to spin about its axis, the stator is configured to spin about its axis, and the rotor and the stator are held at a fixed eccentricity so that the rotor undergoes planetary motion relative to the stator but does not orbit.

In some embodiments of a rotary machine in accordance with a third aspect described above, the epitrochoidal shape of the stator has n−1 lobes, where n is an integer, the inner envelope shape of the rotor has n lobes, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is n:(n−1). In some such embodiments, n=2, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1.

In some embodiments of a rotary machine in accordance with a third aspect described above, the rotary machine further comprises at least one helical seal mounted on the rotor and/or at least one helical seal mounted on the stator.

In a fourth aspect, a rotary machine comprises a stator and a rotor disposed within the stator. The stator has a stator axis and a helical profile, and the stator has a stator shape that is outwardly offset from an epitrochoidal shape at any cross-section transverse to the stator axis along at least a portion of a length of the stator. The rotor has a rotor axis and a helical profile, and the rotor has a rotor shape at any cross-section transverse to the rotor axis, along at least a portion of a length of the rotor, that is an inner envelope formed when the stator shape undergoes planetary motion. In some embodiments, the stator axis is offset relative to the rotor axis. In some embodiments, the rotor is configured to spin about its axis, the stator is configured to spin about its axis, and the rotor and the stator are held at a fixed eccentricity so that the rotor undergoes planetary motion relative to the stator but does not orbit.

In some embodiments of a rotary machine in accordance with a fourth aspect described above, the stator shape has n−1 lobes, where n is an integer, the rotor shape has n lobes, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is n:(n−1). In some such embodiments, n=2, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1.

In some embodiments of a rotary machine in accordance with a fourth aspect described above, the rotary machine further comprises at least one helical seal mounted on the rotor and/or at least one helical seal mounted on the stator.

In some embodiments of the rotary machines described in the various aspects above, the rotor is coupled to a drive mechanism and the machine is configured so that rotation of the rotor drives rotation of the stator. In some embodiments of the rotary machines described in the various aspects above, the stator is coupled to a drive mechanism and the machine is configured so that rotation of the stator drives rotation of the rotor. In some embodiments of the rotary machines described in the various aspects above, the rotor and the stator are coupled to a drive mechanism comprising gears, and the machine is configured so that the rotor and the stator are not in contact.

In some embodiments of the rotary machines described in the various aspects above, the rotary machine is a multi-stage machine and a plurality of chambers are formed between cooperating surfaces of the rotor and the stator. In some embodiments, each of the plurality of fluid chambers has approximately the same volume. In some embodiments, each of the plurality of chambers has approximately the same dimensions and shape. In some embodiments, at least one of the plurality of chambers has dimensions that are different from another of the plurality of chambers. In some embodiments, at least one of the plurality of chambers has a volume that is different from another of the plurality of chambers.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A-**1**G (Prior Art) are schematic diagrams illustrating, in transverse cross-section, the geometry of an elliptical rotor and the stator assembly at different stages of a single revolution of the elliptical rotor.

FIG. **2**A is a side view of a rotor-stator assembly showing an outer cylindrical surface of the stator.

FIG. **2**B is a cross-sectional view of the rotor-stator assembly of FIG. **2**A, taken in the direction of arrows D-D, showing a helical rotor disposed within a helical stator cavity.

FIG. **2**C is an end view and three cross-sectional views taken in the direction of arrows E-E in FIG. **2**A, showing the helical rotor with a two-lobe, elliptical transverse cross-section.

FIG. **3**A is a side view of a helical rotor with an elliptical transverse cross-section.

FIG. **3**B is another side view of the helical rotor of FIG. **3**A, orthogonal to the view of FIG. **3**A.

FIG. **3**C is a cross-sectional side view of the helical rotor of FIG. **3**A taken in the direction of arrows A-A in FIG. **3**B

FIG. **4**A is an end view of a stator with a helical cavity.

FIG. **4**B is a transverse cross-sectional side view of the stator of FIG. **4**A.

FIG. **4**C is an isometric side view of the stator of FIG. **4**A (with the dashed line indicating the stator cavity).

FIG. **5** illustrates a portion of a rotor-stator assembly, showing a helical rotor disposed inside a translucent helical stator.

FIG. **6**A is a side view of a rotor-stator assembly showing an outer cylindrical surface of the stator.

FIG. **6**B is a cross-sectional view of the rotor-stator assembly of FIG. **6**A, showing a helical rotor disposed within a helical stator cavity.

FIG. **6**C shows an end view and various cross-sectional views taken in the direction of arrows A-A, B-B and C-C in FIG. **6**A, showing the helical rotor with a three-lobe transverse cross-section.

FIG. **7**A is a side view of a helical rotor with a three-lobe transverse cross-section.

FIG. **7**B is an isometric view of the helical rotor of FIG. **7**A.

FIG. **8**A is side view of a stator with a helical cavity, showing an outer cylindrical surface of the stator.

FIG. **8**B is a longitudinal cross-sectional view of the stator of FIG. **8**A.

FIG. **8**C is another longitudinal cross-sectional view of the stator of FIG. **8**A orthogonal to the cross-sectional view of FIG. **8**B.

FIG. **8**D is a side isometric view of the stator of FIG. **8**A.

FIG. **9**A is a side view of a rotary machine with a helical rotor-stator assembly having trochoidal geometry.

FIG. **9**B is a cross-sectional side view of the rotary machine of FIG. **9**A, taken in the direction of arrows A-A in FIG. **9**A.

FIG. **10** is a schematic diagram illustrating the geometry of an ellipse rotating about the head of a rotating radial arm.

FIG. **11** is a cross-sectional diagram illustrating a portion of a rotor-stator assembly of a rotary machine.

FIG. **12** is a transverse cross-sectional diagram illustrating rotor-stator geometry for a rotor that has a cross-sectional shape that is inwardly offset from each point on an ellipse, and a correspondingly offset stator cavity shape.

FIG. **13**A shows the cross-sectional shape of a helical stator cavity with no offset, in a plane normal to a longitudinal axis of the stator.

FIG. **13**B shows a close up view of the inverse apex of the helical stator cavity of FIG. **13**A, from the same angle as FIG. **13**A.

FIG. **13**C shows the cross-sectional shape of the stator cavity of FIG. **13**A in a plane normal to the helical path of the stator inverse apex.

FIG. **13**D shows a close up view of the helical stator cavity of FIG. **13**B from the same angle as FIG. **13**C.

FIG. **14**A shows the cross-sectional shape of a helical stator cavity, in a plane normal to a longitudinal axis of the stator, for a stator with an inward offset.

FIG. **14**B shows a close up view of the helical stator cavity of FIG. **14**A from the same angle as FIG. **14**A.

FIG. **14**C shows the cross-sectional shape of the stator cavity of FIG. **14**A in a plane normal to the helical path of the stator inverse apex region.

FIG. **14**D shows a close up view of the inverse apex region from the same angle as FIG. **14**C.

FIG. **15**A shows the cross-sectional shape of a helical elliptical rotor with no offset, in a plane normal to a longitudinal axis of the rotor.

FIG. **15**B shows the cross-sectional shape of the rotor of FIG. **15**A in a plane normal to the helical path of the rotor tips.

FIG. **16**A shows the cross-sectional shape of a helical rotor with an offset, in a plane normal to a longitudinal axis of the rotor.

FIG. **16**B shows the cross-sectional shape of the offset rotor of FIG. **16**A, in a plane normal to the helical path of the rotor tips.

FIG. **17**A shows the sweep width W_1 across the inverse apex region for a stator cavity with an offset, in a plane normal to a longitudinal axis of the stator.

FIG. **17**B shows the sweep width W_2 across the inverse apex region for the offset stator cavity of FIG. **17**A, in a plane normal to the helical path of the stator inverse apex region.

FIG. **18**A shows the sweep width W_3 across the rotor tips for a rotor with no offset, in a plane normal to a longitudinal axis of the rotor.

FIG. **18**B shows the sweep width W_4 across the rotor tips for the elliptical rotor of FIG. **18**A, in a plane normal to the helical path of the rotor tips.

FIG. **19**A shows the sweep width W_5 across the rotor tips for a rotor with an offset, in a plane normal to a longitudinal axis of the rotor.

FIG. **19**B shows the sweep width W_6 across the rotor tips for the rotor of FIG. **19**A, in a plane normal to the helical path of the rotor tips.

FIG. **20** is a perspective view of an embodiment of a helical seal that can be accommodated in a corresponding groove formed in a helical stator or rotor.

FIG. **21**A is a cross-sectional end view showing a helical seal installed in a groove in the interior surface of a stator.

FIG. **21**B is a cross-sectional side view of the assembly of FIG. **21**A taken in the direction of arrows A-A in FIG. **21**A.

FIG. **21**C is a cross-sectional side view of the assembly of FIG. **21**A taken in the direction of arrows B-B in FIG. **21**A.

FIG. 22A is an isometric view of a portion of a rotor-stator assembly with a helical seal.

FIG. 22B is a cross-sectional end view (transverse to the axis of rotation) of the assembly of FIG. 22A.

FIG. 22C is a cross-sectional side view of the assembly of FIG. 22A taken in the direction of arrows A-A in FIG. 22B.

FIG. 22D is a cross-sectional side view of the assembly of FIG. 22A taken in the direction of arrows B-B in FIG. 22B.

FIG. 23A illustrates an embodiment of a stator seal in transverse cross-section (in a plane normal to the axis of the helical stator).

FIG. 23B illustrates another embodiment of a stator seal in transverse cross-section.

FIG. 23C illustrates another embodiment of a stator seal in transverse cross-section.

FIG. 23D illustrates another embodiment of a stator seal in transverse cross-section.

FIG. 24A illustrates an embodiment of a rotor seal in transverse cross-section (in a plane normal to the axis of the helical rotor).

FIG. 24B illustrates another embodiment of a rotor seal in transverse cross-section.

FIG. 24C illustrates another embodiment of a rotor seal in transverse cross-section.

FIG. 24D illustrates another embodiment of a rotor seal in transverse cross-section.

FIG. 24E illustrates another embodiment of a rotor seal in transverse cross-section.

FIG. 24F illustrates another embodiment of a rotor seal in transverse cross-section.

FIG. 25 is a cross-sectional view of a portion of a helical rotor with a rotor seal, where the seal width of the rotor seal is substantially the same as the sweep width of the rotor.

FIG. 26 is a cross-sectional view of a portion of a helical stator and rotor with a rotor seal, where the seal width of the rotor seal is substantially less than the sweep width of the rotor.

FIG. 27 is a graph showing results of testing of a 2-stage helical trochoidal rotary pump in which the overall efficiency and volumetric efficiency of the pump are plotted against the number of cycles.

FIG. 28 is a side cross-sectional view of an embodiment of a fixed-eccentricity rotary machine assembly including a helical rotor with a two-lobe, elliptical transverse cross-section, a stator and a carrier, where the rotor is configured to drive the stator.

FIG. 29 is a side cross-sectional view of an embodiment of a fixed-eccentricity rotary machine assembly including a helical rotor with a two-lobe, elliptical transverse cross-section, a stator, a carrier and tapered journal bearings, where the rotor is configured to drive the stator.

FIG. 30 is a side cross-sectional view of a top-driven, fixed-eccentricity downhole pump assembly with a helical rotor with a two-lobe, elliptical transverse cross-section, a stator, and a carrier, where the rotor is configured to drive the stator.

FIG. 31 is a side cross-sectional view of a direct-drive downhole pump assembly including an electric submersible pump, a helical rotor with a two-lobe, elliptical transverse cross-section, a stator, and a carrier, where the rotor is configured to drive the stator.

FIG. 32 is a side cross-sectional view of a top-driven, fixed-eccentricity downhole pump assembly with an alignment feature to facilitate location of the rotor eccentrically within the stator.

FIG. 33A is a top view of a rotary machine with a helical rotor-stator assembly having trochoidal geometry.

FIG. 33B is a side cross-sectional view of the rotary machine of FIG. 33A, taken in the direction of arrows AK-AK in FIG. 33A.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENT(S)

The present application relates to rotary machines in which a helical rotor undergoes planetary motion relative to a stator. They can provide advantages for various applications, some of which are discussed below. As used herein the term “stator” refers to an outer member, within which a rotor can be disposed, and is not limited to a stationary component of a rotary machine. In some embodiments of the rotary machines described herein, the outer member is configured to be stationary during operation of the rotary machine, for example as a fixed stator. In some embodiments of the rotary machines described herein, the outer member is configured to move during operation of the rotary machine. For example, in some embodiments the outer member may spin about its axis or undergo planetary motion about a rotor.

The rotary machines are based on trochoidal geometries, with the rotor or stator having a trochoidal geometry or an offset trochoidal geometry (in transverse cross-section, i.e. perpendicular to its axis). In some embodiments the rotor has a hypotrochoidal cross-sectional shape, with the corresponding cross-sectional shape of the stator cavity being the outer envelope of the hypotrochoidal rotor shape as it undergoes planetary motion. In some embodiments, the stator cavity has an epitrochoidal cross-sectional shape with the corresponding cross-sectional shape of the rotor being the inner envelope formed by the epitrochoidal stator shape as it undergoes planetary motion. In such machines, one or more specific points on the envelope (whether it be the rotor or the stator) is in continuous contact with the corresponding component, and the contact point traces a trochoidal profile as the components execute their relative motion.

FIGS. 1A-1G are schematic diagrams illustrating the geometry of an example of a known rotary machine where the rotor has a cross-sectional shape that is hypotrochoidal, and the stator cavity is shaped as an outer envelope of the rotor as it undergoes planetary motion. In this example the hypotrochoidal rotor is an elliptical rotor. The rotor **110** and the stator **120** are shown at different points in time during a single revolution of the elliptical rotor within the stator. FIG. 1A shows elliptical rotor **110** in a first position within stator **120**. Stator inner surface **125** comprises an inverse apex **140**. A portion of each of rotor tips **130** and **135** is in contact with inner surface **125** of stator **120**, and outer surface of rotor **110** is in contact with inverse apex **140**. Rotor **110** spins about its longitudinal axis and rotates eccentrically in the direction indicated by arrow X-X (counter-clockwise) about axis **115**. FIG. 1B shows elliptical rotor **110** in a second position after rotor **110** has rotated. A portion of each of rotor tips **130** and **135** remains in contact with stator inner surface **125**, and outer surface of rotor **110** remains in contact with inverse apex **140**. FIG. 1C shows elliptical rotor **110** in a third position after further rotation. FIG. 1D shows elliptical rotor **110** in a fourth position with its major axis oriented vertically, as indicated by dashed line V-V. A portion of rotor tip **130** is in contact with inverse apex **140** and a portion of rotor tip **135** is in contact with stator inner surface **125** directly above inverse apex **140**. For the remainder of the description below for FIGS. 1E-1G, reference numerals have been omitted for clarity. FIGS. 1E-1G show elliptical rotor **110** after further rotations in a counter-clockwise direction. FIG. 1F shows elliptical rotor **110** in a position with its major axis oriented horizontally, as indicated by dashed line H-H. Thus, inner surface **125** of stator **120** in cross-section is designed such that at least a portion of each of rotor tips **130** and **135** is in contact with stator inner surface **125** at all times during a complete revolution of elliptical rotor **110**. Inverse apex **140** is in contact with the outer surface of elliptical rotor **110** at all times during a complete revolution of elliptical rotor **110**. The contact of elliptical rotor **110** with stator **120** at three positions, as described above, divides the interior volume of stator **120** into three chambers (for example, as shown in FIG. **1**F). When elliptical rotor **110** is in contact with stator **120** at only two distinct positions (for example when the major axis of elliptical rotor **110** is oriented vertically, as in FIG. **1**D), elliptical rotor **110** divides the interior volume of stator **120** into just two chambers. Ports (not shown in FIGS. **1**A-**1**G) can be provided for inflow and outflow of fluid as desired. The material being conveyed (typically a fluid) moves in an arc or circumferential direction through the rotary machine. Examples of such a machine are described in U.S. Patent Application Publication No. US2015/0030492, which is incorporated by reference herein.

Herein, the terms horizontal, vertical, front, rear and like terms related to orientation are used in reference to the drawings with the particular orientations as illustrated. Nonetheless, the rotary machines and related sub-assemblies described herein can be placed in any orientation suitable for their end-use application.

In embodiments of the present rotary machines, the hypotrochoid and outer envelope (rotor and the stator transverse cross-sectional shapes, respectively) are each swept along helical paths, the axes of those helices being the axes of rotation of those components in that reference frame in which both parts undergo simple rotary motion (the “centers” of those components). The axes of the rotor and the stator helices are offset or spaced from one another by a distance equal to the eccentricity of the rotor. The helical rotor and corresponding stator have the same pitch, and the ratio of the lead of the rotor to the lead of the stator is the same as the ratio of their number of lobes (which is also the same as the ratio of their number of starts). As used herein, “pitch” is defined as the axial distance between adjacent threads (or crests or roots, for example, on a helix), and “lead” is defined as the axial distance or advance for one complete turn (360°). Pitch and lead are equal with single start helices; for multiple start helices the lead is the pitch multiplied by the number of starts.

Thus, in embodiments of the present rotary machines, when a transverse cross-section is taken in any plane perpendicular to the axis of rotation, the hypotrochoid and envelope (that is, the cross-sectional shape of the rotor and the stator, respectively) are seen just as they would be in the usual two-dimensional profile, such as shown in FIGS. **1**A-**1**G, for example. For example, in some embodiments, the outer surface of a helical rotor is defined by an ellipse swept along a helical path, and a corresponding stator cavity is defined by sweeping the corresponding outer envelope along a helical path with half the lead of the helical rotor. The rotor profile is a double-start helix, and the stator profile is a single-start helical cavity. For such a machine, when a transverse cross-section is taken in any plane perpendicular to the axis of rotation, the outer profile of the rotor and inner profile of the stator will be similar to those illustrated for those components in FIGS. **1**A-**1**G.

FIGS. **2**A-C illustrate an example of such a machine. FIG. **2**A shows a side view of a stator **220**. The exterior surface of stator **220** is cylindrical. FIG. **2**B is a cross-sectional view taken in the direction of arrows D-D in FIG. **2**A, and shows a helical rotor **210** disposed within a helical stator cavity **225** defined by stator **220**. FIG. **2**C shows an end view and various cross-sectional views taken in the direction of arrows E-E in FIG. **2**A. Rotor **210** has an elliptical transverse cross-section, as shown in FIG. **2**C. As the cross-section E-E progresses along the axis of rotation of rotor **210**, the cross-sectional shape of the rotor and the stator progresses in a manner analogous to the motion over time of rotor **110** within stator **120**, as illustrated in FIGS. **1**A-**1**G. In the embodiment illustrated in FIGS. **2**A-**2**C, rotor **210** has two lobes and the stator cavity **225** has one lobe.

FIG. **3**A is a side view of a helical rotor **300** (with an elliptical transverse cross-section) similar to rotor **210** of FIGS. **2**A-C. FIG. **3**B is another side view of helical rotor **300**, orthogonal to the view of FIG. **3**A. FIG. **3**C shows a cross-sectional view of rotor **300** taken in the direction of arrows A-A in FIG. **3**B.

FIG. **4**A is an end view, FIG. **4**B is a cross-sectional view and FIG. **4**C is an isometric view of a stator **400** (with the dashed line indicating the stator cavity). Stator **400** corresponds to rotor **300** of FIGS. **3**A-C (in other words stator **400** can be used with rotor **300**), and is similar to stator **220** of FIGS. **2**A-C.

FIG. **5** illustrates an example of a portion of a machine such as illustrated in FIGS. **2**A-**2**C, showing a helical rotor **510** disposed inside a translucent helical stator **520**. The pitch of the rotor (distance between adjacent threads or crests) is indicated by distance **530**, and the lead of the rotor is indicated by distance **540**. Because the rotor is a double-start helix, the lead is twice the pitch. The pitch of the stator is indicated by distance **550** and, because the stator is a single-start helix, distance **550** is also the lead of the stator. The rotor pitch **530** and the stator pitch **550** are the same. In some embodiments the rotor and the stator are plastic. In other embodiments of the rotary machines described herein both the rotor and the stator can be metal. In other embodiments, depending on the application, the rotor and/or stator can be made from ceramic, elastomeric or other suitable materials or combinations of materials. The material(s) of the rotor can be the same as, or different from, the material(s) of the stator.

In the embodiment illustrated in FIGS. **2**A-**2**C, the rotor and the stator surfaces bound one complete chamber or volume per envelope revolution (each volume constituting a single stage of the machine or pump). The boundaries of these chambers are simple helices at the “top” and “bottom” (the path of the hypotrochoid generating elements, or “points” on the envelope), and a contact curve between the rotor and the stator in the “clockwise” and “counter-clockwise” direction. These chambers do not change size or shape as the device operates. The material to be pumped (typically a fluid) is moved in an axial direction through the pump, and the flow velocity is substantially constant.

There is a quasi-helical contact path between the rotor and the inner “ridge” (or crest) of the stator at all times during rotation of the rotor (just as there is contact between the rotor and the inverse apex in the stator in the machine illustrated in FIGS. **1**A-**1**G). The contact path with the stator moves or oscillates back and forth across the helical “ridge” or crest of the rotor as the rotor rotates relative to the stator (in a manner similar to how the contact point moves back and forth across the tips of elliptical rotor in the machine of FIGS. **1**A-**1**G). The rotor-stator contact path revolves around the machine as pumping action proceeds, “threading” the fluid (or material to be pumped) in a spiral path along the helix, to that it is moved axially from one end of the stator cavity to the other.

Thus, the periodicity of contact between the helical rotor and the stator occurs in space (moving along a continuous contact path over time) rather than in time (with intermittent contact between surfaces such as occurs, for example, in the machine illustrated in FIGS. **1**A-**1**G, where the rotor tips only intermittently contact the inverse apex on the stator). Thus, in the present rotary machines, rather than periodically engaging and disengaging (or touching and separating), the contact surfaces and any associated seals slide across one another, or in close proximity to one another, continuously. This continuous contact line between rotor and the stator can facilitate the provision of sealing in embodiments of the present machines.

Some embodiments of the present rotary machines operate with a small clearance between the helical rotor and the stator, but without seals between them. In some embodiments it can be desirable to dispose a seal between these components to reduce leakage of fluid between stages.

FIGS. **6**A-C illustrate another embodiment of a machine according to the present approach, where in cross-section, the helical trochoidal rotor has three lobes and the stator cavity has two lobes. The rotor and the stator cavity are defined by sweeping these shapes along a helical path. This embodiment has a rotor/stator lead ratio of 3:2. FIG. **6**A shows a side view of a cylindrical stator **620**. FIG. **6**B is a cross-sectional view taken in the direction of arrows D-D in FIG. **6**A, and shows a helical rotor **610** disposed within stator cavity **625** defined by stator **620**. FIG. **6**C shows an end view and various cross-sectional views taken in the direction of arrows A-A, B-B, and C-C in FIG. **6**A. Rotor **610** has rounded triangular transverse cross-section, as shown in FIG. **6**C. Stator cavity has a transverse cross-sectional shape that is roughly circular with two inverse apex regions, **620**A and **620**B swept along a helical path. As one moves along the axis of rotation of rotor **610**, the cross-sectional profile of the rotor and the stator progresses in a manner as shown in FIG. **6**C.

FIG. **7**A is a side view of a helical rotor **700** (with a 3-lobe, rounded triangular transverse cross-section) similar to rotor **610** of FIGS. **6**A-C. FIG. **7**B is an isometric view of rotor **700**.

FIG. **8**A is side view of a 2-lobe stator **800**. FIG. **8**B is a longitudinal cross-sectional view of stator **800**, and FIG. **8**C is another longitudinal cross-sectional view of stator **800** (orthogonal to the cross-sectional view of FIG. **8**B). Both FIGS. **8**B and **8**C show the inner surface of the stator cavity. FIG. **8**D is an isometric view of stator **800**. Stator **800** is similar to stator **620** of FIGS. **6**A-C.

FIGS. **9**A and **9**B illustrate an example of a rotary machine **900** with a helical rotor-stator assembly having trochoidal geometry. FIG. **9**A is a side view of rotary machine **900**, and FIG. **9**B is a cross-sectional view taken in the direction of arrows A-A in FIG. **9**A. Referring primarily to FIG. **9**B, rotary machine **900** comprises helical rotor **910** and helical stator **920** defining stator cavity **925**. Rotary machine **900** further comprises inlet housing **930** and outlet housing **935**. Drive shaft **940** is fixed to carrier **945**, and is mechanically coupled via sun gear **950** and ring gear **955** to cause eccentric rotation of rotor **910** within stator cavity **925**. Rotary machine **900** further comprises thrust bearings **960** and **965**, radial bearings **970** and shaft seals **980**. As rotor **910** rotates with stator cavity **925**, fluid can be drawn into rotary machine **900** via inlet port **990**, and expelled via outlet port **995**.

Much of the description herein focuses on embodiments of helical trochoidal rotary machines with a trochoidal rotor (particularly an elliptical rotor) and corresponding outer envelope stator cavity. In other embodiments, helical trochoidal rotary machines can have an epitrochoidal stator cavity cross-sectional shape and corresponding rotor (inner envelope) cross-sectional shape that are each swept along helical paths. These embodiments have the same relative motion of the rotor and the stator (with the same orbit and spin) as machines with a trochoidal rotor and corresponding outer envelope stator cavity.

The present approach can be applied to generate embodiments of helical rotary machines based on a hypotrochoidal or epitrochoidal rotor (with the corresponding stator cavity cross-sectional shape being the outer envelope or inner envelope, respectively of the rotor cross-sectional shape as it undergoes planetary motion), where the components have more than two or three lobes. Such machines will have more chamber "edge" for each trapped volume of fluid, so may tend to have more leakage per stage, poorer solids handling capability, and/or higher friction if dynamic seals are used. However, for some applications, for example mud motors, such embodiments with lower speed and higher torque can offer advantages.

In the rotary machines described herein, the rotor (and/or optionally the stator) can be rotated using any suitable drive mechanism. Some non-limiting examples of drive mechanisms are briefly discussed below. For 2:1 (rotor:stator lobe) rotary machines with hypotrochoidal rotor with outer envelope stator cavity, or epitrochoidal stator with inner envelope rotor, an example of a suitable drive mechanism has an external gear fixed to the stator meshing with an internal gear with twice as many teeth fixed to the rotor, the distance between the gear centers being equal to the eccentricity of the hypotrochoid, that center distance being maintained by bearings fixed to each part and interacting with an element that revolves with the rotor center; the revolving element being driven by a shaft passing through the sun gear. This type of mechanism is known, and used for instance in Wankel rotary engines. Alternatively, instead of using an internal gear a pair of external gear meshes can be used to achieve a 2:1 gear ratio with the output rotating in the same direction as the input.

For machines with other ratios, the gear ratio can be modified accordingly. In a machine having a three lobe rotor and a two lobe stator, the gear ratio is 3:2. In general, for a machine having an (n+1) lobe rotor and an n lobe stator, the gear ratio can be (n+1):n. For epitrochoid with outer envelope or hypotrochoid with inner envelope machines, the gears can be fixed to the corresponding component, for example, the external gear can be fixed to the rotor and the internal gear can be fixed to the stator.

Other drive mechanisms that do not involve gears can be used. For example, some embodiments are rotary machines in which the rotor is mounted to a flexible or angled shaft (for example, fitted with universal joints) so that it rotates eccentrically, and power is transmitted from the concentric rotation of one end of the drive shaft to the eccentrically rotating rotor. Thus, the shaft can be coupled to and driven by a motor, with the stator acting as a guide for the rotor. Other examples use, for example, Schmidt couplings and/or cycloidal drive mechanisms, in lieu of gears, to provide the relative motion of the rotor and the stator.

Fixed-Eccentricity Helical Trochoidal Rotary Machines

The working principle of the rotary machines described herein is independent of which component of the machine (if any) is "fixed" and which is rotating. In some embodiments, for example, the machine can be operated such that the stator is fixed and the rotor spins and undergoes planetary motion (orbits) within it. This configuration is mechanically compact, but sometimes requires counterweights to provide balance. In some embodiments, the outer stator undergoes planetary motion about the inner rotor.

Some embodiments of the rotary machines described herein are operated such that the rotor spins but does not orbit. For example, in some embodiments, the rotor spins but can be held at a specific eccentricity relative to the stator, and the stator can also be allowed to spin, so that the rotor and the stator each revolve around their respective longitudinal axes. In some such embodiments, even though the rotor and the stator are each spinning (i.e. rotating) about their respective longitudinal axes, the relative motion of the components is basically the same as in corresponding fixed-stator embodiments where the rotor spins and orbits within the stator.

In some embodiments, rotary machines where the rotor or stator is orbiting have problems with vibration and balancing, because of the centrifugal loading and forces associated with the eccentric movement of the component. These forces are dependent on the mass of the component as well as its angular velocity and orbit radius. In some embodiments, the resulting excitation forces and vibration can limit the rotational speed (RPM) at which such machines can be operated, thereby limiting flow rates and volumetric efficiency.

In at least some embodiments, holding the rotor and the stator at a fixed eccentricity and having these components merely spin about their longitudinal axes, rather than having one of them orbit, can significantly reduce problems with vibration and make the machine more balanced in operation. In at least some embodiments, this can allow the machine to operate at higher rotational speeds, and make it significantly less prone to failures due to vibration. With this arrangement, the fluid chambers are translated axially through the pump, without spinning or being flung radially away from the longitudinal axis. This can also reduce tendency for vibration. Because higher rotational speeds can be tolerated, higher flow rates can be achieved for a given geometry and size of machine, or a smaller machine can be used to provide the same flow rate.

With such rotary machine designs, one approach is to drive the rotor, for example by coupling it to a motor via a drive shaft, and allow the rotation of the rotor to drive the rotation of the stator. For embodiments where the rotor has a helical profile and an elliptical shape at any cross-section transverse to the rotor axis (e.g. where the rotor has a hypotrochoidal shape with n=2, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1), the stator will be spun by the rotor at twice the spin rate of the rotor.

In some embodiments, the stator can be driven instead of the rotor. For machines where the rotor has a helical profile and an elliptical shape, the stator drives the rotor to spin at half the speed of the stator, as the stator spins at twice the rate of the rotor no matter if the rotor is driven or the stator is driven. Driving the stator can be advantageous in some circumstances. For example, if for a given motor speed there is a desire to have an overall slower pump speed, driving the stator rather than the rotor reduces the overall speed of the system by half. Direct-drive systems often have a high input drive speed and, in some embodiments, it can be preferable to have a lower overall system speed. For example, if the input speed is 3600 RPM and a rotor output speed of 1800 RPM is desired, this can be accomplished by driving the stator instead of the rotor; whereas, if the rotor was driven, the stator speed would be 7200 RPM.

In another approach, the eccentricity is still fixed, but instead of the rotor driving the stator (or vice versa), a gear set is used and both the rotor and the stator are driven via gears. For machines where the rotor has a helical profile and an elliptical shape, the rotor can be driven at half the speed of the stator. With this approach the gears are influencing the relative motion between the rotor and the stator. The rotor and the stator do not have to contact each other. In at least some embodiments, this can reduce or eliminate the rotor-stator interaction, and can reduce the degree of material wear or degradation between the rotor and the stator. An example of a gear-driven fixed-eccentricity rotary machine is described below in reference to FIGS. **33**A and **33**B.

In at least some of the fixed-eccentricity embodiments of the rotary machines described herein, where the rotor and the stator are held at a fixed eccentricity and both spin about their longitudinal axes, bearings are generally used to support and constrain the stator within the carrier while it is allowed to spin (for a fixed stator machine, stator bearings are not needed). In at least some embodiments, the stator bearings can be a leak path for the fluid being pumped, so additional seals to mitigate the risk of leakage are generally needed.

FIG. **28** is a cross-sectional view of an embodiment of fixed-eccentricity rotary machine assembly **2800**, comprising helical rotor **2810** having a two-lobe, elliptical transverse cross-section, stator **2820** and carrier **2830**. Stator **2820** is constrained concentrically within carrier **2830** and is supported by stator-carrier bearings **2840***a* and **2840***b* so that it can spin about its axis within carrier **2830**, but is constrained axially and radially. In rotary machine assembly **2800**, annular stator-carrier seals **2850***a* and **2850***b* can be used to mitigate or prevent fluid leakage around the rotor-stator assembly. Rotor **2810** is constrained within stator **2820** at a position so that the axis of the rotor is offset or spaced from the axis of stator **2820** and carrier **2830** by a distance equal to the eccentricity. In rotary machine assembly **2800**, rotor **2810** is supported by rotor-carrier bearings **2860***a* and **2860***b* and anchor pin **2870** so that it can spin about its axis within stator **2820**. In some embodiments, rotor **2810** can be coupled to a drive shaft via coupling **2880** and driven by a motor (not shown in FIG. **28**), so that it spins about its axis, and drives stator **2820** to spin at twice the rate of spin of rotor **2810**.

FIG. **29** is a cross-sectional view of another embodiment of fixed-eccentricity rotary machine assembly **2900**. Assembly **2900** is similar to assembly **2800** shown in FIG. **28**, except that the bearings and seals are different. Fixed-eccentricity rotary machine assembly **2900** comprises helical rotor **2910** having a two-lobe, elliptical transverse cross-section, stator **2920** and carrier **2930**. Stator **2920** is constrained concentrically within carrier **2930** and is supported by stator-carrier bearings **2940***a* and **2940***b* so that it can spin about its axis within carrier **2930**, but is constrained axially and radially. In the illustrated embodiment stator-carrier bearings **2940***a* and **2940***b* are tapered journal bearings fitted with annular stator-carrier seals **2950***a* and **2950***b*, respectively, to mitigate or prevent fluid leakage around the rotor-stator assembly. Rotor **2910** is constrained within stator **2920** at a position so that the axis of the rotor is offset or spaced from the axis of stator **2920** and carrier **2930** by a distance equal to the eccentricity. In the illustrated embodiment, rotor **2910** is supported by rotor-carrier bearings **2960***a* and **2960***b* (which, in the illustrated embodiment, are tapered journal bearings) and anchor pin **2970** so that it can spin about its axis within stator **2920**. In some embodiments, rotor **2910** can be coupled to a drive shaft via coupling **2980** and driven by a motor, so that it spins about its axis, and drives stator **2920** to spin at twice the rate of spin of rotor **2910**. Tapered journal bearings have fewer moving parts than the thrust bearings shown in FIG. **28**. The tapered journal bearings provide multiple functions of a bearing surface both radially and thrust, and also provide additional sealing.

For downhole pump or artificial lift applications, the carrier (such as carrier **2830** in FIG. **28** or carrier **2930** in FIG. **29**) can be fixed rigidly to production tubing (e.g. directly or via larger diameter orbit tubing) which can extend to the surface and accommodate a drive-string as well as carrying the pumped fluid. The carriers can have openings or passages to allow the pumped fluids to pass into the carrier and enter the pump intake.

For downhole pump or artificial lift applications of rotary machines in which the stator is fixed and the rotor is configured to spin and orbit within the stator, a drive-string is typically coupled to the rotor and drives the rotor to spin and orbit. For machines where the rotor has a helical profile and an elliptical shape (n=2), the rotor orbits at a radius equal to the eccentricity and it orbits twice as fast as it spins. Thus, with a fixed stator the drive-string also orbits at the same frequency and radius as the rotor. When the eccentricity is fixed and the rotor and the stator each spin about their longitudinal axes, as described in this section, a drive-string used to drive the rotor (or stator) to spin would not need to orbit. This simplifies the drive-string design and operation and, in at least some embodiments, this can have a significant impact on reducing the failures due to vibration in this region of the overall pump system.

FIG. **30** shows an embodiment of top-driven downhole pump assembly **3000** which can be inserted into a well, for example. Torque anchor **3005** is at the base of downhole pump assembly **3000** and is attached to the well-casing (not shown in FIG. **30**), which is a large diameter pipe that forms the walls of the well. In the illustrated embodiment, lower carrier **3030** is mounted to torque anchor **3005** and supports stator **3020** (co-axially) via stator-carrier bearings **3040***a* so that it can spin about its axis, but is constrained axially and radially. Helical rotor **3010** has a two-lobe, elliptical transverse cross-section and extends through stator **3020**. The axis of rotor **3010** is offset at a fixed distance (eccentricity) from the axis of stator **3020**. In the illustrated embodiment, rotor **3010** is supported via anchor pin **3070** and bearings (not shown in FIG. **30**), so that it can spin about its axis within stator **3020**. In the illustrated embodiment, rotor **3010** can be coupled to a drive shaft via coupling **3080** and driven by a motor, so that it spins about its axis, and drives stator **3020** to spin at twice the rate of spin of rotor **3010**. In the illustrated embodiment, stator **3020** is also mounted to and constrained by upper carrier **3035** via stator-carrier bearings **3040***b*. In some embodiments, upper carrier **3035** can be attached to orbit tube **3085** (which in turn connects to production tubing) and/or it can be attached to lower carrier **3030**.

For downhole pump, artificial lift and similar applications, there are numerous ways a system incorporating a fixed-eccentricity pump of the type described herein could be deployed. For example, it can be top-driven where the motor is at the surface and is coupled to the rotor (or stator or gear system) via a drive-string (for example, as shown in FIG. **30**). A top-drive system is often limited to fairly low rotational speeds, not only due to the centrifugal forces from the rotor, but also due to the rotational speeds of the drive-string. Downhole the drive-string often has to go around slight bends, which can cause the drive-string to contact the inner wall of the surrounding production tubing. At high speeds this can cause the drive-string to impact the production tubing, potentially causing failure. A top-drive arrangement can be coupled with a permanent magnet motor (PMM). A PMM is a form of speed increaser that reduces torque, while increasing the output speed. In some embodiments this can be used to reduce the required speed of a top-drive system while increasing the speed of the rotor.

Alternatively, in some embodiments, the pump can be used with a direct-drive system, similar to an electric submersible pump (ESP), where the motor is below the surface (e.g. underground). With such direct-drive ESP systems high rotational speeds are achievable, for example, in excess of 3600 RPM.

FIG. **31** shows an embodiment of direct-drive electric submersible pump assembly **3100** which can be inserted into a well, for example. Assembly **3100** is similar to top-driven pump assembly **3000** of FIG. **30**, except that motor **3105** which drives the rotor is also deployed below the surface, and drives the rotor from below. Again, helical rotor **3110** has a two-lobe, elliptical transverse cross-section and extends through stator **3120**. The axis of rotor **3110** is offset at a fixed distance (eccentricity) from the axis of stator **3120**. In the illustrated embodiment, motor **3105** is coupled via universal joints **3115***a* and **3115***b* to spin the rotor **3110**, which drives stator **3120** to spin at twice the spin rate of rotor **3110**. The universal joints are optional, but allow the motor to be located concentrically with the stator housing. In embodiments with a straight drive shaft, the motor would typically be aligned with the rotor eccentric position (i.e. offset by the eccentricity) and would require a larger diameter space for deployment. Stator **3120** is constrained concentrically within carrier **3130** and is supported by stator-carrier bearings **3140***a* and **3140***b* so that it can spin about its axis within carrier **3130**, but is constrained axially and radially. In the illustrated embodiment, stator-carrier bearings **3140***a* and **3140***b* are tapered journal bearings fitted with annular stator-carrier seals that mitigate or prevent fluid leakage around the rotor-stator assembly. Rotor **3110** is supported by rotor-carrier bearing **3160** (which, in the illustrated embodiment, is a tapered journal bearing) so that it can spin about its axis within stator **3120**. In some embodiments, carrier **3130** can be attached to orbit tubing or to production tubing (not shown in FIG. **31**).

In some embodiments of top-drive systems, a fixed-eccentricity rotary machine can be deployed below the surface with the rotor pre-installed within the stator, and the drive shaft can then be coupled to the rotor, or the stator, directly or via a gear set. In some embodiments, the rotor is deployed through the production tubing and inserted into the stator after the carrier-stator assembly is deployed below the surface. Such an arrangement allows the rotor to be removed by pulling the drive-string, so that the rotor can be inspected, serviced or replaced easily without bringing the entire stator-carrier assembly and production tubing to the surface. In at least some preferred embodiments, a suitable mechanism to facilitate alignment and positioning of the rotor at the correct eccentricity relative to the stator and carrier is provided.

FIG. **32** shows an embodiment of top-driven downhole pump assembly **3200** similar to assembly **3000** illustrated in FIG. **30**. Assembly **3200** has an alignment or locking feature that can be used to locate the rotor in the specified eccentricity once it is inserted into the stator from above. Helical rotor **3210** has a two-lobe, elliptical transverse cross-section and is inserted into stator **3220**. In the illustrated embodiment, an alignment feature comprises stepped flange **3250** surrounding the upper end of rotor **3210**, which inserts into corresponding feature **3240** at the top of carrier **3230**. Once flange **3250** is seated into feature **3240**, rotor **3210** is correctly installed in stator **3220**. The axis of rotor **3210** is offset at a fixed distance (eccentricity) from the axis of stator **3220**. Rotor **3210** can be coupled to a drive-string via coupling **3280** and driven by a motor (not shown in FIG. **32**), so that it spins about its axis, and drives stator **3220** to spin at twice the rate of spin of rotor **3210**. In the illustrated embodiment, carrier **3230** supports stator **3220** (co-axially) so that it can spin about its axis, but is constrained axially and radially.

FIGS. **33**A and **33**B illustrate an example of a fixed-eccentricity trochoidal geometry rotary machine **3300** in which, instead of the rotor driving the stator (or vice versa), both the rotor and the stator are driven via a gear set. In the illustrated embodiment, the rotor is driven at half the speed of the stator. FIG. **33**A is a top view of rotary machine **3300**, and FIG. **33**B is a cross-sectional side view taken in the direction of arrows AK-AK in FIG. **33**A. Referring primarily to FIG. **33**B, rotary machine **3300** comprises helical rotor **3310** and a helical stator (which is formed from two parts, **3320***a* and **3320***b*) defining stator cavity **3325**, and mounted within carrier/housing **3330**. The axis of rotor **3310** is offset at a fixed distance (eccentricity) from the axis of the stator. Drive shaft **3335** is mounted to carrier/housing **3330** and drives both rotor **3310** and the stator. In at least some embodiments, drive shaft **3335** is mechanically coupled to drive rotor **3310** via gear **3312** and gear **3314**. In the illustrated embodiment, drive shaft **3335** is mechanically coupled to drive the stator via gear **3322** and gear **3324**. Rotary machine **3300** can further comprise shaft seals **3340** and **3345** between rotor **3310** and carrier/housing **3330**, rotor bearings **3350** and **3355**, shaft seal **3360** between the stator and carrier/housing **3330**, tapered roller bearings **3370** and **3375**, and gear bearings **3380** and **3385**. As the rotor and the stator are driven and rotate, fluid can be drawn into rotary machine **3300** via inlet port **3390** (shown in FIG. **33**A and expelled via outlet port **3395**.

In many of the embodiments of fixed-eccentricity helical trochoidal rotary machines described above, the rotor is constrained axially and radially at or near both ends, and the stator is constrained axially and radially at or near both ends. Other arrangements are possible, including, for example, that the rotor and/or stator can be constrained axially and radially at or near just one end; the rotor and/or stator can be constrained axially at or near one end, and be constrained radially at or near the other end; the rotor could be constrained axially and radially at or near one end, and the stator could be constrained axially and radially at or near the other end; and the like.

In at least some embodiments, it is possible to take existing rotary machines of the types described herein where the rotor is configured to spin and orbit within the stator, and modify or retrofit them so that the eccentricity is fixed and the rotor and the stator each spin about their longitudinal axes as described in this section. For example, such a modification can include adding a carrier to which the stator and the rotor can be anchored, and incorporating suitable radial and thrust sliding surfaces.

In at least some embodiments, the approach described herein of fixing the eccentricity so that neither the stator nor rotor orbits, can be applied to various classes of rotary machines based on trochoidal geometries that comprise a rotor or stator whose cross-section is bounded by a certain family of curves, known as trochoids or trochoidal shapes. In at least some embodiments, the approach can also be applied to conventional progressive cavity pumps.

Partial-, Single- and Multi-Stage Helical Trochoidal Rotary Machines

It is possible to make a machine based on the present approach with a helical rotor and the stator having a single stage, multiple stages or, in some embodiments, with less than a complete stage (where there is no complete trapped chamber or volume of fluid between the ends of the pump). For the latter, end plates can be provided at each end of the rotor-stator, with an inlet port provided in one end plate and an outlet port in the other. If somewhat more than one complete rotor revolution is provided (i.e. sufficient length and number of rotor pitches that at least one bounded volume of fluid is isolated from both ends of the pump simultaneously), end plates may not be needed.

In multi-stage embodiments of the present machines as described above, if the rotor-stator geometry remains substantially constant along the axis of the machine, the volume and dimensions of the bounded volumes or fluid chambers formed between the helical rotor and the stator will be the same, and the volume of each fluid chamber will remain constant during operation of the machine, as the rotor rotates within the stator. This is explained further in reference to FIG. **10**.

FIG. **10** is a schematic diagram illustrating the geometry of an ellipse rotating about the head of a rotating radial arm. In geometric configuration **1000**, ellipse **1010** has a center C, a major axis indicated by dotted line A-A and a minor axis indicated by dashed line B-B. Major axis A-A is the longest diameter of ellipse **1010**, and minor axis B-B is the shortest diameter of ellipse **1010**. Ellipse **1010** rotates about center C at an angular velocity ω_1 in a counter-clockwise direction relative to a frame of reference in which center C is stationary. Center C is located at the head of a rotating radial arm **1020**. Radial arm **1020** has length k and rotates about a fixed end O at an angular velocity ω_2 in a counter-clockwise direction relative to a frame of reference in which fixed end O is stationary. If angular velocity ω_1 is negative, it indicates that rotation of ellipse **1010** about center C is in a clockwise direction relative to a frame of reference in which center C is stationary. If angular velocity ω_2 is negative, it indicates that rotation of radial arm **1020** about fixed end O is in a clockwise direction relative to a frame of reference in which fixed end O is stationary.

Circle **1030** is the locus of the head of radial arm **1020** as it rotates about fixed end O. Line O-C is also referred to as the crank arm, and length k is referred to as the crank radius.

Geometric configuration **1000** can represent a helical rotor assembly in transverse cross-section. In embodiments of the rotary machines as described herein, it is desirable that inverse apex (or ridge or crest) of the corresponding helical stator is in contact with the outer surface of helical elliptical rotor at all times during a complete revolution of elliptical rotor. This can be achieved by configuring the geometry **1000** such that the difference between the semi-major axis of the rotor with elliptical cross-section (shown in FIG. **10** as length “a”) and the semi-minor axis of the rotor (shown in FIG. **10** as length “b”) is twice the crank radius, k. In other words, in preferred embodiments:

$$a-b=2k$$

If the rotor and the stator pitch and all dimensions (including a, b and k as shown in FIG. **10**) remain constant along the length of the rotor-stator assembly, then the volume and dimensions of the fluid chambers formed between the helical rotor and the stator will be the same along the length of the assembly. Such rotary machines can be used, for example, as pumps and, if driven at constant speed can provide a fairly steady volumetric flow rate or output.

In other multi-stage embodiments, the rotor-stator geometry can be varied, in a continuous or stepwise manner, along the axis of the rotary machine. In some embodiments, such variations can cause the volume of the fluid chambers to vary along the axis of the machine, such as may be desirable for compressor or expander applications, for example. In other embodiments, it can be advantageous to vary the geometry of the rotor-stator along the axis of the rotary machine, while keeping the volume of the fluid chambers formed between the helical rotor and the stator approximately the same along a length of the rotor-stator assembly. Such embodiments are described in further detail below, again with reference to FIG. **10**.

Instead of the rotor and the stator pitch and other parameters (including a, b and k) being constant along the axis of the machine, the rotor-stator geometry can be varied along the axis of a rotary machine, for example, as follows:

(1) By varying the pitch of the rotor and the stator. For example, the pitch can increase in the flow direction so that the volume of the fluid chambers increases along the axis of the machine. This may be desirable for compressor applications, for example.

(2) By varying the aspect ratio of the rotor (a/b) and keeping crank radius, k, constant, where a minus b remains equal to 2k. The corresponding stator profile is varied along its axis accordingly.

(3) By varying the crank radius k, where a minus b remains equal to 2k. This involves also changing the aspect ratio of the rotor by varying at least one of dimensions a or b. The corresponding stator profile is varied along its axis accordingly. When the crank radius is varied the rotor and the stator axes will be inclined relative to one another (i.e. be non-parallel).

(4) By varying the degree of offset of the rotor cross-sectional shape from a true ellipse (or hypotrochoid) along the axis of the rotor, and correspondingly varying the stator profile along its axis.

In some embodiments, varying one or more of these parameters can cause the volume of the fluid chambers to vary along the axis of the machine, for example, getting smaller or larger. In some embodiments, the parameters are varied so that the size of the elliptical rotor cross-section and corresponding stator is scaled or reduced linearly in the axial direction.

In some embodiments, different rotor-stator geometries, cross-sectional shapes or profiles can be used in different portions or segments of the machine to meet various requirements. For example, a "precompressor" section with different dimensions but equal or slightly greater displacement can be used to reduce Net Positive Suction Head (NPSH) requirements in a pump. A different geometry that is more favorable for sealing can be used downstream along the main body of the pump. In another example, a tapered embodiment can be used as a nozzle or diffuser.

In some embodiments, multiple parameters can be varied in combination so that the volume of fluid chambers formed between the helical rotor and the stator remains approximately the same along a length of the rotor-stator assembly, with the variation of one parameter at least partially compensating for the variation in another parameter with respect to the effect on the volume of the fluid chambers. For example, variations described in (2) and (3) may change the flux area, but the change in flux area could be compensated for by, for example, increasing the rotor-stator pitch. It can be advantageous to manipulate other characteristics by having a different geometry in one section of the rotor-stator assembly than in another section, even if the fluid throughput along the length is roughly or substantially constant. For example, it could be desirable to have a high flux area near the intake (to draw a fluid in and encapsulate it), and then gradually change the geometry towards the discharge end.

FIG. **11** is a sketch illustrating a portion of a rotor-stator assembly **1100** in cross-section, to illustrate an embodiment in which, multiple parameters are varied in combination so that the volume of the fluid chambers formed between a helical rotor **1110** and a corresponding stator **1120** remains approximately the same along a length of the rotor-stator assembly. In this embodiment, the rotor and the stator axes are non-parallel. When the rotor and the stator axes are non-parallel, instead of being mapped on to plane that is perpendicular to both axes, the "cross-sectional" shape of the rotor and the stator is mapped on to the surface of a sphere which is perpendicular to both axes (the center of sphere being the point at which the rotor axis **1115** and the stator axis **1125**, if extrapolated, would intercept).

The crank radius, k, is the arc length (on the surface of the sphere at that point along the axes) between the longitudinal axis **1115** of rotor **1110**, and the longitudinal axis **1125** of stator **1120**. Crank radius, k, is varying along the length of the assembly (decreasing toward the lower end of the illustrated assembly), and the rotor and the stator longitudinal axes **1115** and **1125** are non-parallel. The length of minor transverse axis of the elliptical rotor **1110** mapped onto the sphere is shown in FIG. **11** as 2b. As in FIG. **10** where $a-b=2k$, at any point along the length of rotor-stator assembly **1100** in FIG. **11** the major transverse axis (2a) of the elliptical rotor **1110** (mapped onto the sphere) is $2b+4k$. In the embodiment illustrated in FIG. **11**, the crank radius k and the dimensions of the rotor and corresponding stator are continuously scaling or decreasing along a length of the assembly so that the rotor and the stator transverse cross-sectional shapes at any axial position differ only in their size. The pitch of the rotor and the stator can be correspondingly increased, so that the volume of the fluid chambers formed between rotor **1110** and the stator **1120** remains approximately the same along the length of the rotor-stator assembly. In the embodiment of FIG. **1**, the pitch is varied continuously, and the pitch between various pairs of points along the length of the assembly is shown gradually increasing, from P_0 to P_1 to P_2. To maintain constant chamber volume in the case described, instantaneous pitch at any point is inversely proportional to the square of the distance to that point from the center of the sphere (zero eccentricity point). Without such a change in pitch, the volume of fluid chamber would decrease, and such a machine could be used as a compressor, for example.

The changes in geometry can be continuous or gradual or there can be a step change. If the latter, preferably the eccentricity of the pump remains constant so that single rotor and the stator parts can be used throughout the machine, and two or more rotor sections can be driven as a single component. In embodiments with a step change, it can be desirable to provide a space or chamber between the sections where the fluid can switch between flow paths. The pressure in this intermediate space is preferably slightly positive, to reduce the likelihood of cavitation. In some embodiments this can be achieved by providing a slightly smaller displacement in the upstream section. Alternatively, slip caused by pressure differential across the pump can provide this positive pressure. It can further be desirable in some instances to provide a pressure relief device in the intermediate space to control load on the upstream pump section and/or "motoring" of the downstream pump section.

In variations on the helical trochoidal-based rotary machines described herein, the rotor and the stator cross-sectional shapes can be offset along the normals of their planar transverse cross-sections. For example, in some such embodiments where the rotor cross-sectional shape is based on hypotrochoidal geometry and undergoes planetary motion relative to a stator that is shaped as an outer envelope of that rotor, the rotor and the stator can have cross-sectional shapes that are inwardly offset. In other embodiments where the stator is cross-sectional shape is based on epitrochoidal geometry, and the rotor undergoes planetary motion relative to the stator and is shaped as the inner envelope of that stator, the rotor and the stator can have cross-sectional shapes that are outwardly offset. Such variations in geometry can offer additional advantages, while still retaining at least some of the benefits provided by helical trochoidal rotary machines.

FIG. **12** is a transverse cross-sectional diagram of a rotor-stator assembly **1200**, in which a rotor has a cross-sectional cross-sectional shape **1210** that is inwardly offset from each point on an ellipse **1215** by a fixed distance "d" measured perpendicular to a tangent to ellipse **1215** at that point. The resulting rotor cross-sectional shape **1210** is not a true ellipse. The corresponding stator cavity cross-sectional shape **1220** can be defined as the outer envelope generated when rotor cross-sectional shape **1210** undergoes planetary motion, or defined as the correspondingly inward offset of the envelope **1225** generated by the non-offset hypotrochoid (ellipse **1215**).

Referring again to FIG. **12**, with this "offset" geometry, the inverse apex region **1240** of stator is rounded with a circular arc, centered on the inverse apex **1245** of the "non-offset" geometry. In the plane of the diagram, the contact between inverse apex region **1240** of the stator and the rotor tips is continuous, but moves back and forth along the circular arc of the inverse apex region between points **1250** and **1255**. The distance between these points along the circular arc is the stator arc length (A_S), and the shortest distance between these two points is the sweep width (W_S) of the inverse apex region. On the rotor, contact with the inverse apex region **1240** of the stator occurs between points **1260***a* and **1265***a* on one rotor tip and between points **1260***b* and **1265***b* on the other rotor tip. The distance between points **1260***a* and **1265***a* (or **1260***b* and **1265***b*) around the rotor is the rotor arc length (A_R), and the shortest distance between these two points is the sweep width (W_R) of the rotor.

For a helical rotor-stator assembly, contact between the rotor and the stator occurs along curves that are the locus of contact points between the rotor and the stator in each transverse "cross section". For non-offset trochoid generating points in the envelope (i.e. the stator "inverse apex" of a hypotrochoid with outer envelope, or the "rotor tips" of an epitrochoid with inner envelope), this locus is a true helix. For offset trochoid generating points, the contact point moves across the arc length of the stator or rotor. This contact curve deviates from the true helix, but is visually substantially similar.

The locus of contact points between trochoid and envelope is more complex; in most embodiments, it sweeps across a substantially longer arc, so the contact path is a distorted helix. It is then "interrupted" as the contact point crosses the trochoid generating point. The resulting contact curves are discrete segments, roughly helical in appearance, but not true helices. These have a different slope than the continuous curve of the trochoid generating contact, and "bridge" points on that contact to form closed chambers.

FIG. **13**A shows the cross-sectional shape **1310** of a helical stator cavity with no offset (such as the stator cavity **410** of FIGS. **4**B and **4**C) in a plane normal to a longitudinal axis of the stator. FIG. **13**B shows a close up view of the inverse apex region from the same angle as FIG. **13**A. FIG. **13**C shows the cross-sectional shape **1320** of the same stator cavity in a plane normal to the helical path of the stator inverse apex. FIG. **13**D shows a close up view of the inverse apex region from the same angle as FIG. **13**C. In this cross-section the tip or peak of the inverse apex is much sharper (the angle is more acute). More broadly, when a given planar profile is used to generate a helical pump, the apex becomes narrower and sharper in at least one direction. Practically, having an interior surface of the stator defining such a sharp helical thread or crest (which is also a continuous contact line with the rotor) can be problematic. Such a sharp feature can be subject to rapid wear, and can be fragile and prone to breakage.

FIG. **14**A shows the cross-sectional shape **1410** of a helical stator cavity in a plane normal to a longitudinal axis of the stator, for a stator with a similar size to that of FIGS. **13**A-B but with an inward offset (as described in reference to FIG. **12**). FIG. **14**B shows a close up view of the inverse apex region from the same angle as FIG. **14**A. From this viewpoint, the inverse apex region defines a circular arc with the radius of circle R_1. FIG. **14**C shows the cross-sectional shape **1420** of the same stator cavity (with inward offset) in a plane normal to the helical path of the stator inverse apex region. FIG. **14**D shows a close up view of the inverse apex region from the same angle as FIG. **14**C. The inverse apex region defines a non-circular arc that has a minimum radius of curvature that is the radius of a circle R_2. Circle R_2 has a much smaller radius than circle R_1 (again, in this cross-section, the feature is sharper). Nonetheless, a stator with an offset geometry defines an inwardly protruding helical thread or crest that is less sharp than in a helical stator of similar dimensions but with no offset.

FIG. **15**A shows the cross-sectional shape **1510** of a helical hypotrochoidal rotor, in a plane normal to a longitudinal axis of the rotor. The rotor has no offset (it is a true ellipse in cross-section), and corresponds to stator cavity shown in FIG. **13**A. The tips of the rotor have a minimum radius of curvature that is the radius of circle R_3. FIG. **15**B shows the cross-sectional shape **1520** of the rotor in a plane normal to the helical path of the rotor tips. In this projection, the threads or crests of the helical rotor have a minimum radius of curvature that is the radius of circle R_4. The radius of circle R_4 is much smaller than the radius of circle R_3.

FIG. **16**A shows the cross-sectional shape **1610** of a helical rotor in a plane normal to a longitudinal axis of the rotor. The helical rotor in transverse cross-section has the same major diameter (A-A) and minor diameter (B-B) as the helical rotor of FIG. **15**A, but is not a true ellipse. Its transverse cross-sectional shape **1610** is inwardly offset from each point on an ellipse (indicated by dashed outline **1615**) by a fixed distance "d" measured normal to a tangent to the ellipse at each point on the ellipse. The offset rotor corresponds to the stator cavity illustrated in FIG. **14**A. The tips of the offset rotor have a minimum radius of curvature that is the radius of circle R_5. Circle R_5 has a smaller radius than circle R_3. In other words the offset rotor is more "pointy" in transverse cross-section than a similarly sized elliptical (truly hypotrochoidal) rotor. FIG. **16**B shows the cross-sectional shape **1620** of the offset rotor in a plane normal to the helical path of the rotor tips. At this angle, the crests of the helical rotor have a minimum radius of curvature which is the radius of circle R_6. Circle R_6 has a radius that is smaller than the radius of circle R_5, and much smaller than the radius of circle R_4.

For the stator with no offset illustrated in FIGS. **13**A-D, the sweep width across the inverse apex is infinitesimally small. FIG. **17**A shows the sweep width W_1 across the inverse apex region for a stator cavity with an offset (same as in FIG. **14**A), having cross-sectional shape **1410** in a plane normal to a longitudinal axis of the stator. FIG. **17**B shows the sweep width W_2 across the inverse apex region for the same stator cavity with cross-sectional shape **1420** (same as in FIG. **14**C) in a plane normal to the helical path of the stator inverse apex region. FIG. **18**A shows the sweep width W_3 across the rotor tips for an elliptical rotor with cross-sectional shape **1510** (same as in FIG. **15**A) in a plane normal to a longitudinal axis of the rotor. FIG. **18**B shows the sweep width W_4 across the rotor tips for the same elliptical rotor with cross-sectional shape **1520** (same as in FIG. **15**B) in a plane normal to the helical path of the rotor tips. FIG. **19**A shows the sweep width W_5 across the rotor tips for an offset rotor with cross-sectional shape **1610** (same as in FIG. **16**A) in a plane normal to a longitudinal axis of the rotor. FIG. **19**B shows the sweep width W_6 across the rotor tips for the same rotor with cross-sectional shape **1620** (same as in FIG. **16**B) in a plane normal to the helical path of the rotor tips.

For the stator with no offset illustrated in FIGS. **13**A-D, the arc length across the inverse apex is infinitesimally small. FIG. **17**A shows the arc length A_1 across the inverse apex region for a stator cavity with an offset (same as in FIG. **14**A), having cross-sectional shape **1410** in a plane normal to a longitudinal axis of the stator. FIG. **17**B shows the arc length A_2 across the inverse apex region for the same stator cavity with cross-sectional shape **1420** (same as in FIG. **14**C) in a plane normal to the helical path of the stator inverse apex region. FIG. **18**A shows the arc length A_3 across the rotor tips for an elliptical rotor with cross-sectional shape **1510** (same as in FIG. **15**A) in a plane normal to a longitudinal axis of the rotor. FIG. **18**B shows the arc length A_4 across the rotor tips for the same elliptical rotor with cross-sectional shape **1520** (same as in FIG. **15**B) in a plane normal to the helical path of the rotor tips. FIG. **19**A shows the arc length A_5 across the rotor tips for an offset rotor with cross-sectional shape **1610** (same as in FIG. **16**A) in a plane normal to a longitudinal axis of the rotor. FIG. **19**B shows the arc length A_6 across the rotor tips for the same elliptical rotor with cross-sectional shape **1620** (same as in FIG. **16**B) in a plane normal to the helical path of the rotor tips.

In summary, the offset rotor has sharper features than the non-offset rotor, whereas the offset stator has a more rounded inverse apex region than the non-offset stator. For both the offset and non-offset component geometries, the helicization makes the features sharper than they would be in a straight (non-helicized version) of the rotor-stator assembly. Because the lead of the stator is shorter than that of the rotor (by half in the case of a 2:1 rotor lobe:stator lobe rotary machine) the "sharpening" of the stator features upon helicization is more dramatic than for the corresponding rotor.

The degree of offset can be selected to give desirable relative rotor and the stator profiles. In particular, the degree of offset can be selected to achieve a particular design objective that may offer practical advantages.

In one approach, the offset geometry can be selected based on the radius of curvature of the outwardly protruding thread or crest of the rotor relative to the radius of curvature of the inwardly protruding inverse apex region (or thread or crest) of the stator. In some embodiments, for example, the degree of offset may be selected so that circle R_6 in FIG. **16**B (for the rotor) has about the same radius as circle R_2 in FIG. **14**D (for the stator). Selecting the offset geometry of the stator-rotor assembly so that these radii are approximately or precisely matched, can assist with balancing stresses in the rotary machine, and improving durability. If there is a big discrepancy between these radii, one component may be more subject to failure than the other. For example, with a very small or no offset the inwardly protruding thread or crest of the stator will be very sharp. If, during operation of the rotary machine there is a large contact load between the rotor and the stator along their contact lines, the fragile stator thread or crest may be prone to breakage or excessive wear. It may be possible to improve the durability of the rotor-stator assembly by using an offset geometry to increase the minimum radius of curvature of the stator thread or crest so that it is the same as or even greater than the minimum radius of curvature of the rotor thread or crest (when viewed in a plane normal to the helical threads).

In other embodiments, the degree of offset may be selected so that circle R_5 in FIG. **16**A (for the rotor) has about the same radius as circle R_1 in FIG. **14**B (for the stator).

In another approach, the offset geometry can be selected based on the relative sweep widths of the rotor and the stator. In some embodiments, the degree of offset may be selected so that the sweep width on the helical rotor is about the same as the sweep width on the corresponding helical stator (in a plane normal to the helical paths of the rotor and the stator, respectively), or so that the sweep width on the rotor is even less than on the stator. For example, the degree of offset may be selected so that sweep width W_2 in FIG. **17**B for the stator is about the same as sweep width W_6 in FIG. **19**B for the rotor. Consideration of relative rotor/stator sweep widths can be important, for example, if dynamic seals are used on the rotor and the stator. If the sweep widths are the same or similar, for example, the rotor and the stator seals can be made to be more similar in their properties. In embodiments of the rotary machines described herein that do include rotor and/or stator seals, the rotor seal width can be greater than, substantially the same as, or less than the rotor sweep width, and/or the stator seal width can be greater than, substantially the same as, or less than the stator sweep width. In some embodiments, it can be desirable that the rotor seal width is substantially the same as the rotor sweep width, and the stator seal width is substantially the same as the stator sweep width. In some of the latter embodiments, it can be desirable that the rotor seal width, rotor sweep width, stator seal width and the stator sweep width are all substantially the same.

In other embodiments, the degree of offset may be selected so that sweep width W_1 in FIG. **17**A for the stator is about the same as sweep width W_5 in FIG. **19**A for the rotor.

In another approach, the offset geometry can be selected based on the relative arc lengths on the rotor and the stator. For example, the degree of offset may be selected so that the arc length on the helical rotor is about the same as the arc length on the corresponding helical stator (in a plane normal to the helical paths of the rotor and the stator, respectively), or so that the arc length on the rotor is shorter than on the stator. For example, the degree of offset may be selected so that arc length A_2 in FIG. **17**B for the stator is about the same as arc length A_6 in FIG. **19**B for the rotor. The relative rotor and the stator arc lengths can be important, for example, in relation to the tendency of each component to be subject to wear. The component with the shorter arc length may be more subject to wear. It could be desirable to have the two components wear more evenly, or to have the component that is easier to repair or replace (typically the rotor) be the one which tends to wear more quickly. In embodiments of the rotary machines described herein that do include rotor and/or stator seals, the arc length of the rotor seal can be greater than, substantially the same as, or less than the arc length of the rotor, and/or the arc length of the stator seal can be greater than, substantially the same as, or less than the arc length on the stator. In some embodiments, it can be desirable that the arc length of the rotor seal width is substantially the same as the arc length on the rotor, and the arc length of the stator seal is substantially the same as the arc length on the stator. In some of the latter embodiments, it can be desirable that the arc length on the rotor, the arc length on the stator, the arc length of the rotor seal and the arc length of the stator seal are all substantially the same.

In other embodiments, the degree of offset may be selected so that arc length A_1 in FIG. **17**A for the stator is about the same as arc length A_5 in FIG. **19**A for the rotor.

The offset geometry of the stator-rotor assembly can also be selected so that the tendency for a fluid leak path to exist or form between the stator and the rotor (at their various contact points) is reduced. For example, if fluid leakage is assumed to be a function of a separation distance between the rotor and the stator as well as the length of a constricted path between rotor and the stator, it is possible to adjust these variables to reduce the tendency for leakage. For non-offset embodiments, the leak path looks more like an orifice, whereas for offset embodiments, the leak path looks more like a pipe or channel.

For rotary machines based on a stator that is epitrochoidal and the rotor is shaped as the inner envelope of that stator, the rotor and the stator can have cross-sectional shapes that are outwardly offset along the normals of their planar transverse cross-sections. Even though the offset is the other way around in such machines, the degree of offset can be selected based on similar considerations to those discussed above.

In other variations on the helical trochoidal rotary machines described herein, instead of being offset along the normals of their planar transverse cross-sections, the rotor and the stator cross-sectional shapes can be offset along the normals of their outer or inner body surface, respectively. Geometrically, for example, this would be equivalent to adding a coating of substantially uniform thickness to the rotor or the inner surface of the stator, and removing a layer of substantially uniform thickness from the corresponding stator or rotor. For example, in embodiments where the rotor is hypotrochoidal and undergoes planetary motion relative to a stator that is shaped as an outer envelope of that rotor, the rotor cross-sectional shape can be inwardly offset in a manner equivalent to having a layer of substantially uniform thickness removed from the outer surface of the rotor, with the corresponding stator cross-sectional shape being inwardly offset in a manner equivalent to having a layer of substantially uniform thickness added to the inner surface or cavity of the stator. In other embodiments where the stator is epitrochoidal, and the rotor undergoes planetary motion relative to the stator and is shaped as the inner envelope of that stator, the rotor and the stator can have cross-sectional shapes that are outwardly offset along the normals of their outer and inner surfaces, respectively, in a manner equivalent to adding a layer of substantially uniform thickness to the rotor and removing a layer of substantially uniform thickness from the inner surface or cavity of the stator.

Sealing in Helical Trochoidal Rotary Machines

There are various approaches to reducing leakage between the rotor and the stator, and between stages, of rotary machines. In one approach, a simple tight fit of rotor and the stator can reduce the tendency for leak paths. High tolerance manufacturing can be used, so that the components move in extremely close proximity to one another, however this approach is generally expensive and can be challenging for certain machine geometries or architectures. It can also be difficult to accommodate thermal expansion/contraction of the inner diameter of the stator and/or outer diameter of the rotor, for example. Such thermal expansion or contraction can increase the tendency for the leakage, or result in jamming or aggressive wear of the components during operation of the machine.

A flexible or elastomeric rotor and/or stator (or an elastomeric sleeve or liner) can be used to provide a resilient, interference fit between components, however such material can be subject to wear and/or may tend to degrade when in prolonged contact with a working fluid.

Abraded surfaces can be used to provide a tight tolerance fit, however such surfaces tend to have high wear rates with abrasive fluids, typically require a break-in period, and generally one of the surfaces must be made of softer material which can have limitations in certain applications.

As mentioned above, for the helical rotary machines described herein, the periodicity of contact between the helical rotor and the stator occurs in space (moving along a physically continuous contact path over time) rather than in time (with intermittent contact between surfaces). Thus, in the present rotary machines, rather than periodically engaging and disengaging (or touching and separating), the contact surfaces and any associated seals slide across one another, or in close proximity to one another, continuously, with a kind of "scissoring" action relative to one another. In embodiments with an elliptical helical rotor, at least some portion of each of the two outwardly protruding crests (or threads) of the helical rotor continuously contact the stator, and at least some portion of the helical inverse apex region (or crests) of the stator continuously contacts the rotor. These contacting regions move along the crests of the rotor helical threads and helical inverse apex region of the stator, during rotation of the rotor in the stator. The entire inner surface area of the stator and the entire outer surface area of the rotor are swept at some point time during rotation of the rotor within the stator. Thus, there is a quasi-helical contact path between the rotor and the stator at all times during rotation of the rotor (just as there is contact between the rotor tips and the stator, and between the inverse apex of the stator and the rotor, in the machine of FIGS. **1**A-**1**G). The rotor-stator contact paths revolve around the machine as pumping action proceeds, "threading" the fluid (or material to be pumped) in a spiral path along the helix, so that it is moved axially from one end of the stator cavity to the other.

In the type of rotary machines described herein, rotor and the stator seals (if both present) do not strike each other intermittently—they slide across one another. This, and having one or more continuous contact paths between rotor and the stator, can facilitate the provision of sealing in embodiments of the present machines. In some embodiments it can be desirable to dispose one or more seals between the rotor and the stator components to reduce leakage of fluid between stages. Such seals can be mounted on the rotor or the stator, or both. They can be designed to be coextensive with the regions (lines or bands) on the rotor and/or stator that have continuous contact with the other component. For example, in embodiments of the present rotary machine with an offset geometry, the seals can span the arc lengths on the rotor and the stator, as described in reference to FIGS. **17-19**.

In some embodiments, for example, a helical seal may be provided in the stator, positioned along the locus of the trochoid generating point as the envelope is swept to produce the stator cavity, and/or seals may be provided along the crests of the two threads of the corresponding helical rotor that is elliptical in transverse cross-section. In both cases, the seals replace a defined portion of the rotor or stator cross-section. While the contact path is not necessarily precisely helical, the seal may be helical with the contact path sweeping across a seal surface of some finite width. In some embodiments, depending on the manufacturing tolerances of the components, the seal may protrude slightly from the surface of the rotor or stator. This can be done deliberately to energize the seal.

FIG. **20** shows an example of a helical seal **2000** that can be accommodated, for example, in a corresponding groove formed in a helical stator or rotor, with the seal lead distance matching the lead of the corresponding stator or rotor.

FIGS. **21**A-**21**C show a helical seal **2100** installed in a groove **2105** in the interior surface of stator **2120** along the locus of the inverse apex region (i.e. along the inwardly protruding crest). Stator seal **2100** touches rotor **2110** continuously, the contact path with the rotor moving continuously along stator seal **2100**, as rotor **2110** undergoes planetary motion relative to stator **2120**. FIG. **21**A is a cross-sectional view (transverse to the axis of rotation of rotor **2110**) and FIGS. **21**B and **21**C are cross-sectional views as indicated by A-A and B-B in FIG. **21**A, respectively.

FIGS. **22**A-**22**D show a pair of seals **2200***a* and **2200***b* installed in corresponding grooves in the exterior surface of helical rotor **2210**, along the two outwardly protruding helical threads or crests. Seals **2200***a* and **2200***b* touch stator **2220** continuously, the contact path with the stator moving continuously along the rotor seals **2200***a* and **2200***b* over time, as rotor **2210** undergoes planetary motion relative to stator **2220**. FIG. **22**A is an isometric view of a portion of a rotor-stator assembly with a helical seal. FIG. **22**B is a cross-sectional view (transverse to the axis of rotation) and FIGS. **22**C and **22**D are cross-sectional views as indicated by A-A and B-B in FIG. **22**B, respectively. In FIGS. **22**A and **22**C stator **2220** is shown partially cut away to more clearly reveal rotor **2210** disposed therein, and seals **2200***a* and **2200***b* are partially cut away for clarity to show a portion of the rotor without the seals in place.

The stator and the rotor seals can be made of any suitable material or combination of materials, subject to typical considerations for seal design and operation, and the nature of the working fluid. For example, softer materials can sometimes reduce the tendency for leakage, and hard materials can be more durable and less subject to wear.

Furthermore, the seal and corresponding mating features for the rotor and/or stator seals can be designed such that the seals are held securely in place during operation of the rotary machine. Some non-limiting examples of a stator seal profiles are illustrated in FIGS. **23**A-D which show, in transverse cross-section (in a plane normal to the axis of the helical stator), partial views of stators (**2310**A to D) with various stator seals (**2300**A to D) mounted therein. Some non-limiting examples of rotor seal profiles are illustrated in FIGS. **24**A-F which show, in transverse cross-section (in a plane normal to the axis of the helical rotor), partial views of rotors (**2410**A to F) with various rotor seals (**2400** A to F) mounted therein.

Stator seal **2300**A illustrated in FIG. **23**A has parallel sides, whereas the stator seal **2300**B illustrated in FIG. **23**B has tapered sides. Seal **2300**A may tend to maintain a better seal against corresponding stator **2310**A. For example, as the seals wear, flex or move out of the corresponding grooves in stator (i.e. radially inwardly in a rotary-stator assembly), fluid is less likely to pass underneath seal **2300**A than seal **2300**B, where a gap under the seal may open up in this situation. However, this tendency for leakage around seal **2300**B may be mitigated if there is a pressure differential across the seal, such that it is pushed against one side wall of the groove. In stator seals **2300**C and **2300**D illustrated in FIGS. **23**C and **23**D respectively, the corners of the seal are rounded rather than being sharp.

Similarly, rotor seals **2400**A, **2400**B and **2400**D may tend to maintain a better seal against their corresponding grooved rotors, **2410**A, **2410**B and **2410**D, respectively, than tapered rotor seal **2400**C with rotor **2410**C. Rotor seal **2400**E has a parallel-sided groove **2420**E in it, and there is a corresponding protruding ridge **2430**E along the crest of rotor **2410**E which fits into the seal groove **2420**E. Seal groove **2420**E tends to make the seal more flexible and springy, so that it accommodates radial in and out flexing, and/or wear of the rotor seal. Rotor seal **2400**F has a protruding ridge **2420**F that fits into corresponding tapered groove **2430**F in rotor **2410**F. Seal ridge **2420**F tends to make the seal stiffer, which might be advantageous in some situations. Seals **2400**E and **2400**F are fatter (providing a wider resilient sweep width, relative to seals **2400**A-D), and their stiffness can be controlled by the choice of material and their profile, as discussed above.

The seals on the rotor may be energized or pushed against the stator to provide a tighter seal, and to self-adjust or compensate for wear during operation of the rotary machine. Energization may be accomplished in a number of ways including, for example, using downstream high pressure fluid to exert a force on the underside of the seal, or using spring force as is done in conventional seal designs. For example, a rotor seal can be made with a seal radius (see FIG. **20**) that is slightly too large, or oversized. The seal can be tightened (contracted radially) for installation on the rotor by rotating the ends of the seal in the direction indicated as T by the arrows shown in FIG. **20**. The seal will then tend to press against the interior surface of the stator, and as the rotor seal wears it will tend to expand radially (outwardly) and continue to press against the interior surface of the stator. Similarly, the stator seal can be made with a seal radius (see FIG. **20**) that is slightly too small, or undersized. The seal will then be pushed outwardly into the groove in the stator by the rotor, opening up the stator seal in the direction indicated as L by the arrows shown in FIG. **20**. As the stator seal wears it will tend to contract radially (inwardly) and continue to press tightly against the rotor. In this way the spring-like properties of the spiral rotor and/or stator seals can be used to energize the seals, enhance the resiliency of the seals, and/or accommodate wear and thermal expansion/contraction.

As discussed above, in some embodiments of the rotary machines described herein, a seal that is used on the rotor or stator does not necessarily have to span the entire contact width or contact area between the rotor and the stator. For example, the rotor or stator seal width can be less than the corresponding rotor or stator sweep width and/or the arc length of the rotor or stator seal can be less than the arc length of the corresponding rotor or stator.

FIG. **25** is a cross-sectional view of a portion of a helical rotor with a rotor seal, and illustrates an example of a rotor seal **2500** where the seal width, W_{RS}, of the rotor seal (at the surface of the rotor) is substantially the same as the sweep width W_R of the rotor **2510**.

FIG. **26** is a cross-sectional view of a portion of helical stator **2620** and rotor **2610**, with a rotor seal **2600** mounted in a groove **2615** in rotor **2610**. In this example, the seal width, W_{RS}, of rotor seal **2600** is substantially less than the sweep width W_R of the rotor **2610**. Seal **2600** can be sized so that as the rotor rotates relative to the stator, seal **2600** comes out of groove **2615** slightly and protrudes from the surface of rotor **2610** along at least a portion of its length, so that it may still contact the inner surface of stator **2620** and thereby maintain some sealing function between the stator and the rotor. Such an arrangement can be beneficial. For example, narrower seals tend to be more flexible and resilient than fatter seals of the same material—this can enhance their dynamic sealing capabilities. Also, the rotor strength and durability may be less compromised by a narrower groove than a wider groove to accommodate the seal, and the rotor seal may be better supported by the thicker walls of the groove when the groove itself is narrower. A similar approach can be taken with a stator seal.

In operation of the rotary machine, frictional force will tend to move the rotor and/or stator seals helically, thus threading them out of the corresponding rotor or stator to which they are mounted. Various features can be used at one or both the ends of seals (and/or at one or more locations along the length of the seal) to limit or prevent seal travel. These include, for example, incorporating "dead ends" in the grooves, a feature at the end of the seal that is larger than the seal groove, and or a pin or fastener at one end of the seal.

In some embodiments each rotor seal is attached to the helical rotor at one end of rotor seal (the end from which the rotor seal tends to travel as the rotor revolves), and not at the other end, such that the action of rotor friction against the stator will hold the seal in tension, resulting in the seal tending to be drawn inwards into the rotor channel, and thereby reduce the tendency for wedging, camming or excessive friction against the stator. In some embodiments the stator seal is not attached to the stator, but the groove or channel which accommodates the seal can have a wall or dead-end (at least at the end toward which the stator seal tends to travel as the rotor revolves), which constrains or blocks the seal from moving along any further along the stator cavity. The stator seal will then abut or bottom out to the end of the groove in the stator. This will then tend to increase the radius of the stator seal, which in turn reduces the tendency for wedging, camming or excessive friction of the stator against the rotor.

The manner in which the rotor and the stator seals are mounted and/or constrained may depend upon how the machine is to be driven. In some gearless embodiments the rotor is coupled to and driven by a motor (via a shaft) and the stator acts as a guide for the rotor to centralize and constrain motion of the rotor. In some such embodiments, it can be desirable that the stator seal has a channel depth equivalent to the seal depth such that the contact between the adjacent rotor and the stator seal consistently transfers guidance forces. Similarly it can be desirable that a rotor, with a stator guiding the rotor motion, also has rotor seals that bottom out in their respective channels allowing the rotor to maintain a controlled path. If the channels are deeper than the depth of the seals on the rotor and/or stator, the seals could retract into the channel and no longer provide stable rotor guidance from the interaction with the stator.

In some embodiments of the present rotary machines the rotor and/or stator seals are designed to be removable and easily replaceable. For example, in some rotary machines it may be relatively straightforward to remove the helical rotor from the stator and replace the rotor seals. In situations where it is easier to replace the rotor seal than the stator seal, it can be beneficial to design the stator seal to be more durable than the rotor seal.

In some of the embodiments of the rotary machines described herein, the various components (such as, for example, the rotor, stator cavity and rotor and the stator seals) are truly helical or have a mathematically helical profile or shape. In other embodiments of the rotary machines described herein, it will be understood that the descriptive term "helical" is used more broadly to encompass components that have the general or approximate form of a helix or are "quasi-helical", and also to encompass variations on a helical form such as, for example, variable pitch helical or conical helical components.

As with other positive displacement machines, embodiments of the machines described herein can be used as hydraulic motors, pumps (including vacuum pumps), compressors, expanders, engines and the like. The helical rotary machines described herein can provide relatively high displacement/pump volume for their size, relative to PCPs for example.

In one application, embodiments of the machines described herein can be used in electric submersible pump systems, for example, as downhole pumps in the oil and gas industry for pumping production fluids to the surface.

In the same application, embodiments of the machines described herein can be used for top driven submersible pumps driven by rotating shafts connecting a surface mounted drive system to the pump for example, as downhole pumps in the oil and gas industry for pumping production fluids to the surface.

Various different embodiments of the machines described herein can be particularly suitable for:

handling highly viscous fluids, as shear is low and the pump chambers have constant shape and volume (unless designed otherwise);

handling large pressure differentials with modest specific flow, as numerous stages can readily be provided;

use as vacuum pumps and compressors, because they are fully scavenging;

handling fluids with significant gas or solids content (because of their low shear operation, and particularly if additional features are used to enhance solids handling or tolerance);

pumping applications that require a long, narrow form (e.g. electrical submersible pump;

applications where positive displacement pumping with steady flow is a high priority (e.g. very dense materials, such as concrete; flow metering or dosing, e.g. filling injection molds).

There are some important differences between conventional progressive cavity pumps (PCPs), and rotary machines having architectures as described herein. In rotary machines having architectures as described herein, there is a continuous line of contact between the rotor and the stator. In some embodiments a metal spring seal (similar to a slinky toy or piston ring) can be used between the stator and the rotor to provide a positive seal with no elastomer. In PCPs the stator is often made from or lined with an elastomer, to provide sealing. This material often degrades and needs to be replaced. In PCPs, the rotor interacts with a particular portion of the stator in at least two orientations. In rotary machines as described herein, the moving line of contact along the crest of the helical rotor only interacts with the stator in one orientation, which can provide operational advantages. A transverse cross-section of a typical PCP rotor-stator assembly shows a circular rotor positioned or contained between two parallel sides of the stator profile. This arrangement limits the ability of the rotor to move when a foreign particle such as sand or another hard substance becomes trapped in this contact region. The result is a potentially high abrasion condition. The rotor in rotary machines having architectures as described herein is not constrained in this manner. Furthermore, the rotary machines described herein have different flow characteristics than PCPs, which may be more favorable for certain applications.

All-metal PCPs typically have lower volumetric efficiencies and lower overall pump efficiencies than PCPs with an elastomer. The use of an elastomer in a PCP also typically enhances the solids handling capability of the pump versus an all-metal PCP, resulting in longer operational lifetimes in many applications. For example, in one study in a high temperature oil well application, the overall efficiency of an all-metal pump ranged from about 20-50% with a lifetime of less than 500 days, whereas a comparable elastomer PCP operated with efficiency in the range of 25-65% with about a 30 day longer lifetime. The efficiency of both types of PCP tends to decline quite rapidly during operation of the pump.

Embodiments of the helical trochoidal rotary machines described herein have been shown to provide high volumetric and overall efficiencies, and to operate with low degradation in efficiency over time.

EXAMPLE

Longevity testing was performed on a 2-stage helical trochoidal rotary pump (12 inches (30.48 cm) long, 2.8 inches (7.11 cm) diameter) having a rotor with an inward offset (relative to an elliptical transverse rotor cross-section) such that the rotor and the stator peaks have a similar minimum radius. The rotor and the stator were made of 4140 hardened steel. The operating fluid was mineral seal oil, a wellbore simulated fluid with a viscosity of 3 cP, intended to simulate a downhole lift application of oil with water cut. The pump was operated at 400 RPM with the pressure set at 25 psi per stage (50 psi total), and the flow rate was 25 GPM. The pump was operated and tested under these conditions over a period of 136 days, which at 400 RPM represents 78 million cycles. FIG. **27** is a graph showing the overall efficiency (plot A) and the volumetric efficiency (plot B) of the pump versus the number of cycles. Total efficiency is a measure of how much shaft power is converted into useful work. Volumetric efficiency is a measure of slip. Slip is the ratio of actual flow delivered by a pump at a given pressure to its theoretical flow, where the theoretical flow can be calculated by multiplying the pump's displacement per revolution by its driven speed. The observed volumetric and overall efficiency values are high, especially considering that both the rotor and the stator are made of metal, and the pump did not have dynamic seals on the rotor or stator. As can be seen from FIG. **27**, the pump demonstrated very little loss in overall and volumetric efficiency over the test period, and almost no loss over the first 70 million cycles.

While particular elements, embodiments and applications of the present invention have been shown and described, it will be understood that the invention is not limited thereto since modifications can be made by those skilled in the art without departing from the scope of the present disclosure, particularly in light of the foregoing teachings.

What is claimed is:

1. A rotary machine comprising an outer-member having an outer-member length and an outer-member axis, and a rotor having a rotor length and a rotor axis, said rotor disposed within said outer-member,

said rotor, along at least a portion of said rotor length, having a rotor helical profile, and a rotor shape that is inwardly offset from a hypotrochoidal shape at any cross-section transverse to said rotor axis, said rotor configured to spin about said rotor axis,

said outer-member, along at least a portion of said outer-member length, having an outer-member helical profile, and an outer-member shape at any cross-section transverse to said outer-member axis that is an outer envelope formed when said rotor shape undergoes planetary motion, said outer-member configured to spin about said outer-member axis,

wherein said rotor and said outer-member are held at a fixed eccentricity with said rotor axis offset relative to said outer-member axis so that during operation of said rotary machine, said rotor undergoes planetary motion relative to said outer-member without orbiting.

2. The rotary machine of claim **1** wherein:

said hypotrochoidal shape has n lobes, where n is an integer;

said outer-member shape has (n−1) lobes;

said rotor has a rotor pitch and a rotor lead;

said outer-member has an outer-member pitch and an outer-member lead;

said rotor pitch is the same as said outer-member pitch; and

a ratio of said rotor lead to said outer-member lead is n:(n−1).

3. The rotary machine of claim **2** wherein said hypotrochoidal shape is an ellipse, and n=2.

4. The rotary machine of claim **3** wherein said rotor is coupled to a drive system to spin said rotor about said rotor axis, and said rotary machine is configured so that spinning of said rotor causes said outer-member to spin about said outer-member axis.

5. The rotary machine of claim **3** wherein said outer-member is coupled to a drive system to spin said outer-member about said outer-member axis, and said rotary machine is configured so that spinning of said outer-member causes said rotor to spin about said rotor axis.

6. The rotary machine of claim **3** wherein said rotary machine is a multi-stage machine and a plurality of chambers are formed between cooperating surfaces of said rotor and said outer-member.

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