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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
7 July 2016 (07.07.2016)

WIPO | PCT

(10) International Publication Number
WO 2016/109551 A1

(51) International Patent Classification:
F01N 5/02 (2006.01)

(21) International Application Number:
PCT/US2015/067885

(22) International Filing Date:
29 December 2015 (29.12.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
4024/DEL/2014 30 December 2014 (30.12.2014) IN

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

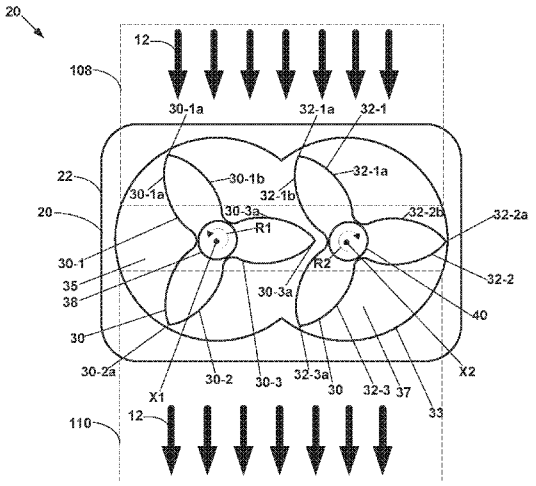
— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

(54) **Title**: OPTIMAL EXPANDER OUTLET PORTING

FIG. 3



(57) **Abstract**: An optimized mechanical expander or fluid expansion device with a delayed opening timing is disclosed. In the optimized design, rotors in the expander alternatingly rotate sequentially through an intake position in which the transport volume is open to the housing inlet, a closed position in which the transport volume is closed to the housing outlet, and a discharge position in which the transport volume is open to the housing outlet. During rotation, a first opening forms between the housing and each rotor. After further rotation, a second opening is formed that is located between the first opening and a back end of the rotor. In one aspect, the mechanical expander has an opening profile including an initial opening phase in which the opening between the rotor and outlet forms at a lesser rate than during a subsequent secondary opening phase.

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OPTIMAL EXPANDER OUTLET PORTING

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is being filed on December 29, 2015 as a PCT International Patent Application and claims the benefit of Indian Patent Application No. 4024/DEL/2014, filed on December 30, 2014, the disclosure of which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present disclosure relates to systems for recovering waste heat. More particularly, the present disclosure relates to waste heat energy recovery with a roots expander.

BACKGROUND

[0003] Waste heat energy is necessarily produced in many processes that generate energy or convert energy into useful work, such as a power plant. Typically, such waste heat energy is released into the ambient environment. In one application, waste heat energy is generated from an internal combustion engine. Exhaust gases from the engine have a high temperature and pressure and are typically discharged into the ambient environment without any energy recovery process. Alternatively, some approaches have been introduced to recover waste energy and re-use the recovered energy in the same process or in separate processes. However, there is still demand for enhancing the efficiency of energy recovery.

SUMMARY

[0004] An optimized mechanical expander or fluid expansion device with a delayed opening timing is disclosed. In one aspect, the expander includes a housing having an interior structure defining an interior volume, an inlet, and an outlet. The expander also includes a pair of parallel helical rotors disposed within the housing in a counter rotating non-contacting arrangement. Each of the rotors can have a plurality of lobes, wherein each lobe defines a cusp extending between a front end and a back end. The rotors are

rotatable within the housing to form a transport volume between a leading lobe cusp, a trailing lobe cusp, and the housing interior structure. In the optimized design, the rotors alternatingly rotate sequentially through an intake position in which the transport volume is open to the housing inlet, a closed position in which the transport volume is closed to the housing outlet, and a discharge position in which the transport volume is open to the housing outlet. In one aspect, the rotors rotate from the closed position to the discharge position. During this rotational phase, a first opening forms between the housing interior structure and the leading lobe cusp proximate the front end. Subsequently, a second opening forms between the housing interior structure and the leading lobe cusp between the first opening and the leading lobe cusp back end, the second opening forming after the first opening has been at least partially formed. After further rotation, a third opening forms between the housing sidewall and the leading lobe cusp between the second opening and the leading lobe cusp back end, the third opening forming after the second opening has been at least partially formed.

[0005] In one aspect, the mechanical expander has an opening profile including an initial opening phase followed by a secondary opening phase, wherein only the first opening is formed and enlarged during the initial opening phase and both the first and second openings are enlarged during the secondary opening phase. In one example, the first rate of enlargement of a total opening area during the initial opening phase is less than a second rate of enlargement of the total opening area during the secondary opening phase to result in a delayed timing of the rotors.

[0006] A variety of additional aspects will be set forth in the description that follows. These aspects can relate to individual features and to combinations of features. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the broad concepts upon which the embodiments disclosed herein are based.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figure 1 is a schematic view of a vehicle having a volumetric fluid expansion device having features that are examples of aspects in accordance with the principles of the present disclosure.

[0008] Figure 2 is a schematic side view of the fluid expansion device shown in Figure 1.

[0009] Figure 3 is a schematic end view of a stage inlet of the fluid expansion device shown in Figure 1.

[0010] Figure 4 is a schematic showing geometric parameters of the rotors of the fluid expansion device shown in Figure 1.

[0011] Figure 5 is a top perspective view of a physical example of the volumetric fluid expansion device depicted in Figures 1-4.

[0012] Figure 6 is a bottom perspective view of the fluid expansion device shown in Figure 5.

[0013] Figure 7 is a top view of the fluid expansion device shown in Figure 5.

[0014] Figure 8 is a bottom view of the fluid expansion device shown in Figure 5.

[0015] Figure 9 is a front view of the fluid expansion device shown in Figure 5.

[0016] Figure 10 is cross-sectional view of the fluid expansion device shown in Figure 5, taken along the line A-A shown in Figure 9.

[0017] Figure 11 is cross-sectional view of the fluid expansion device shown in Figure 5, taken along the line B-B shown in Figure 9.

[0018] Figure 12 is cross-sectional view of the fluid expansion device shown in Figure 5, taken along the line C-C shown in Figure 9.

[0019] Figure 13 is a bottom perspective view of a model of the fluid expansion device shown in Figure 5, wherein the rotors in the fluid expansion device are in a first rotational position.

[0020] Figure 13A is a bottom perspective view of the model view shown in Figure 13, but with the rotors removed such that only the interior surfaces of the fluid expansion device are shown.

[0021] Figure 14 is a bottom view of the fluid expansion device model shown in Figure 13.

[0022] Figure 14A is a bottom view of the model view shown in Figure 14, but with the rotors removed such that only the interior surfaces of the fluid expansion device are shown.

[0023] Figure 15 is a bottom perspective view of the fluid expansion device model shown in Figure 13.

[0024] Figure 16 is an enlarged bottom perspective view of the fluid expansion device model shown in Figure 13, as indicated at Figure 15.

[0025] Figure 17 is a bottom view of the model of the fluid expansion device shown in Figure 13, wherein the rotors in the fluid expansion device are in a second rotational position.

[0026] Figure 18 is an enlarged bottom view of the fluid expansion device model shown in Figure 17, as indicated at Figure 17.

[0027] Figure 19 is a bottom perspective view of the model of the fluid expansion device shown in Figure 13, wherein the rotors in the fluid expansion device are in a third rotational position.

[0028] Figure 20 is a bottom view of the fluid expansion device model shown in Figure 19 with the rotors in the third rotational position.

[0029] Figure 21 is a bottom perspective view of the model of the fluid expansion device shown in Figure 13, wherein the rotors in the fluid expansion device are in a fourth rotational position.

[0030] Figure 22 is a bottom view of the fluid expansion device model shown in Figure 21 with the rotors in the fourth rotational position.

[0031] Figure 23 is a bottom perspective view of the model of the fluid expansion device shown in Figure 13, wherein the rotors in the fluid expansion device are in a fifth rotational position.

[0032] Figure 24 is a bottom view of the fluid expansion device model shown in Figure 23 with the rotors in the fifth rotational position.

[0033] Figure 25 is a graph showing an opening profile of the fluid expansion device shown in Figure 5.

DETAILED DESCRIPTION

[0034] Modern demands for fuel efficient vehicles and power plants have led to development of hybrid power-generation and propulsion systems. Generally, such systems combine a power-plant, such as an internal combustion engine or a fuel cell, and

an electric motor to drive the vehicle. Each of the internal combustion engine and fuel cell emits high temperature exhaust as a byproduct of the power-generation cycle employed therein. The high temperature exhaust constitutes energy that is lost from the power-generation cycle, which, if recaptured, could be employed to improve efficiency of the cycle, and, therefore, of the propulsion system employing the same. Improvements in other applications are also desired, for example in marine and agricultural industries. Another example is stationary generator sets.

Systems including Fluid Expansion Devices

[0035] Referring to Figure 1, a vehicle 10 is shown having wheels 12 for movement along an appropriate road surface. The vehicle 10 includes a power-generation system 14. The system 14 includes a power-plant 16 employing a power-generation cycle. The power-plant 16 uses a specified amount of oxygen, which may be part of a stream of intake air, to generate power. The power-plant 16 also generates waste heat such in the form of a high-temperature exhaust gas in exhaust line 17 a byproduct of the power-generation cycle. In one embodiment, the power-plant 16 is an internal combustion (IC) engine, such as a spark-ignition or compression-ignition type which combusts a mixture of fuel and air to generate power. In one embodiment, the power-plant 16 may be or a fuel cell which converts chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent.

[0036] The vehicle 10 may also include an energy recovery device, for example volumetric fluid expansion device 20, which recovers waste heat from the power-plant 16 to improve the efficiency of the power-plant 16.

[0037] In one embodiment, and as shown in Figure 1, an organic Rankine cycle (ORC) is used to power the fluid expansion device 20. In such an embodiment, a piping system 1000 including a heat exchanger 18 is provided that transfers heat from the exhaust gas line 17 to a working fluid 12 that is then delivered to the volumetric fluid expansion device 20. The working fluid 12 may be a solvent such as ethanol, n-pentane, or toluene. A condenser 19 is also provided which creates a low pressure zone for the working fluid 12 and thereby provides a location for the working fluid 12 to condense. Once condensed, the working fluid 12 can be delivered to the heat exchanger 18 via a pump 17. A more

detailed description of an ORC system being utilized to drive an energy recovery device 20 is provided in Patent Cooperation Treaty (PCT) International Application Publication Number WO 2013/30774 entitled VOLUMETRIC ENERGY RECOVERY DEVICE AND SYSTEMS. WO 2013/30774 is hereby incorporated herein by reference in its entirety. The volumetric fluid expansion device 20 may also be utilized in a direct exhaust gas heat recovery process wherein the exhaust gas is the working fluid 12, as disclosed in Patent Cooperation Treaty (PCT) International Application Publication Number Wo 2014/107407, the entirety of which is incorporated by reference herein. Additional expander systems are disclosed in Patent Cooperation Treaty (PCT) International Application Publication Number WO 2014/117159, the entirety of which is incorporated by reference herein.

[0038] In one aspect, the fluid expansion device 20 may also include a power output device 25 configured to transfer useful work from the fluid expansion device 20. Such mechanical work generated by the rotation of the output shaft 38 (discussed later) of the fluid expansion device 20 may be delivered to any elements or devices as necessary. For example, the output shaft 38 can be directly or indirectly coupled to another power plant, another fluid expansion device, a turbocharger, a supercharger, a generator, a motor, a hydraulic pump, and/or a pneumatic pump via gears, belts, chains or other structures. In some examples, the recuperated energy may be accumulated in an energy storage device, such as a battery or an accumulator, and the energy storage device may release the stored energy on demand. In other examples, the recovered energy may return to the power plant 16 by mechanically coupling the output shaft of the device 20 to a power input location 17 (e.g. a crankshaft of an engine). A power transmission link 25 may also be employed between the volumetric fluid expander 20 and the power plant 16 to provide a better match between rotational speeds of the power plant 16 and the output shaft of the device 20. In some embodiments, the power transmission link 25 can be configured as a planetary gear set to provide two outputs for the power plant 16 and a generator.

Fluid Expansion Device General Construction

[0039] Referring to Figures 2-4, a volumetric fluid expansion device 20 in accordance with the present teachings is shown in schematic form. Figures 5-12 show a physical embodiment of the fluid expansion device 20. As shown, the fluid expansion device 20

includes a main housing 102 that defines a first working fluid passageway 106 extending between a first inlet 108 and a first outlet 110. The fluid expansion device 20 can also be provided with compartments 150, 152 to house bearings, timing gears, and/or step gears, for example, as explained in PCT Publication WO 2014/117159. Disposed within the working fluid passageway 106, is a pair of meshed rotors 30, 32. Each pair of meshed rotors 30, 32 is configured such that the rotors 30, 32 are overlapping or intermeshed, and rotate synchronously in opposite directions.

[0040] As the working fluid 12 passes through the inlet 108 across the meshed rotors 30, 32 and to the respective outlet 110, the working fluid 12 undergoes a pressure drop which imparts rotational movement onto the rotors 30, 32, thus creating mechanical work that can be input back into the power plant 16. Accordingly, the inlet port 108 is configured to admit the working fluid 12 at an entering pressure whereas the corresponding outlet port 110 is configured to discharge the working fluid 12 at a leaving pressure lower than the entering pressure. In such a configuration, the working fluid 12 enters inlet 108 at a first pressure and leaves outlet 110 at a second pressure lower than the first. In one embodiment, the pressure drop from the inlet 108 to the outlet 110 is between about 2 bar and about 10 bar, for example 5 bar.

[0041] Each of the rotors 30, 32, as most easily seen at Figure 3, is provided with a plurality of lobes. As shown, each rotor 30, 32 can be provided with three lobes, 30-1, 30-2, 30-3 in the case of the rotor 30, and 32-1, 32-2, 32-3 in the case of the rotor 32. As shown, each of the lobes 30-1 to 30-3 and 32-1 to 32-3 form a respective tip or cusp edge 30-1a to 30-3a and 32-1a to 32-3a. Although three lobes are shown for each rotor 30 and 32, each of the two rotors may have any number of lobes that is equal to or greater than two. For example, PCT Publication WO 2013/30774 shows a suitable rotor having four lobes.

[0042] As presented, the number of lobes is the same for each rotor 30 and 32. This is in contrast to the construction of typical rotary screw devices and other similarly configured rotating equipment which have a dissimilar number of lobes (e.g. a male rotor with "n" lobes and a female rotor with "n+1" lobes). Furthermore, one of the distinguishing features of the expansion device 20 is that the rotors 30 and 32 are identical, wherein the rotors 30, 32 are oppositely arranged so that, as viewed from one axial end, the lobes of

one rotor are twisted clockwise while the lobes of the meshing rotor are twisted counter-clockwise. Accordingly, when one lobe of the rotor 30, such as the lobe 30-1 is leading with respect to the inlet port 24, a lobe of the rotor 32, such as the lobe 30-2, is trailing with respect to the inlet port 24, and, therefore with respect to a stream of the high-pressure fluid 12.

[0043] As previously mentioned, the first and second rotors 30 and 32 are interleaved and continuously meshed for unitary rotation with each other. In one embodiment, the lobes of each rotor 30, 32 are twisted or helically disposed along the length L of the rotors 30, 32. The length L can be defined as the distance between a first end 30a, 32a and a second end 30b, 32b of the respective rotors 30, 32. Upon rotation of the rotors 30, 32, the lobes, at the cusp edges, at least partially seal the fluid 12 against the interior structure or surface 33 of the housing 102 to define a transport volume 35, 37, at which point expansion of the fluid 12 only occurs to the extent allowed by leakage which represents an inefficiency in the system. In contrast to some expansion devices that change the volume of the fluid when the fluid is sealed, the transport volume 35, 37 defined between the lobes and the interior structure or surface 33 of the housing is constant as the fluid 12 traverses the length of the rotors 30, 32. Accordingly, the expansion device 20 is referred to as a "volumetric device" as the sealed or partially sealed fluid volume does not change wherein the working fluid 12 is generally not reduced or compressed.

[0044] In operation, rotor shafts 38, 40, respectively attached to rotors 30, 32, are rotated by the working fluid 12 as the fluid undergoes expansion from the higher first pressure working fluid 12 to the lower second pressure working fluid 12. Accordingly, the shafts 38, 40 are configured to capture the work or power generated by the expansion device 20 during the expansion of the fluid 12 that takes place between the inlet port 108 and the respective outlet port 110. As discussed previously, the work is transferred from the shafts 38, 40 as output torque from the expansion device 20 via output device 25.

[0045] In one aspect of the geometry of the expansion device 20, each of the rotor lobes 30-1 to 30-3 and 32-1 to 32-3 has a lobe geometry in which the twist of each of the first and second rotors 30 and 32 is constant along their substantially matching length L. Alternatively, the lobes 30, 32 can be provided without a twist although a drop in efficiency may be expected to occur.

[0046] As shown schematically at Figure 4, one parameter of the lobe geometry is the helix angle HA. By way of definition, it should be understood that references hereinafter to "helix angle" of the rotor lobes is meant to refer to the helix angle at the pitch diameter PD (or pitch circle) of the rotors 30 and 32. The term pitch diameter and its identification are well understood to those skilled in the gear and rotor art and will not be further discussed herein. As used herein, the helix angle HA can be calculated as follows: Helix Angle (HA) = (180/.pi.* arctan (PD/Lead)), wherein: PD = pitch diameter of the rotor lobes; and Lead = the lobe length required for the lobe to complete 360 degrees of twist. It is noted that the Lead is a function of the twist angle and the length L of the lobes 30, 32, respectively. The twist angle is known to those skilled in the art to be the angular displacement of the lobe, in degrees, which occurs in "traveling" the length L of the lobe from the rearward end of the rotor to the forward end of the rotor. In one embodiment, the twist angle is about 120 degrees, although the twist angle may be fewer or more degrees, such as 160 degrees.

[0047] Because the inlet port 108 introduces the fluid 12 to both the leading and trailing faces of each rotor 30, 32, the fluid 12 performs both positive and negative work on the expansion device 20. To illustrate, Figure 3 shows that lobes 30-2, 30-3, 32-2, and 32-3 are each exposed to the fluid 12 through the inlet port opening 108. Each of the lobes has a leading surface and a trailing surface, both of which are exposed to the fluid at various points of rotation of the associated rotor. The leading surface is the side of the lobe that is forward most as the rotor is rotating in a direction R1, R2 while the trailing surface is the side of the lobe opposite the leading surface. For example, rotor 30 rotates in direction R1 thereby resulting in side 30-1a as being the leading surface of lobe 30-1 and side 30-1b being the trailing surface. As rotor 32 rotates in a direction R2 which is opposite direction R1, the leading and trailing surfaces are mirrored such that side 32-1a is the leading surface of lobe 32-1 while side 32-1b is the trailing surface.

[0048] In generalized terms, the fluid 12 impinges on the trailing surfaces of the lobes as they pass through the inlet port opening 24b and positive work is performed on each rotor 30, 32. By use of the term positive work, it is meant that the fluid 12 causes the rotors to rotate in the desired direction: direction R1 for rotor 30 and direction R2 for rotor 32. As shown, fluid 12 will operate to impart positive work on the trailing surface 30-1b of rotor 30-1. The fluid 12 is also imparting positive work on the trailing surface 32-2b of rotor 32-

2. However, the fluid 12 also impinges on the leading surfaces of the lobes, for example surfaces 30-3a and 32-1a, as they pass through the inlet port opening thereby causing negative work to be performed on each rotor 30, 32. By use of the term negative work, it is meant that the working fluid 12 causes the rotors to rotate opposite to the desired direction, R1, R2.

Optimized Fluid Expansion Device

[0049] The exemplary embodiment of the fluid expansion device 20 shown at Figures 5-12 includes a housing outlet configuration which is optimized increase performance by defining and controlling the manner in which the transport volume 35, 37, defined by the housing interior structure or surface 33 and the rotors 30, 32, is opened to the housing outlet 110. In operation, the fluid expansion device 20 rotors 30, 32 alternately rotate through an intake position in which the transport volume 35, 37 is open to the housing inlet, a closed position in which the transport volume 35, 37 is generally closed to the housing outlet, and a discharge position in which the transport volume 35, 37 is open to the housing outlet. As noted previously, some leakage of the working fluid 12 is possible between the lobe cusp edges and the interior structure or surface 33 of the housing 102, since there may be a small clearance or gap therebetween. As such, by use of the terms "closed" or "sealed" with respect to the closed position of the rotors 30, 32, it is meant to indicate that the working fluid 12 is prevented from exiting the transport volume 35, 37 through any pathway not due to the clearance between the rotors 30, 32 and housing 102.

[0050] Figures 13-24 show the interaction between the rotors 30, 32 and the housing interior structure or surface 33 at various rotational points of the rotors 30, 32, beginning at the closed position of the rotor 32. For the purpose of clarity, Figures 13-24 show the interior structure or surface 33 of the housing 102 as the outermost layer in the drawings with the portions of the housing 102 beyond the interior structure or surface 33 not shown. Additionally, Figures 13A and 14A are presented without the rotors 30, 32 being shown, such that the surface 33 and the below discussed related surface features can be more clearly understood. As configured, the housing 102 interior structure or surface 33 defines a chamber portion 300 within which the rotors 30, 32 are primarily disposed. In one aspect, the chamber portion 300 has an obround or race-track shaped cross-sectional profile to accommodate the two rotors 30, 32. An outlet portion 302 is also provided as a

portion of the interior structure or surface 33 and is oriented such that the outlet portion 302 overlays the end of the chamber portion 300 and such that the outlet portion 302 is generally orthogonally to the chamber portion 300.

[0051] The interior structure or surface 33 is further provided with a dome portion 304 that further interconnects the chamber portion 300 and the outlet portion 302. As shown, the dome portion 304 is generally v-shaped or tent-shaped and functions to control the timing of the opening of the rotors 30, 32 into the discharge position. The dome portion 304 also provides for increased volume for the working fluid 12 to evacuate from the transport volume 35, 37 and to the outlet 110.

[0052] As most easily seen at Figure 13, the dome portion 304 extends generally laterally across the width of the rotors 30, 32 from a first end 306 to lateral ends 308 and 310. The dome portion 304 is further shown as extending from the first end 306 along the length of and away from the rotors 30, 32 towards an outlet end 312 proximate the outlet 110. It is noted that each of the ends 306 to 312 can be formed as rounded ends that gradually converge with the surfaces of the chamber portion 300 and outlet portion 302. In one aspect, the ends 306 and 308 define an interface line or zone 314 between the dome portion 304 and the chamber portion 300 while ends 306 and 310 define a second interface line or zone 316 between the dome portion 304 and the chamber portion 300. Similarly, ends 306 and 312 form an interface line or zone 318 that forms an axis of symmetry for the dome portion 304 extending parallel to the length of the rotors 30, 32. Ends 308 and 312 can form an interface line or zone 320 while ends 310 and 312 can form an interface line or zone 322. As with the ends 306 to 310, the interface lines or zones 314 to 322 can be formed with a generally rounded profile. In one aspect, the ends 306, 308, and 312 which define interface lines or zones 314, 318, and 320 can be said to define a first surface 304a of the dome portion 304 while the ends 306, 310, and 312 which define interface lines or zones 316, 318, and 322 can be said to define a second surface 304b of the dome portion 304, wherein the first and second surfaces 304a, 304b define the dome portion 304.

[0053] As shown at Figures 13-14, the rotor 32 is rotated into the closed position such that the transport volume 37 is defined between lobes 32-2 (leading), 32-1 (trailing) and the chamber portion 300 of the interior structure or surface 33. As such, the transport volume

37 is isolated from both the outlet portion 302 and the dome portion 304 such that no working fluid 12 can pass from the transport volume 37 to the outlet 110 of the fluid expansion device 20.

[0054] Referring to Figures 15 - 18, the rotor 32 (and rotor 30) has been rotated by one degree (1o) from the closed position towards the discharge position such that a first opening 400 forms between the leading lobe 32-2 and the interior structure or surface 33 proximate the outlet portion 302. As shown, the first opening 400 is proximate the discharge end 32b of the rotor 32. At this rotational position of the rotor 32, the first opening 400 is the only opening between the transport volume 37 and the interior structure or surface 33 and represents about 10% of the maximal opening area for the first opening 400 before additional openings are created between the transport volume 37 and the outlet 110 by further rotation of the rotor 32.

[0055] Referring to Figures 19-20, the rotor 32 (and rotor 30) has been further rotated by can be further rotated by another 12 degrees (12o) for a total rotation of 13 degrees (13o) which results in the first opening area 400 be further enlarged. However, the first opening area 400 still remains as the only opening between the transport volume 37 and the interior structure or surface 33. In the position shown at Figure 19-20, the first opening area 400 represents about 100% of the maximal opening area for the first opening 400 before additional openings are created between the transport volume 37 and the outlet 110 by further rotation of the rotor 32.

[0056] Figures 21-22 show the rotor 32 (and rotor 30) having been rotated beyond the position shown in Figures 19-20 such that a second opening 402 forms between the transport volume 37 and the interior structure or surface 33 and such that the first opening 400 is further enlarged. As shown, the rotor 32 (and rotor 30) has been rotated an additional 5 degrees (5o) for a total rotation of 18 degrees (18o) from the closed position. The second opening 402 is located at about the mid-point of the rotor 32 and the interior structure or surface 33 proximate the dome portion 304 at zone or line 316.

[0057] Figures 23-24 show the rotor 32 (and rotor 32) having been rotated beyond the position shown in Figures 21-22 such that a third opening 404 forms between the transport volume 37 and the interior structure or surface 33, and such that the first and second

openings 400, 402 are further enlarged. As shown, the rotor 32 (and rotor 30) has been rotated an additional 5 degrees (5o) for a total rotation of 23 degrees (23o) from the closed position. The third opening 404 is located at the inlet end 32a of the rotor and forms between the rotor 32 and the interior structure or surface 33 proximate the chamber portion 300.

[0058] In one non-limiting example embodiment, the opening areas 400, 402, 404 at various rotational positions of the rotor 32 (or 30) are as shown in Table 1 below.

Table 1

Rotational Position of Rotor (degrees)	**1st Opening Area 400 (mm^2)**	**2nd Opening Area 402 (mm^2)**	**3rd Opening Area 404 (mm^2)**
0^o	0	0	0
1^o	8.4	0	0
2^o	19.2	0	0
3^o	30	0	0
13^o	80.0	0	0
18^o	128.0	57.5	0
23^o	171.6	154.4	6.1

[0059] In comparison to a fluid expander having a standard outlet configuration, the disclosed fluid expansion device 20 is configured to have a delayed opening timing,

meaning that the formation of the opening area between the transport volume 35, 37 and the outlet 110 occurs at a decreased rate in comparison to a standard design. Referring to Figure 25, a graphical representation of the data shown in Table 1 is presented, wherein an opening profile 500 of the expansion device 20 is shown. The opening profile 500 can be characterized as having an initial opening phase 502 during which the first opening 400 enlarges and accounts entirely for the total open area between the rotor 32 and the interior structure or surface 33. The initial opening phase 502 can be further characterized as having a first portion 502a and a second portion 502b in which the first portion 502a has a greater slope than the second portion 502b, meaning that the first opening 400 enlarges at a faster rate during the first portion 502a as compared to the second portion 502b. The opening profile 500 can be further characterized as having a secondary opening phase 504 during which the second and third openings 402, 404 develop and enlarge in conjunction with further enlargement of the first opening 400. As can be seen, the secondary opening phase 504 has a significantly greater slope than the initial opening phase 502 which reflects that the opening area enlarges at a slower rate during the initial opening phase 502 as compared to the secondary opening phase 504.

[0060] The difference in slopes of the phases 502, 504 can be referred to as creating a delayed opening timing of the rotors 30, 32. Accordingly, with each degree of rotation of the rotor 30, 32, the opening area of the optimized outlet expander 20 is smaller than that of an expander having a standard outlet. In some cases, the opening area of a non-optimized expansion device can be twice as much or more than that of the disclosed device 20 after only one degree of rotation from the closed position. This timing delay significantly increases the velocity of the working fluid 12 exiting the expansion device 20. The resulting concentrated high velocity stream at the rotor exhaust creates an entrapment effect that results in a vacuum. This vacuum increases the delta pressure across the expander rotors 30, 32 which drives a higher output torque. Delaying venting at the front and back cusps of the rotor 30, 32 for a minimum of 2 to 3 degrees relative to the small pocket near the middle of the rotor maximizes torque output.

[0061] It is also noted that a standard outlet configuration can result in the opening between the rotors and the housing being initially formed near the middle of the rotor and then towards the inlet side of the rotor. This early opening towards the inlet end of the rotor can result in increased back pressure on the rotor by the working fluid which can

cause negative work to be performed by the working fluid. In contrast, the disclosed fluid expansion device 20 opens first at opening 400 proximate the discharge end of the rotors 30, 32, then the middle portion of the rotors 30, 32, and then at the inlet end of the rotors 30, 32.

[0062] The above cited differences are illustrated in Table 2 (below) which provides a comparison between a fluid expander having an unmodified or standard outlet and a fluid expander 20 in accordance with the above description.

TABLE 2

Design Parameter	**Standard outlet fluid expander**	**Optimized outlet fluid expander 20**
Working Fluid	Ethanol	Ethanol
Expander Speed	10000	10000
Torque	4.98	5.13
Expander Power	5.217	5.363
Expander Press IN	3.237	3.237
Expander Press OUT	1.841	1.841
Mass Flow of Working Fluid	163.9	162
Expander Average Inlet Temp	246	246
Expander Average Outlet Temp	222	222
Working Fluid Velocity at 1° Opening (m/s)	403	440

Isentropic Efficiency	**55.06%**	**57.27%**

[0063] By optimizing the outlet port as described above, the lowest level of vacuum draw that is possible created at the rotor exhaust event which subsequently maximizes efficiency and torque generation. As can be seen from the table above, the working fluid velocity at 1 degree of opening for the optimized expander is 440 meters per second, which represents about a 10 percent increase in working fluid velocity through the first opening 400. This increased velocity of the disclosed design aids in developing the performance enhancing vacuum draw and has been shown to result in isentropic efficiency improvements of over 2 percent. These improvements are gained by controlling the location and timing of the initial opening between the transport volume and the interior structure or surface 33. For example, the location of the initial opening (i.e. first opening 400 located at the front end of the rotor) is controlled such that positive work by the working fluid 12 is maximized. Additionally, by designing the rotors 30, 32 and housing interior structure or surface 33 such that the initial opening enlarges at as slow of a rate as possible through the first few degrees of rotation of the rotors 30, 32 out of the closed position.

[0064] From the forgoing detailed description, it will be evident that modifications and variations can be made without departing from the spirit and scope of the disclosure.

WHAT IS CLAIMED IS:

1. A mechanical expander comprising:
    a. a housing having an interior structure defining an interior volume, an inlet, and an outlet;
    b. a pair of parallel helical rotors disposed within the housing in a counter rotating non-contacting arrangement, each of the rotors:
        i. having a plurality of lobes, wherein each lobe defines a cusp extending between a front end and a back end; and
        ii. being rotatable within the housing to form a transport volume between a leading lobe cusp, a trailing lobe cusp, and the housing interior structure,
    c. each rotor being sequentially rotatable through:
        i. an intake position in which the transport volume is open to the housing inlet;
        ii. a closed position in which the transport volume is closed to the housing outlet; and
        iii. a discharge position in which the transport volume is open to the housing outlet;
    d. wherein, as each rotor is being rotated from the closed position to the discharge position:
        i. a first opening forms between the housing interior structure and the leading lobe cusp proximate the front end;
        ii. a second opening forms between the housing interior structure and the leading lobe cusp between the first opening and the leading lobe cusp back end, the second opening forming after the first opening has been at least partially formed.

2. The mechanical expander of claim 1, wherein, as each rotor is being rotated from the closed position to the discharge position, a third opening forms between the housing sidewall and the leading lobe cusp between the second opening and the leading lobe cusp back end, the third opening forming after the second opening has been at least partially formed.

3. The mechanical expander of claim 1, wherein the first opening is at least partially open when the rotor has been rotated by about three degrees of rotation from the closed position.

4. The mechanical expander of claim 3, wherein the second opening remains closed when the rotor has been rotated by less than about thirteen degrees of rotation from the closed position.

5. The mechanical expander of claim 1, wherein the mechanical expander has an opening profile including an initial opening phase followed by a secondary opening phase, wherein only the first opening is enlarged during the initial opening phase and both the first and second openings are enlarged during the secondary opening phase.

6. The mechanical expander of claim 5, wherein a first rate of enlargement of a total opening area during the initial opening phase is less than a second rate of enlargement of the total opening area during the secondary opening phase.

7. A mechanical expander comprising:
    a. a housing having an interior structure defining an interior volume, an inlet, and an outlet;
    b. a pair of parallel helical rotors disposed within the housing in a counter rotating non-contacting arrangement, each of the rotors:
        i. having a plurality of lobes, wherein each lobe defines a cusp extending between a front end and a back end; and
        ii. being rotatable within the housing to form a transport volume between a leading lobe cusp, a trailing lobe cusp, and the housing interior structure,
    c. each rotor being sequentially rotatable through:
        i. an intake position in which the transport volume is open to the housing inlet;
        ii. a closed position in which the transport volume is closed to the housing outlet; and
        iii. a discharge position in which the transport volume is open to the housing outlet;

d. wherein the mechanical expander has an opening profile between the leading lobe cusp and the housing outlet including an initial opening phase followed by a secondary opening phase, wherein only the first opening is enlarged during the initial opening phase and both the first and second openings are enlarged during the secondary opening phase

8. The mechanical expander of claim 7, wherein a first rate of enlargement of a total opening area of the opening profile during the initial opening phase is less than a second rate of enlargement of the total opening area of the opening profile during the secondary opening phase.

9. The mechanical expander of claim 7, wherein the initial opening phase occurs when the rotor is rotated such that the leading lobe cusp edge is initially moved past the closed position and the secondary opening phase occurs when the rotor is rotated such that the leading lobe cusp edge is rotated between about 12 and 14 degrees.

10. The mechanical expander of claim 7, wherein the initial opening phase includes a first portion and a subsequent second portion, wherein a first rate of enlargement of a total opening area of the opening profile during the initial opening phase first portion is greater than a second rate of enlargement of the total opening area of the opening profile during the initial opening phase second portion.

11. The mechanical expander of claim 10, wherein the second rate of enlargement is less than a third rate of enlargement of the total opening area of the opening profile during the secondary opening phase.

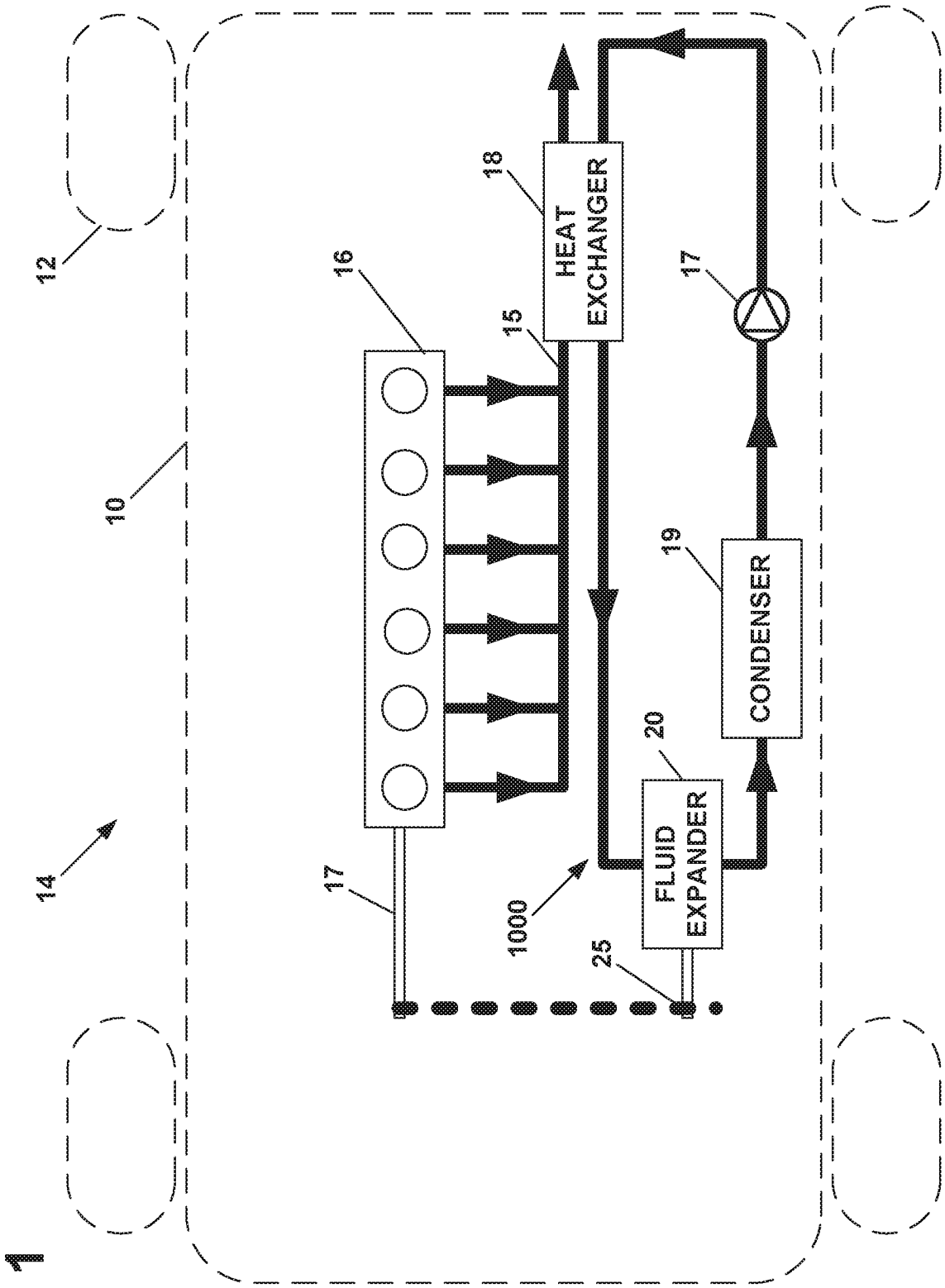

12
10
14
16
15
18
HEAT EXCHANGER
17
17
19
CONDENSER
20
FLUID EXPANDER
1000
25

FIG. 1

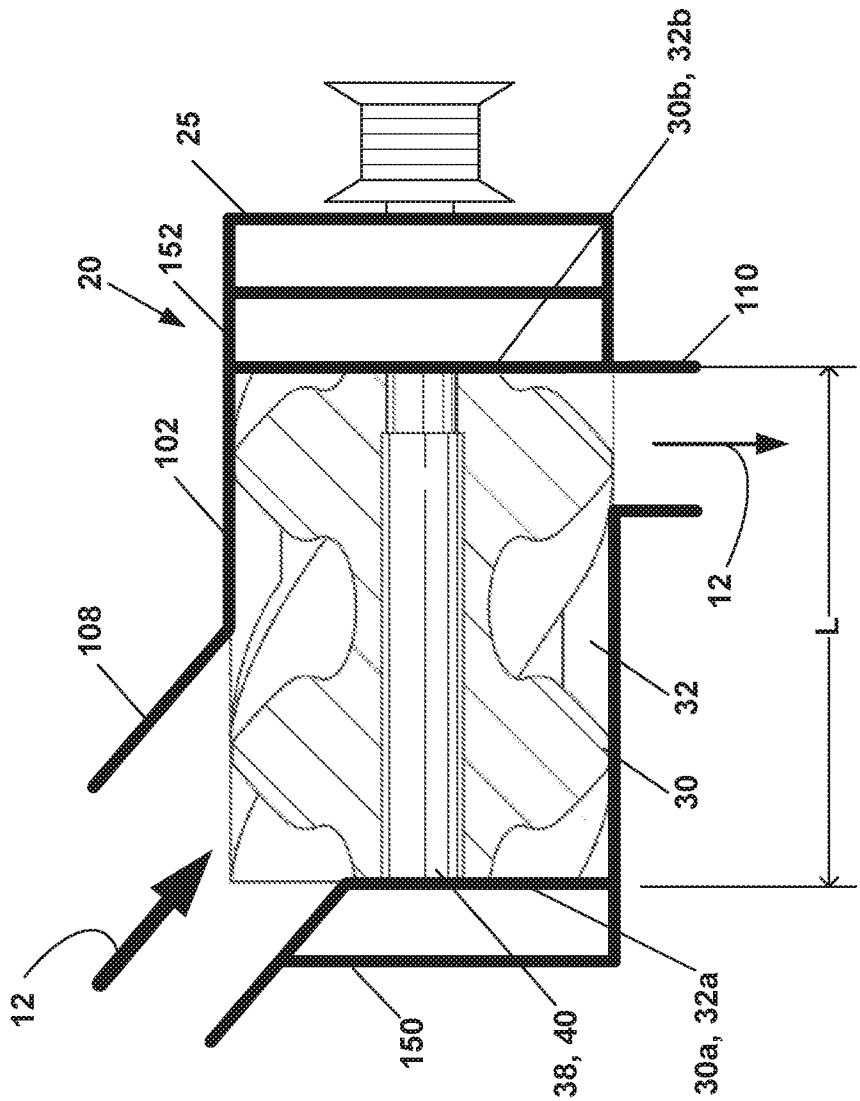


FIG. 2

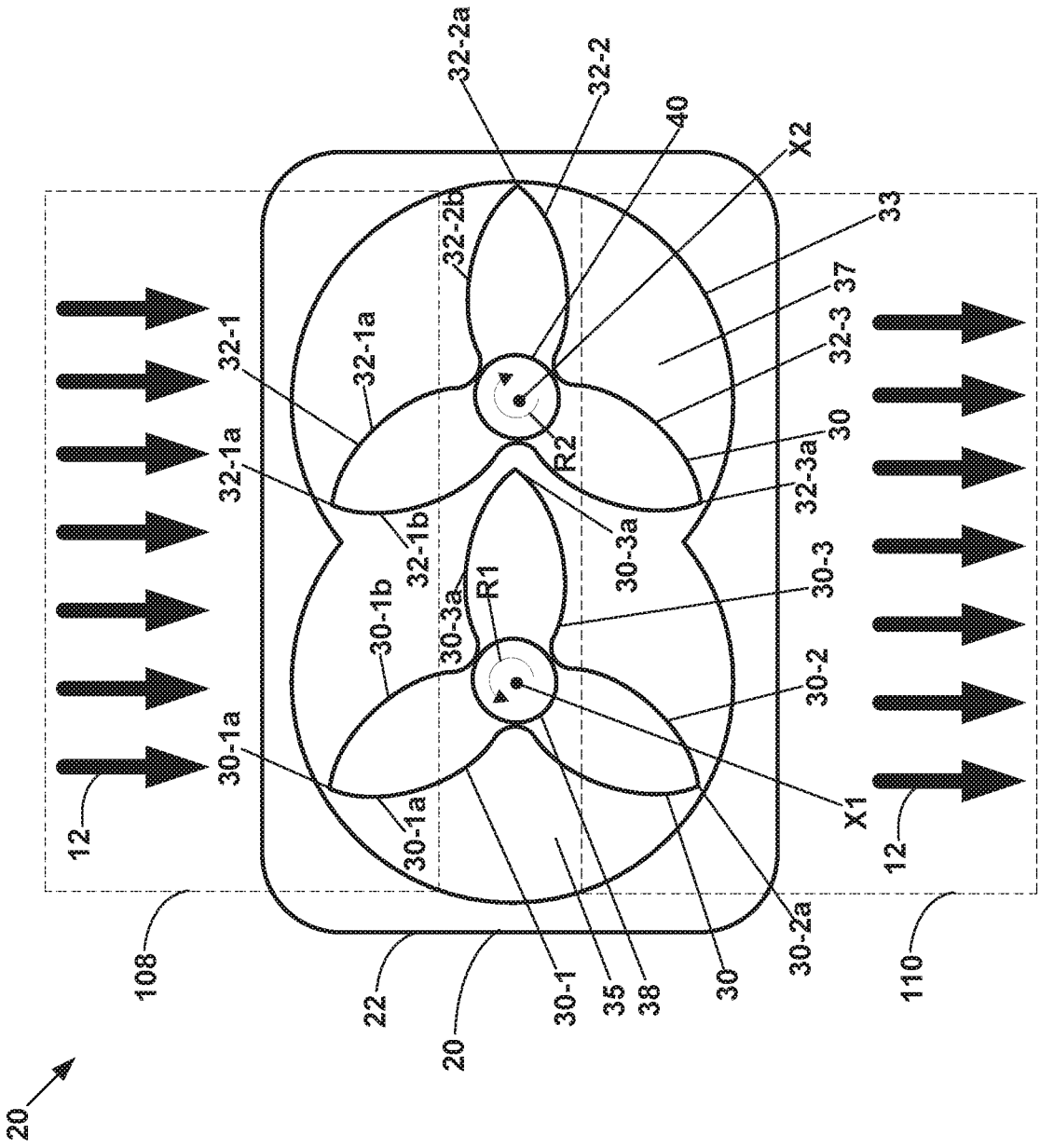

20
108
22
20
30-1
35
38
30
30-2a
110
12
30-1a
30-1b
32-1
32-1a
32-1b
30-3a
R1
R2
32-2a
32-2
40
X2
33
37
32-3
30
32-3a
30-3
30-2
X1
12
32-2b

FIG. 3

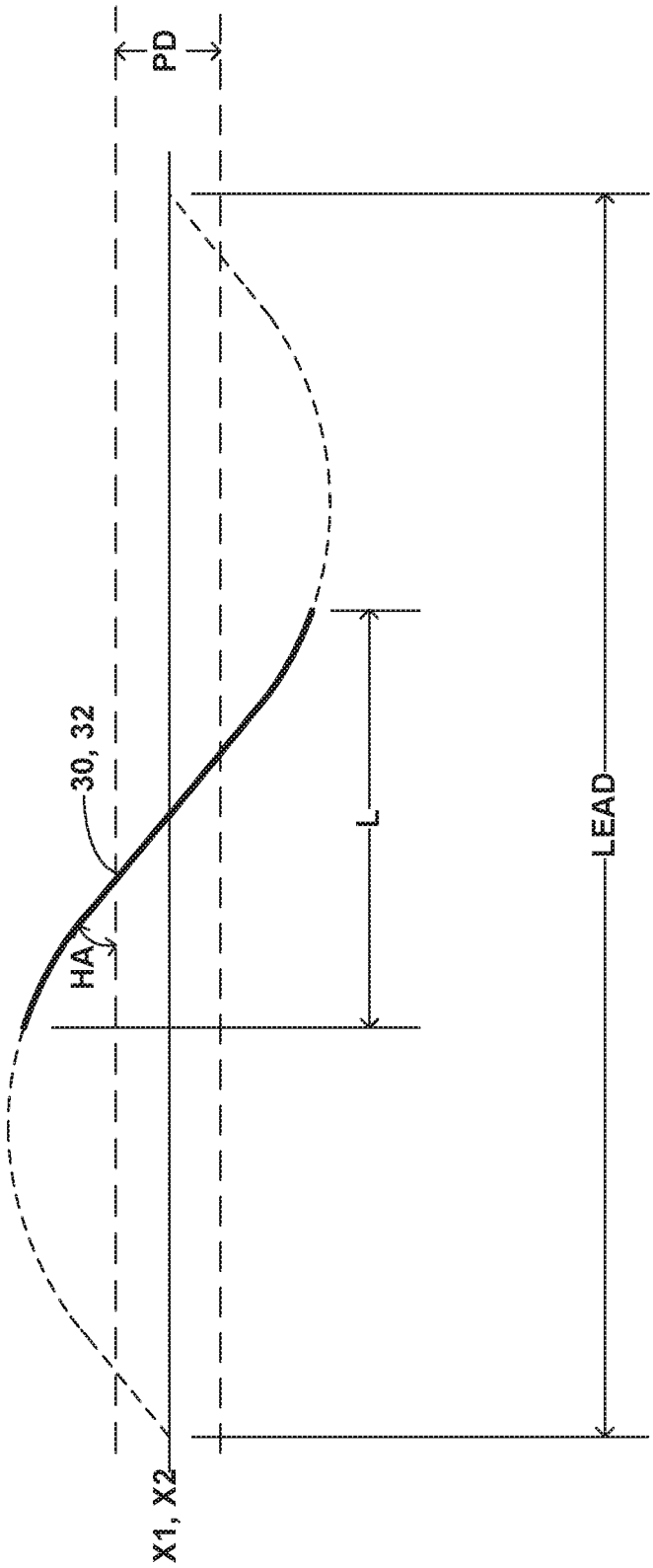


FIG. 4

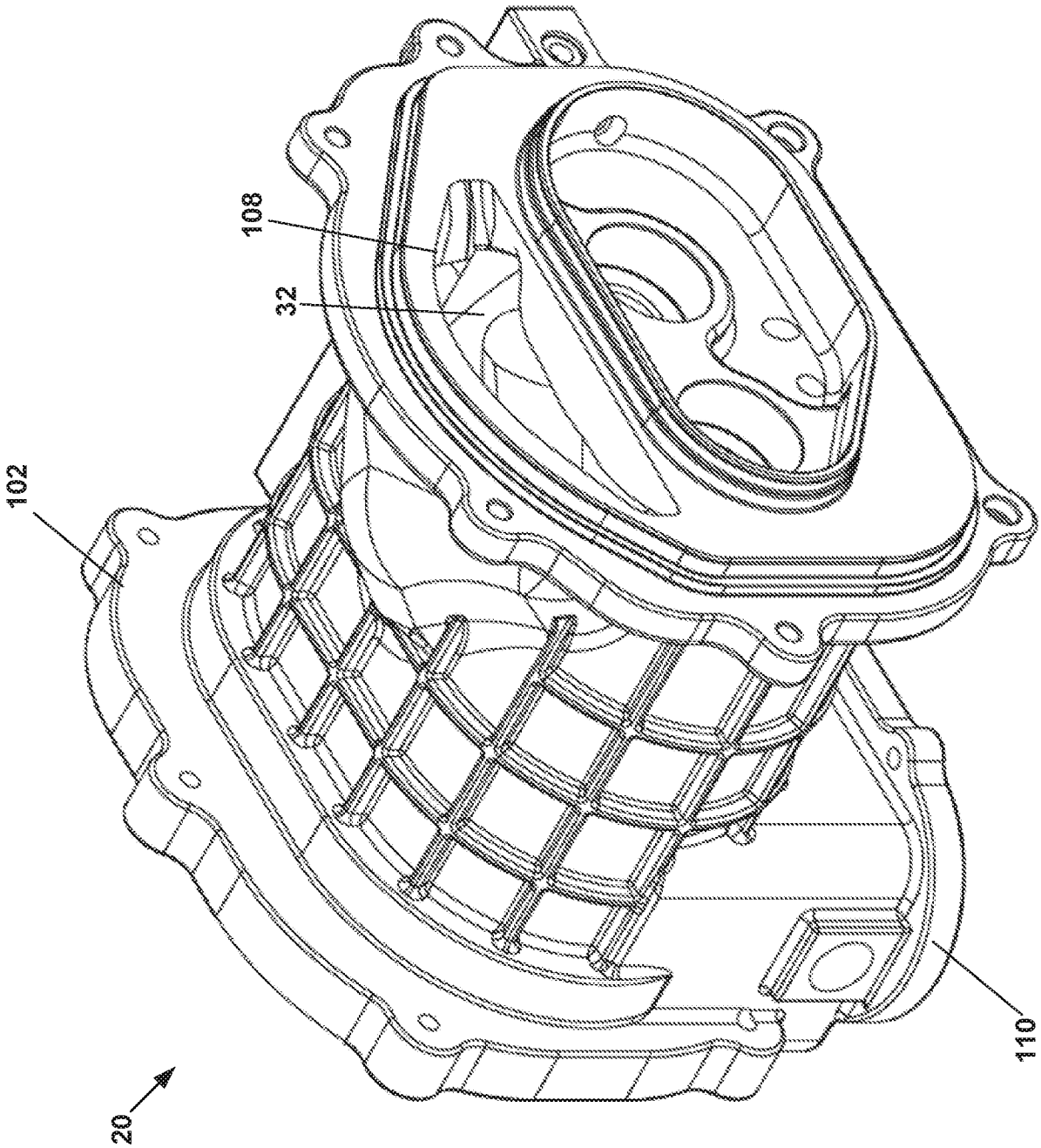


FIG. 5

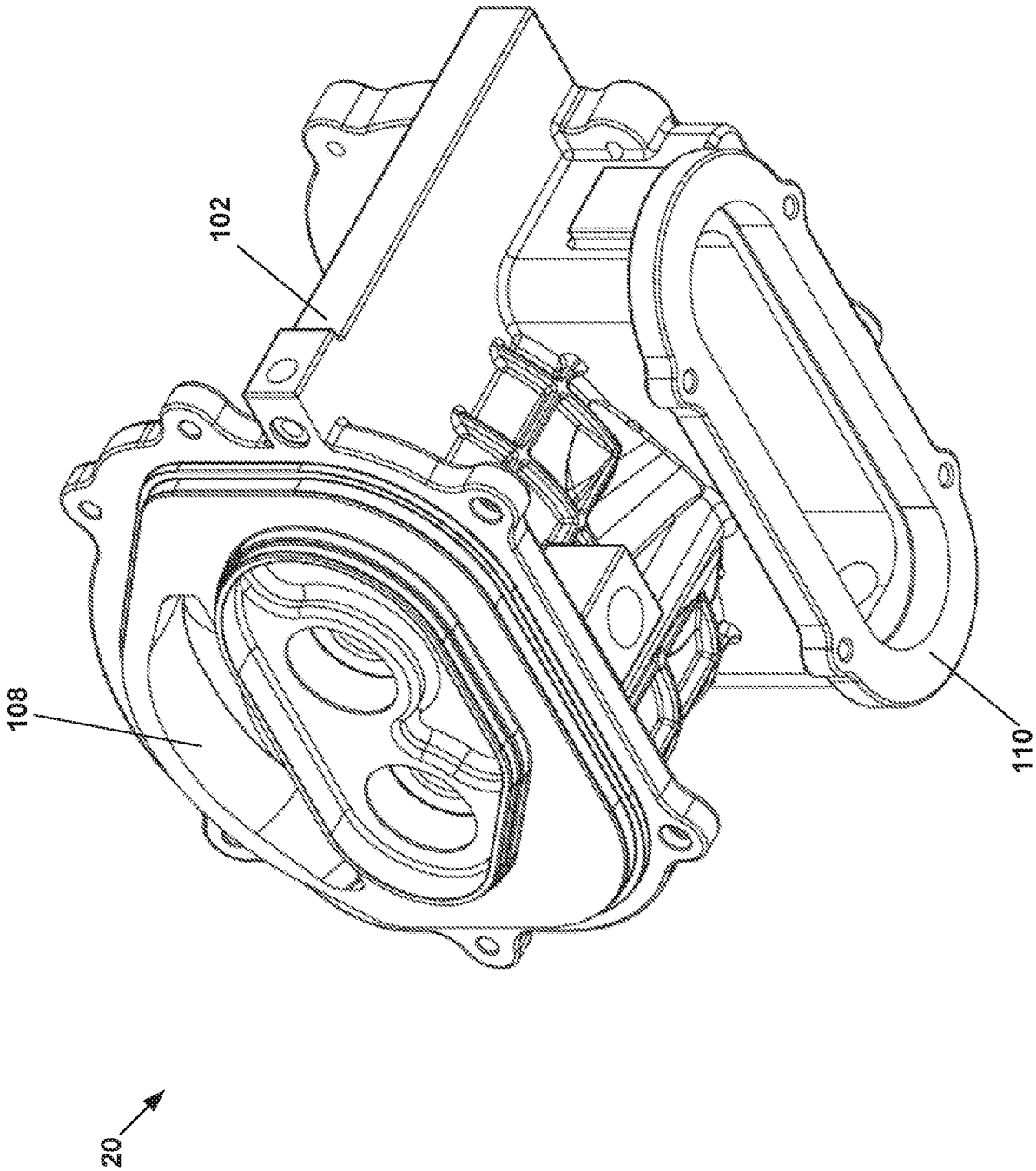


FIG. 6

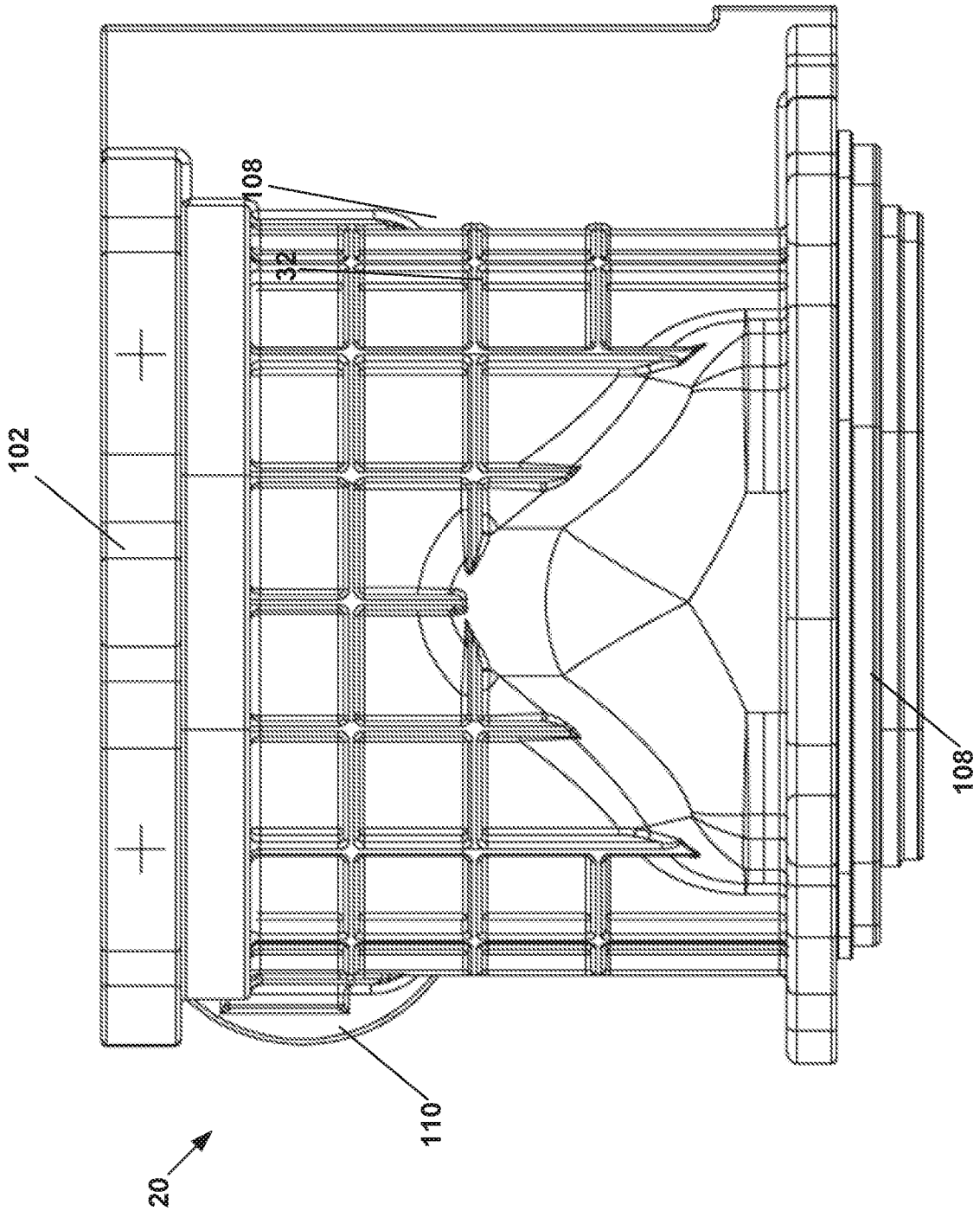


FIG. 7

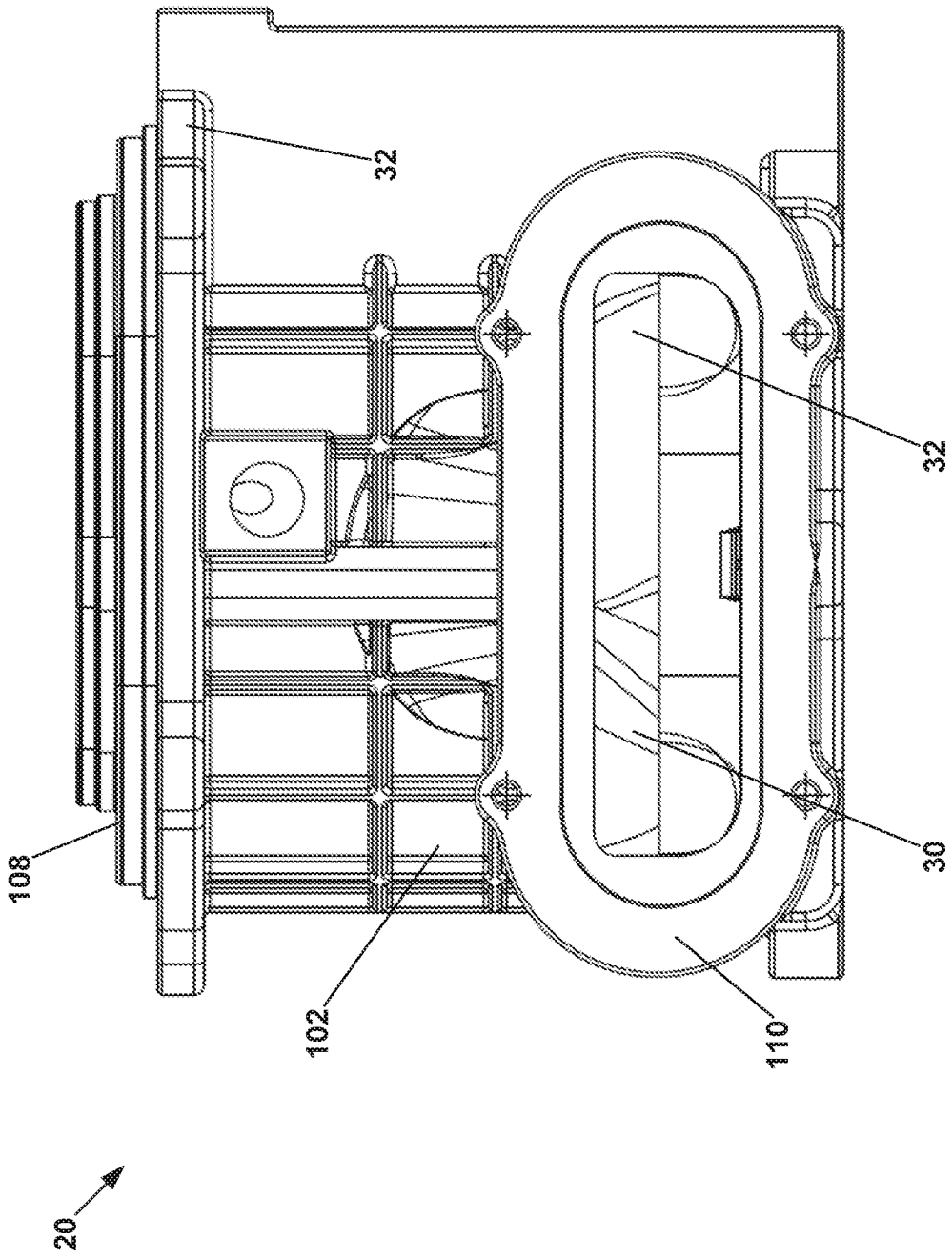


FIG. 8

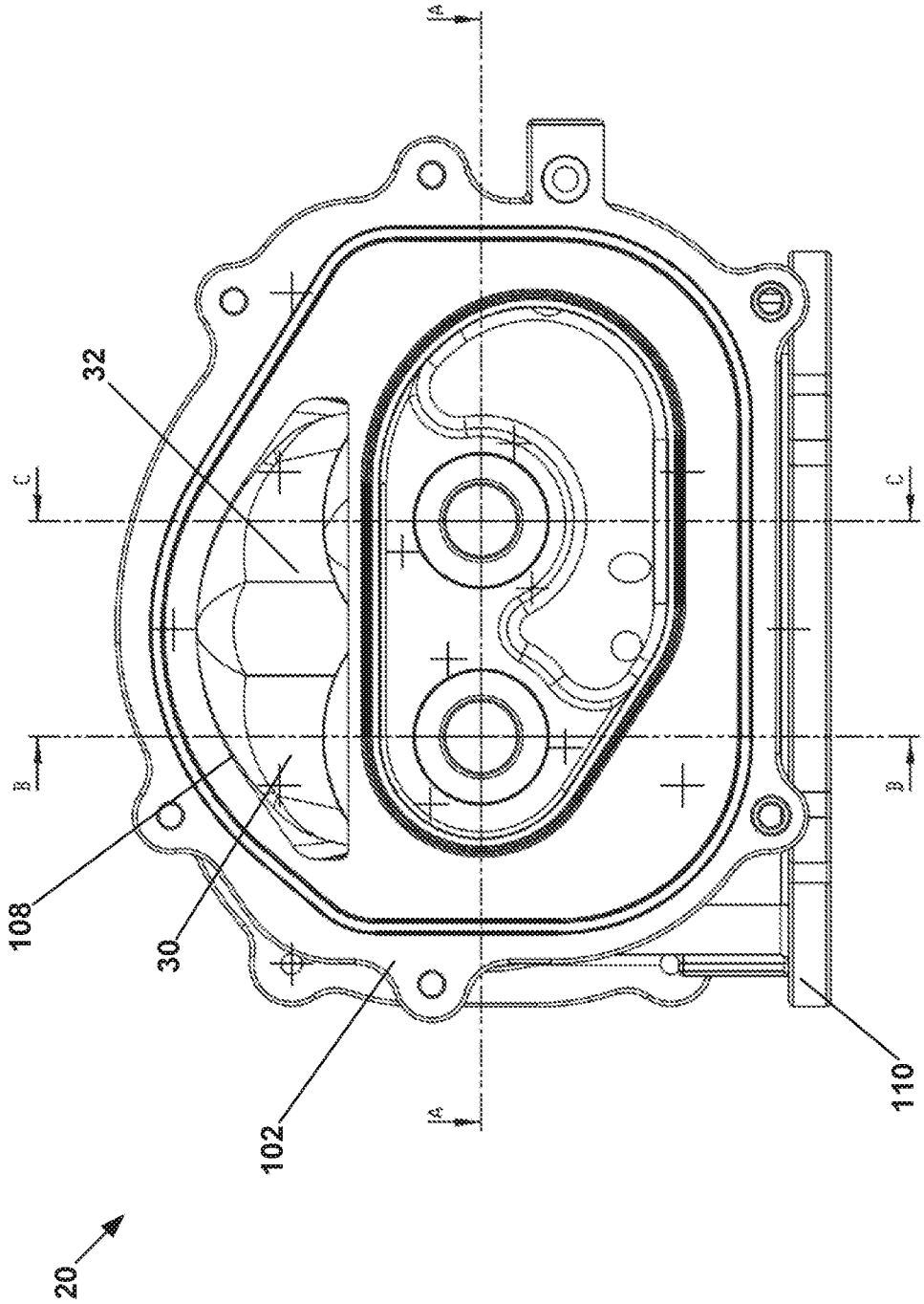


FIG. 9

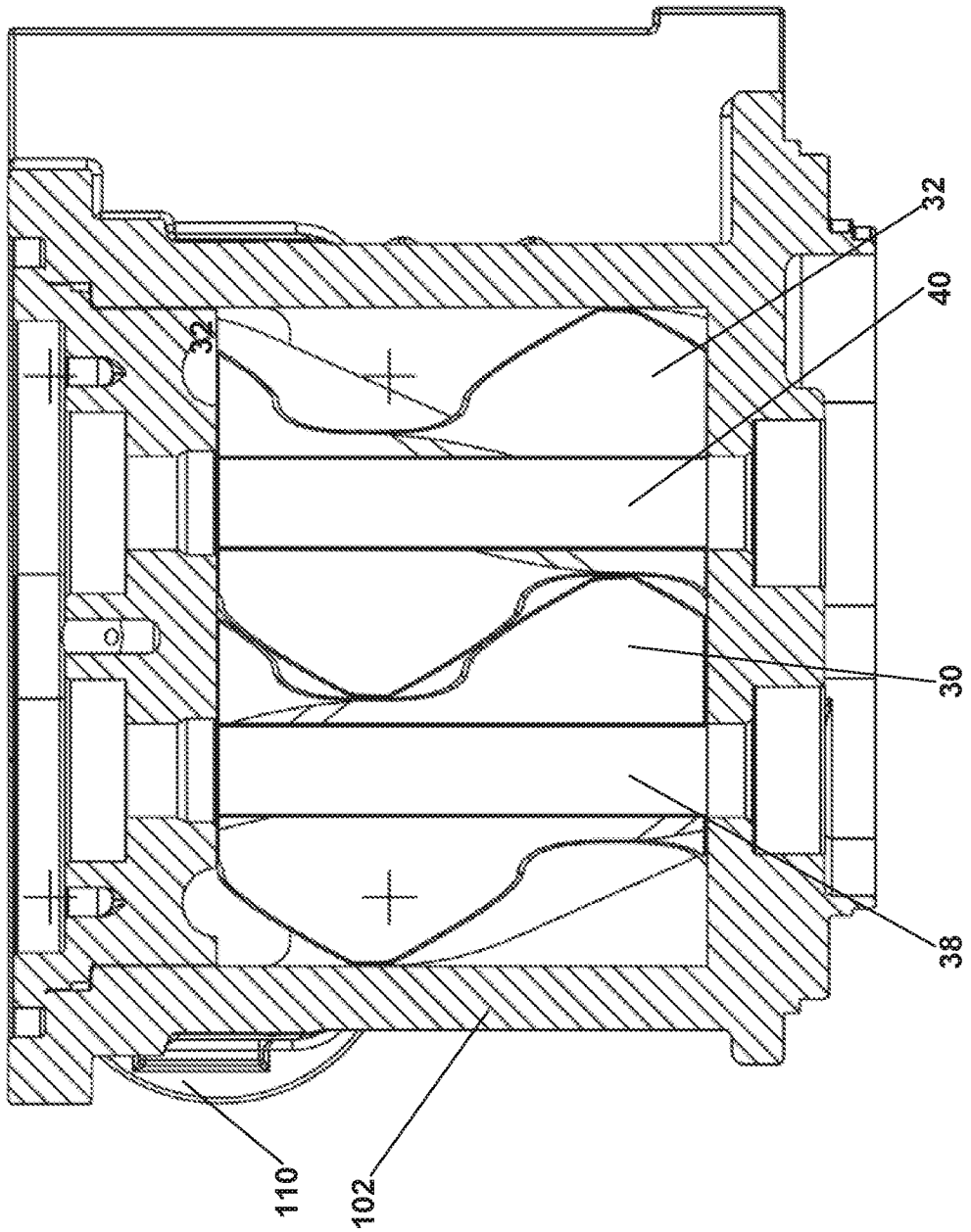


FIG. 10

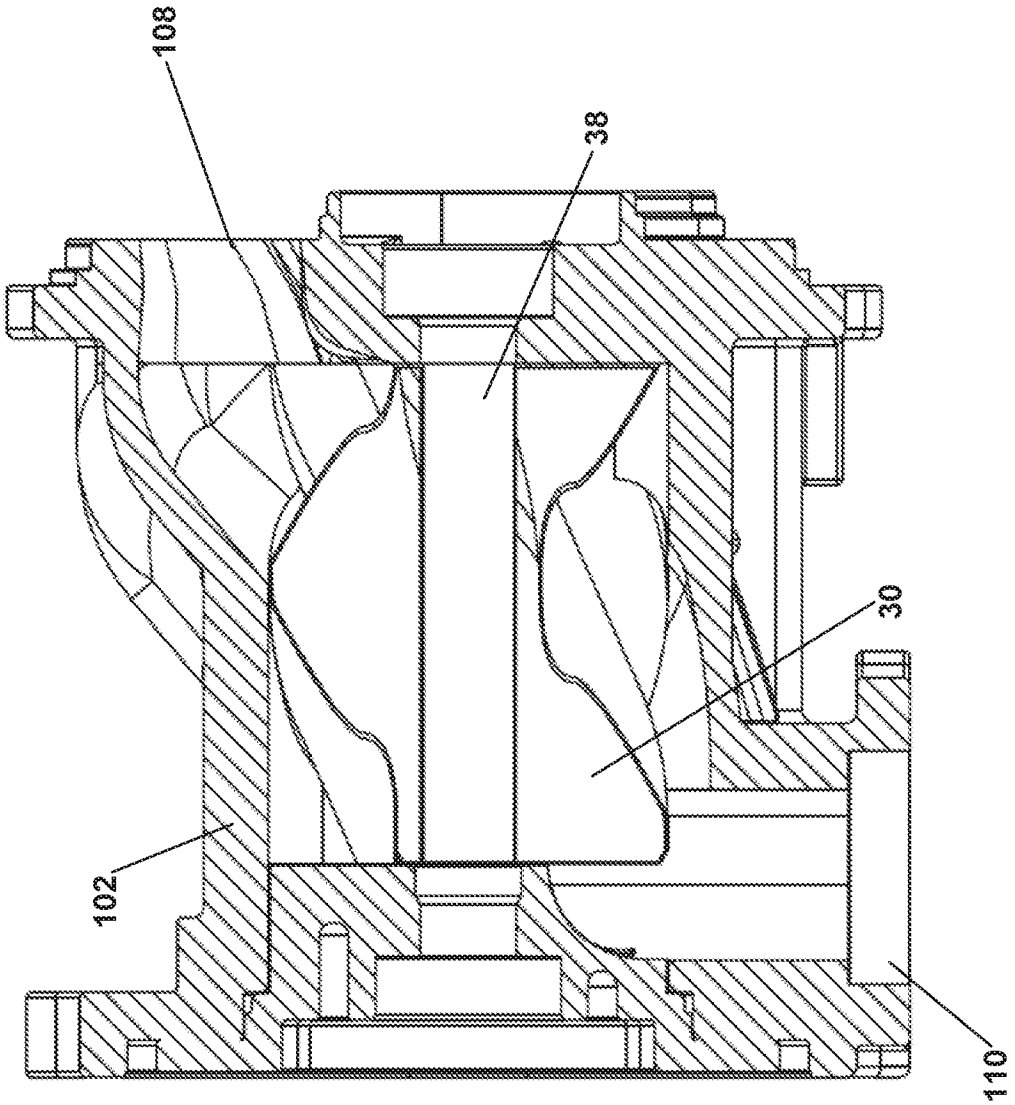


FIG. 11

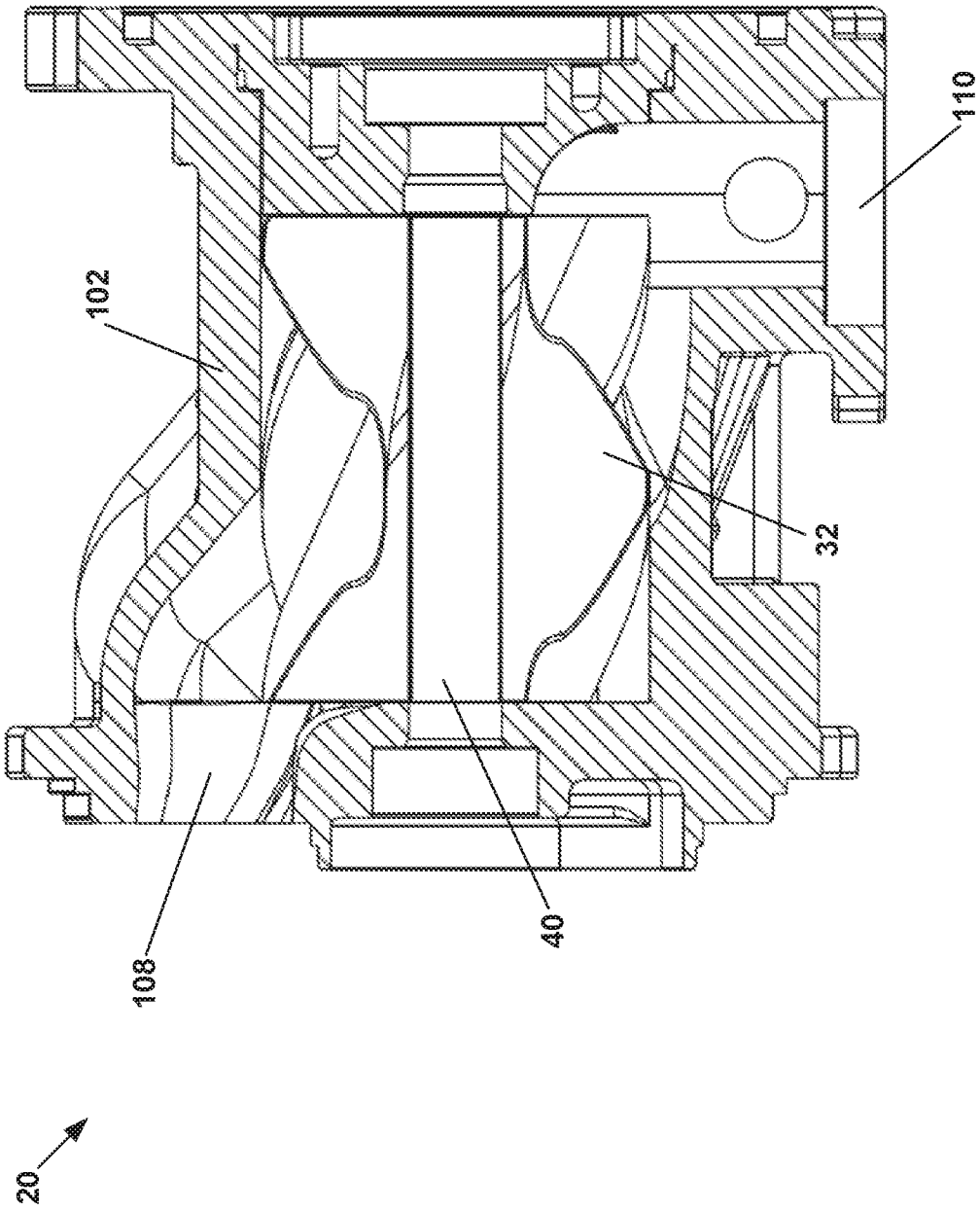


FIG. 12

FIG. 13A

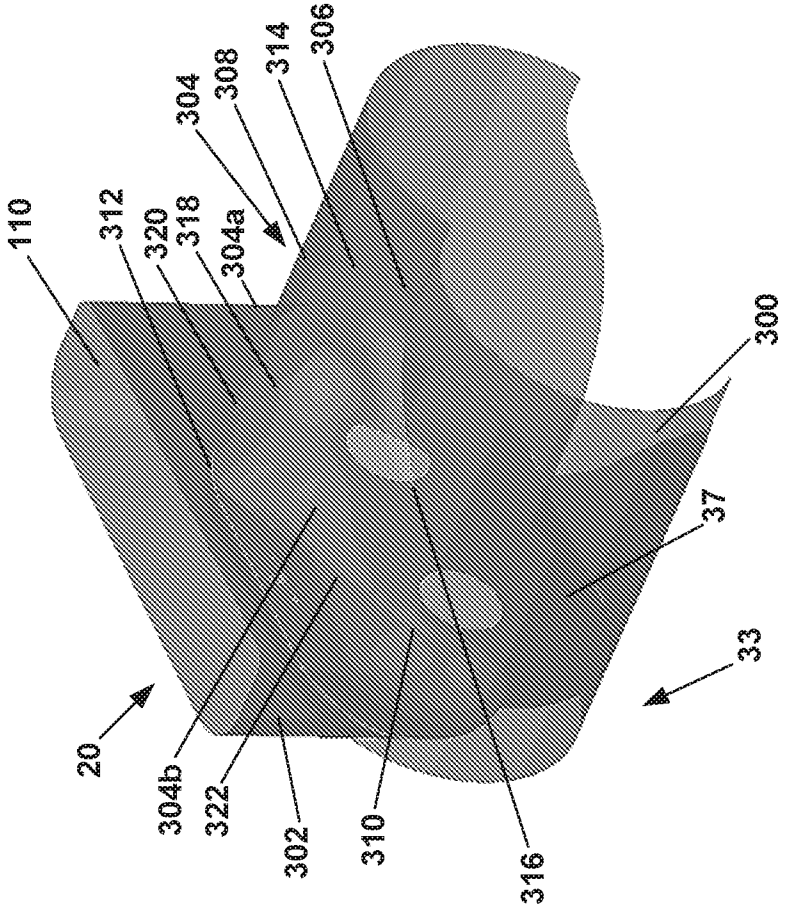


FIG. 13

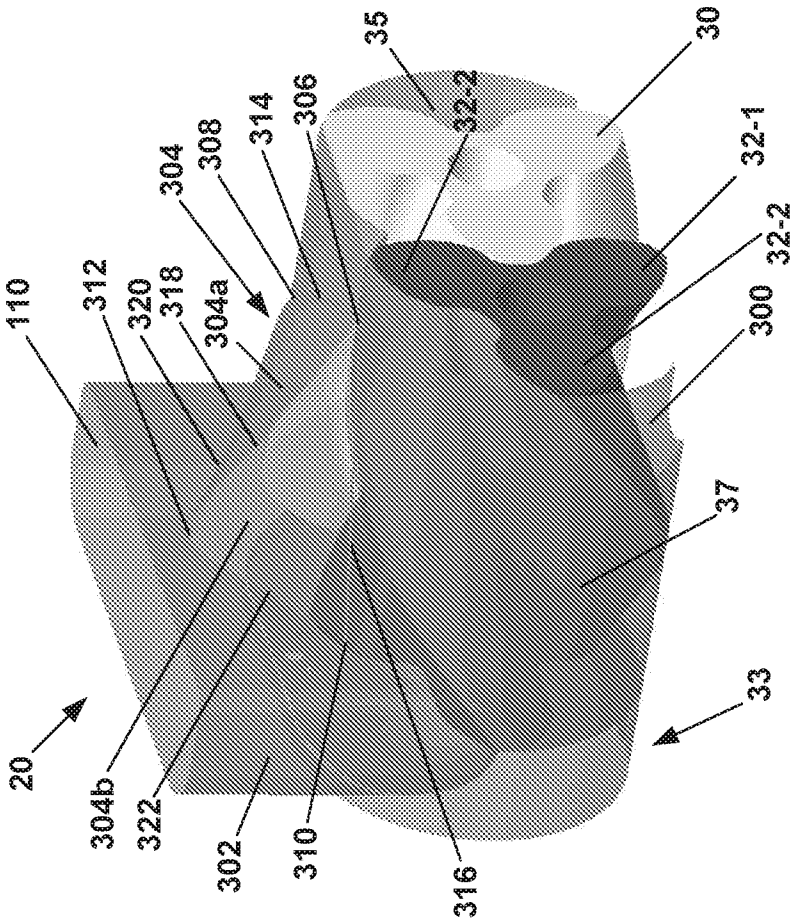


FIG. 14A

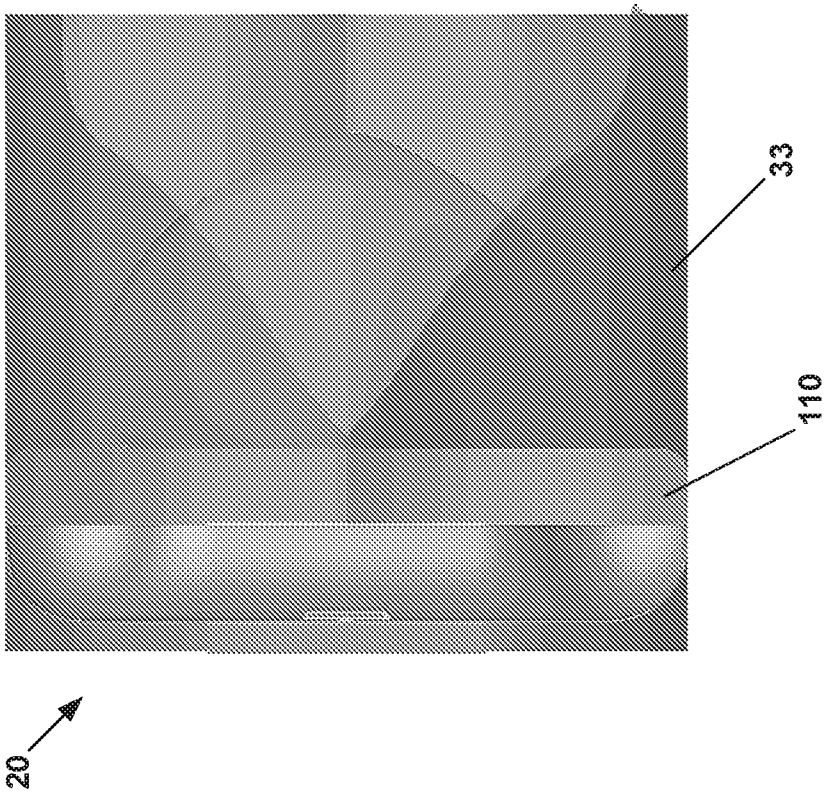


FIG. 14

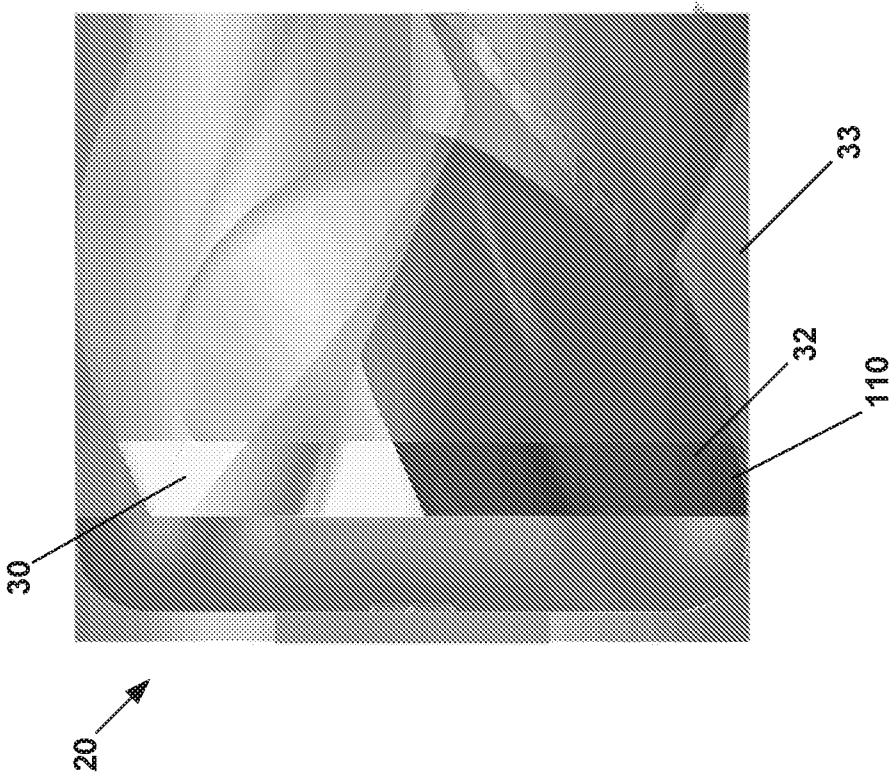


FIG. 16

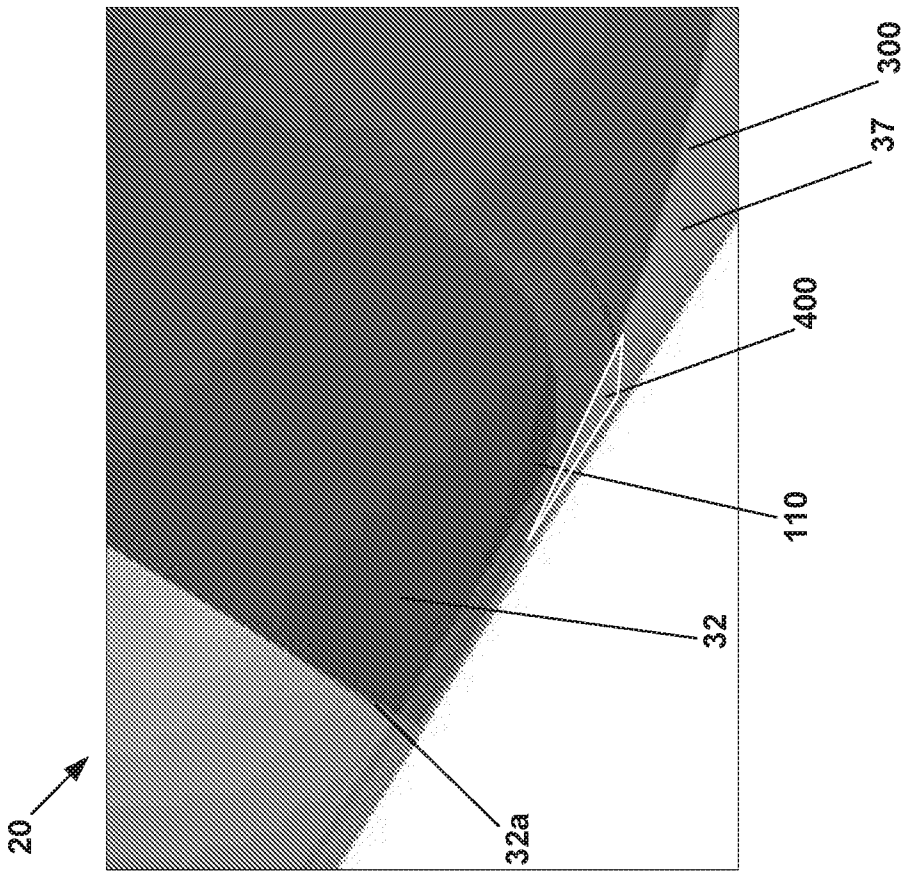


FIG. 15

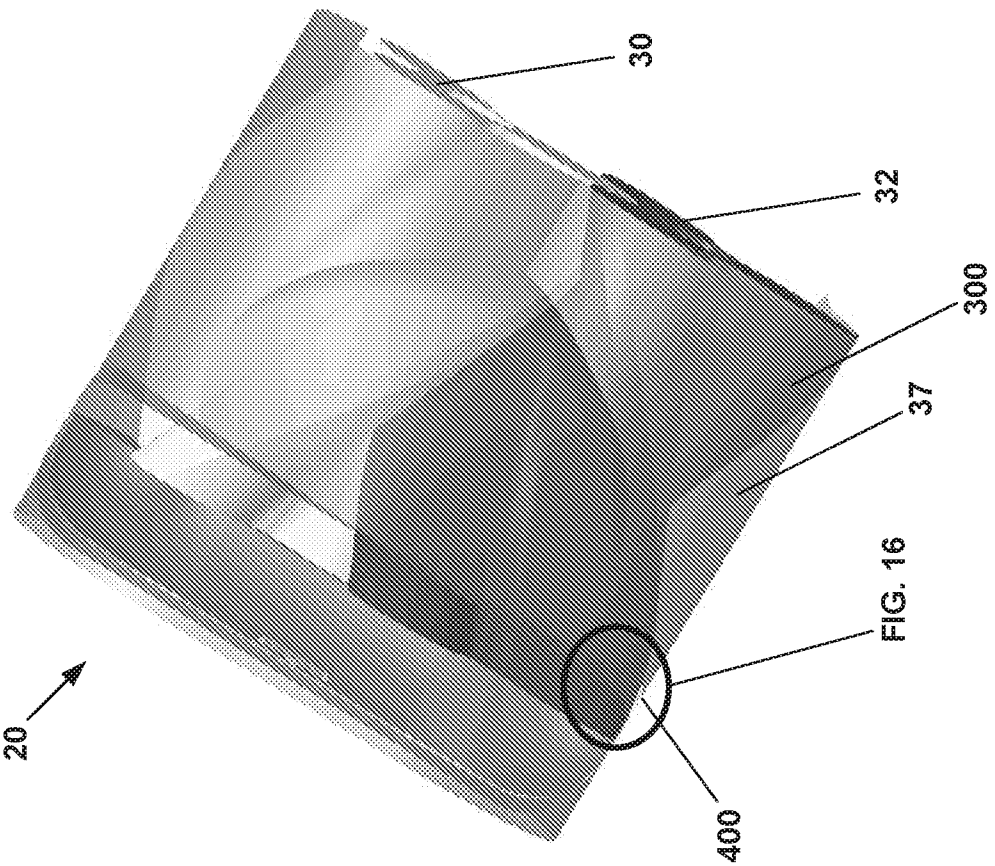


FIG. 18

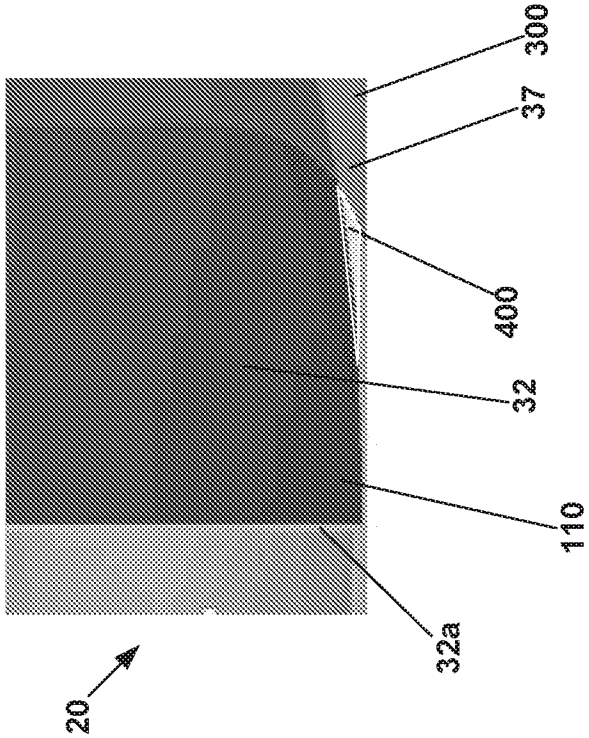


FIG. 17

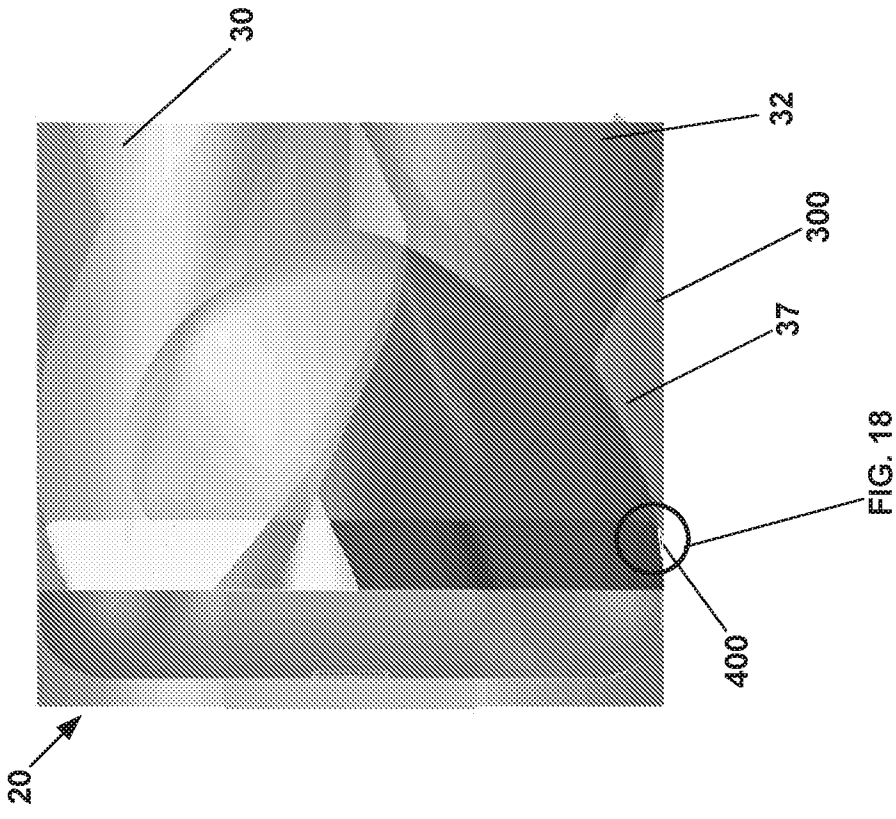


FIG. 20

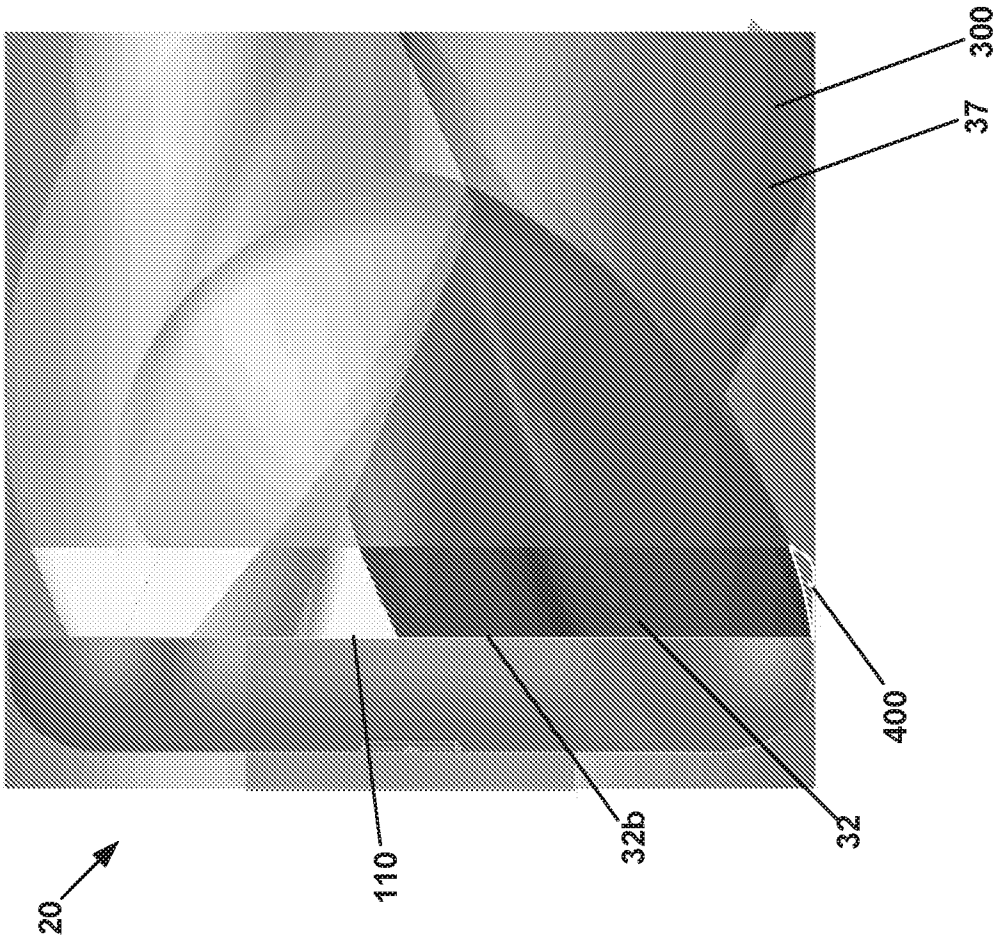


FIG. 19

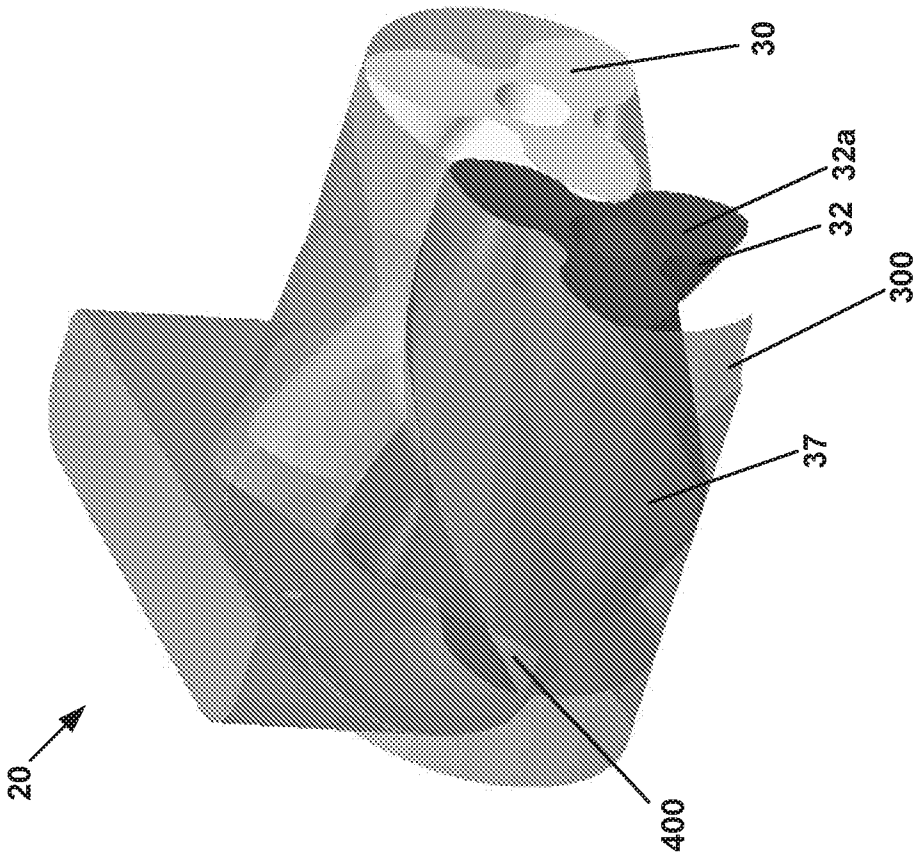


FIG. 22

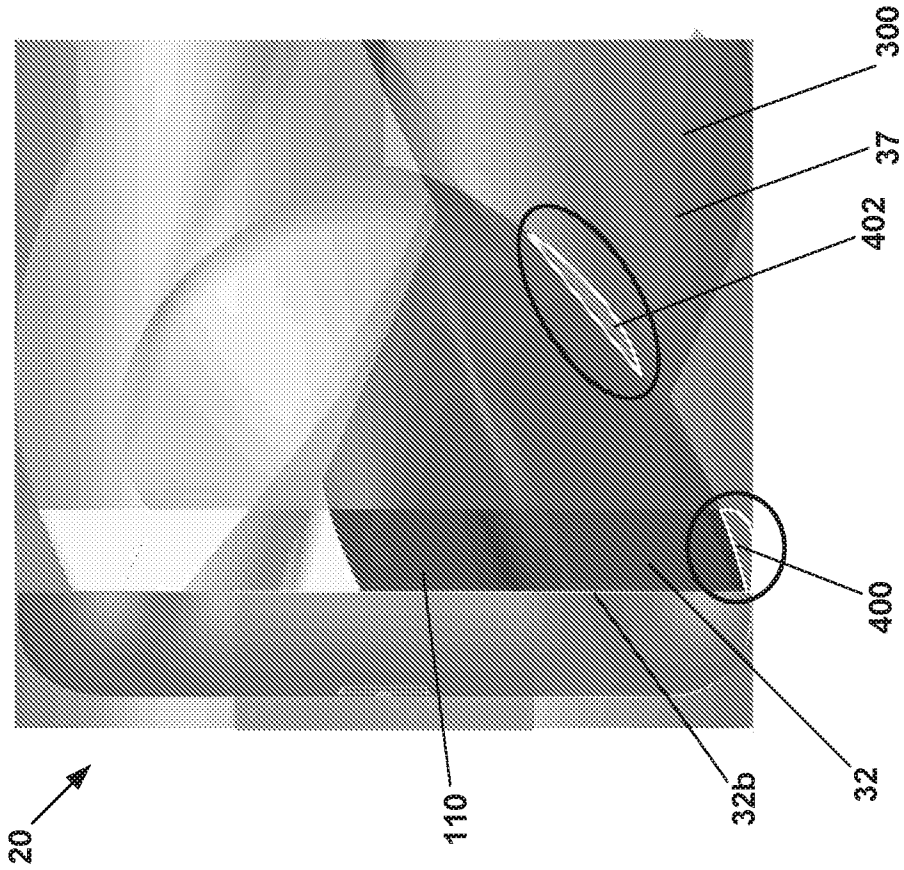


FIG. 21

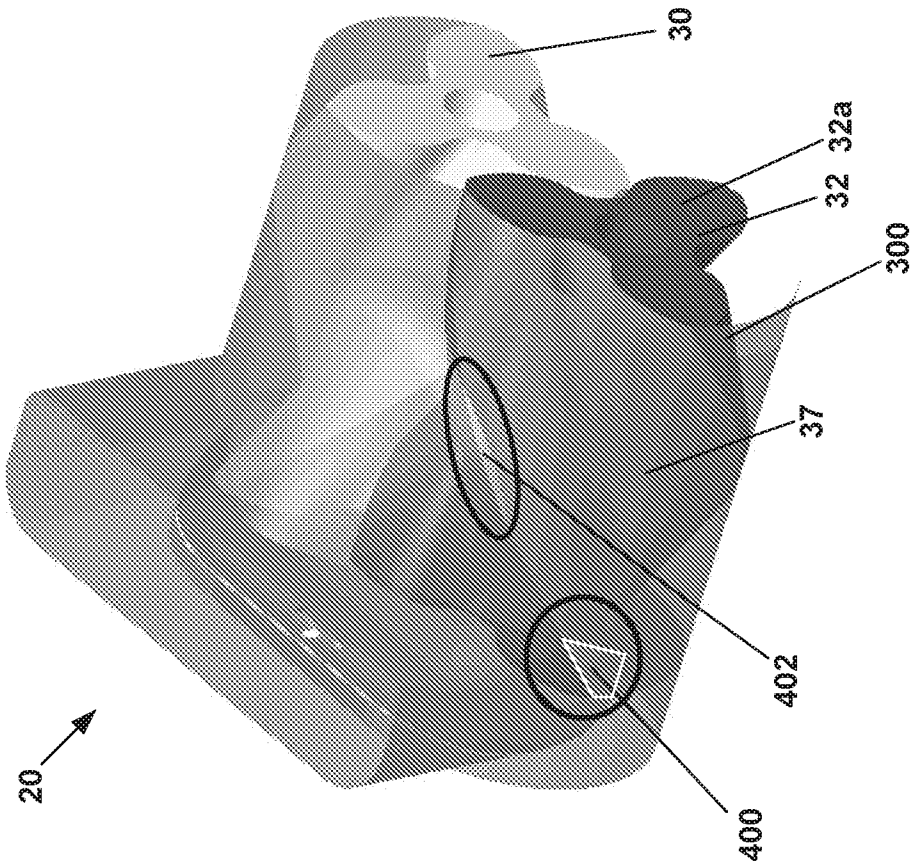


FIG. 24

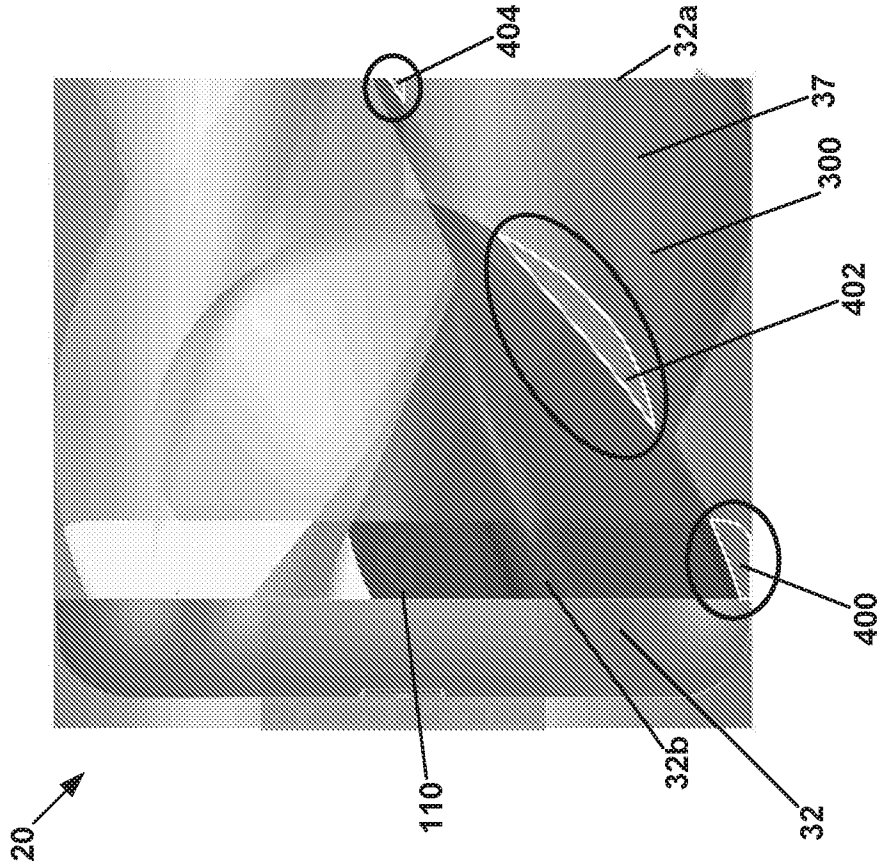
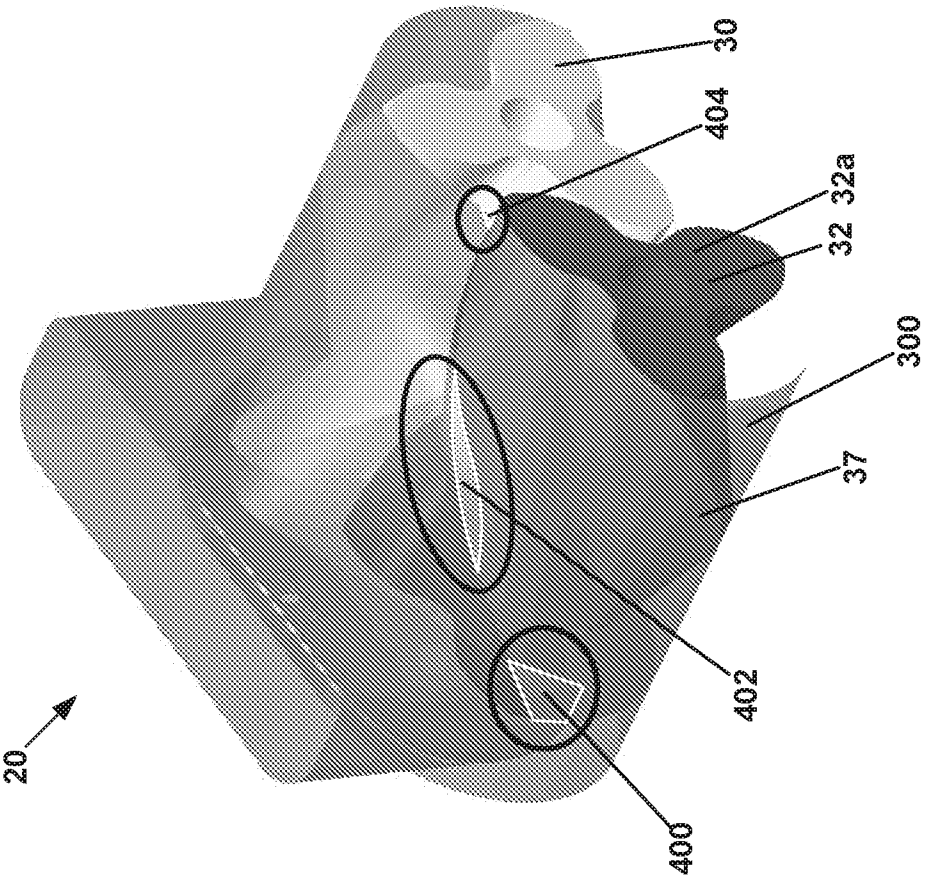

404
32a
37
300
402
400
20
110
32b
32

FIG. 23


30
404
32a
32
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37
402
400
20

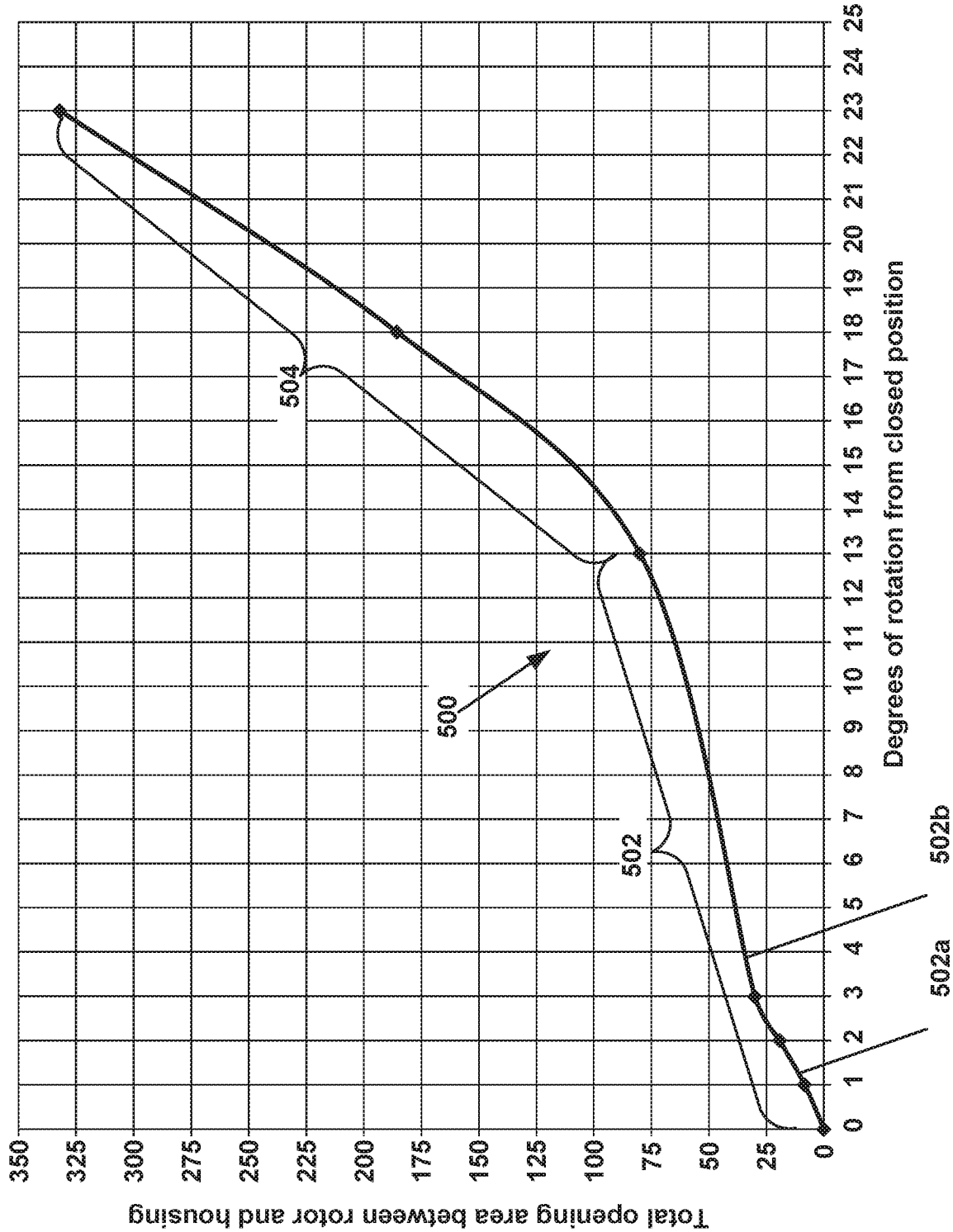

Total opening area between rotor and housing
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Degrees of rotation from closed position
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
500
502
502a
502b
504

FIG. 25

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/067885

A. CLASSIFICATION OF SUBJECT MATTER

F01N 5/02(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F01N 5/02; F04C 18/18; F04B 17/00; F01K 7/26; F04B 41/06; F02M 35/104; F04C 18/16

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: expander, rotor, lobe, cusp, intake, close, discharge, opening, volume

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2014-117159 A1 (EATON CORPORATION et al.) 31 July 2014 See paragraphs [0047]-[0048], [0055], [0067]-[0069]; and figures 2, 9.	1-11
Y	US 2014-0193285 A1 (EATON CORPORATION) 10 July 2014 See paragraphs [0008], [0028], [0043]; and figures 1, 3-4, 7.	1-11
A	US 2006-0067835 A1 (DUWEL et al.) 30 March 2006 See paragraphs [0039], [0046]-[0050]; and figures 3-7.	1-11
A	US 2008-0168961 A1 (PRIOR et al.) 17 July 2008 See paragraphs [0011], [0013], [0015]; and figures 1-4.	1-11
A	US 2004-0208770 A1 (PRIOR, GREGORY P.) 21 October 2004 See paragraphs [0017]-[0018]; and figures 1-2.	1-11

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 March 2016 (29.03.2016)	**30 March 2016 (30.03.2016)**

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
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Facsimile No. +82-42-481-8578

Authorized officer
LEE, Dal Kyong
Telephone No. +82-42-481-8440

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/067885

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/067885

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