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(12) **Reissued Patent**  
**Müller et al.**

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(54) <b>WAVE ROTOR APPARATUS</b>	2,904,245 A	9/1959	Pearson
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(75) Inventors: <b>Norbert Müller</b> , Haslett, MI (US);	2,970,745 A	2/1961	Berchtold
<b>Pejman Akbari</b> , New York, NY (US);	3,106,073 A *	10/1963	Kentfield ..... 62/402
<b>Janusz Piechna</b> , Warsaw (PL); <b>Florin Iancu</b> , Silver Spring, MD (US)	3,190,542 A *	6/1965	Vickery ..... 417/64
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(73) Assignee: **Board of Trustees of Michigan State University**, East Lansing, MI (US)

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(21) Appl. No.: <b>13/023,568</b>	BE	443643	1/1942
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(22) Filed: **Mar. 1, 2011**

**Related U.S. Patent Documents**

Reissue of:

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(51) **Int. Cl.**  
**F02C 3/02** (2006.01)

(52) **U.S. Cl.**  
USPC ..... **60/39.45**

(58) **Field of Classification Search**  
USPC ..... 60/39.45, 726, 772, 39.38, 39.39,  
60/39.76–39.78, 247; 431/1; 417/64  
See application file for complete search history.

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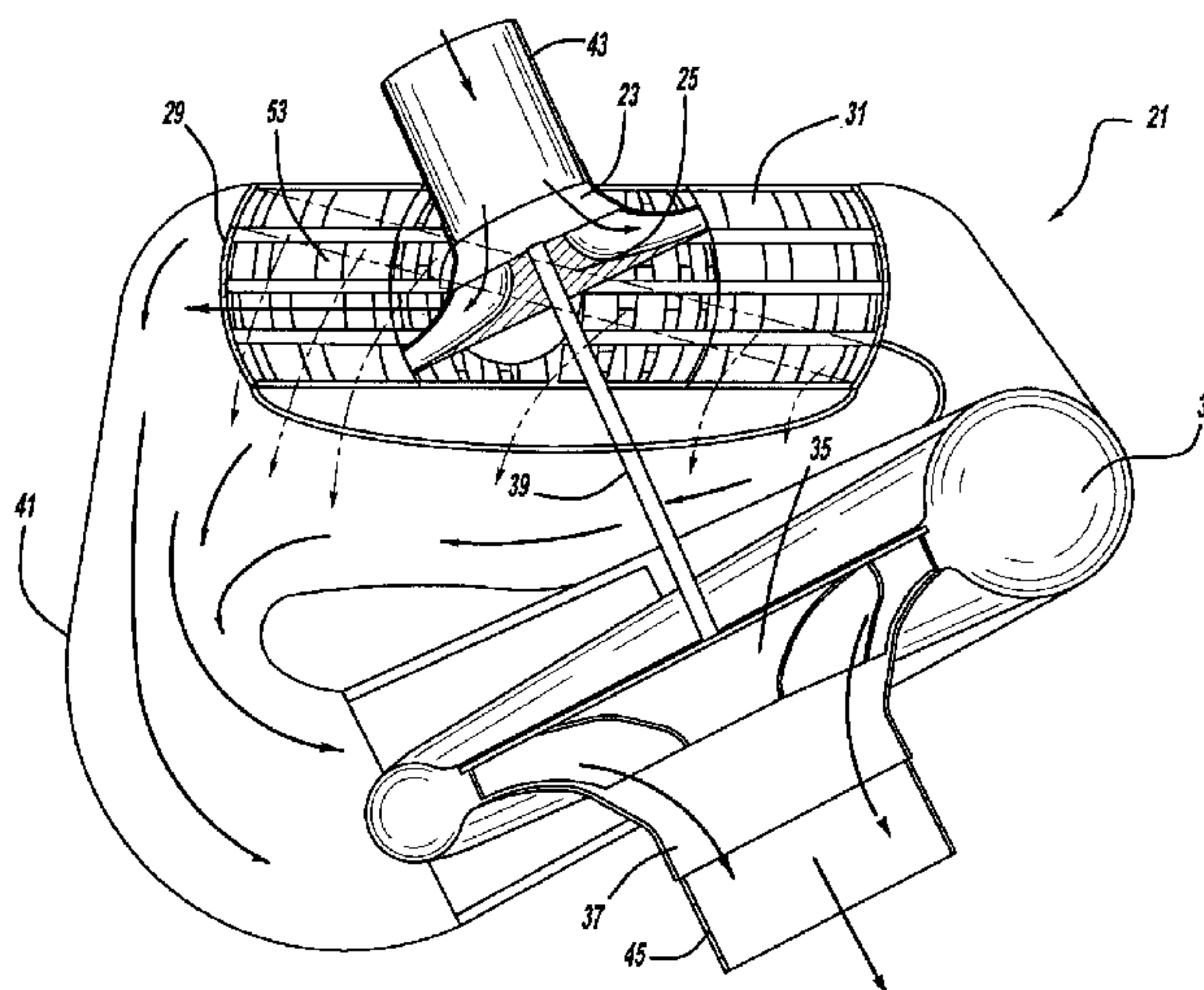
*Primary Examiner* — Andrew Nguyen

(74) *Attorney, Agent, or Firm* — Harness, Dickey & Pierce, P.L.C.

(57) **ABSTRACT**

A wave rotor apparatus is provided. In another aspect of the present invention, a radial wave rotor includes fluid passage-ways oriented in a direction offset from its rotational axis. A further aspect of the present invention employs stacked layers of generally radial channels in a wave rotor. Moreover, turbomachinery is located internal to a wave rotor in yet another aspect of the present invention. In yet another aspect of the present invention, a radial wave rotor has an igniter and fuel injector. Correctional passages are employed in still another aspect of the present invention wave rotor.

**121 Claims, 26 Drawing Sheets**





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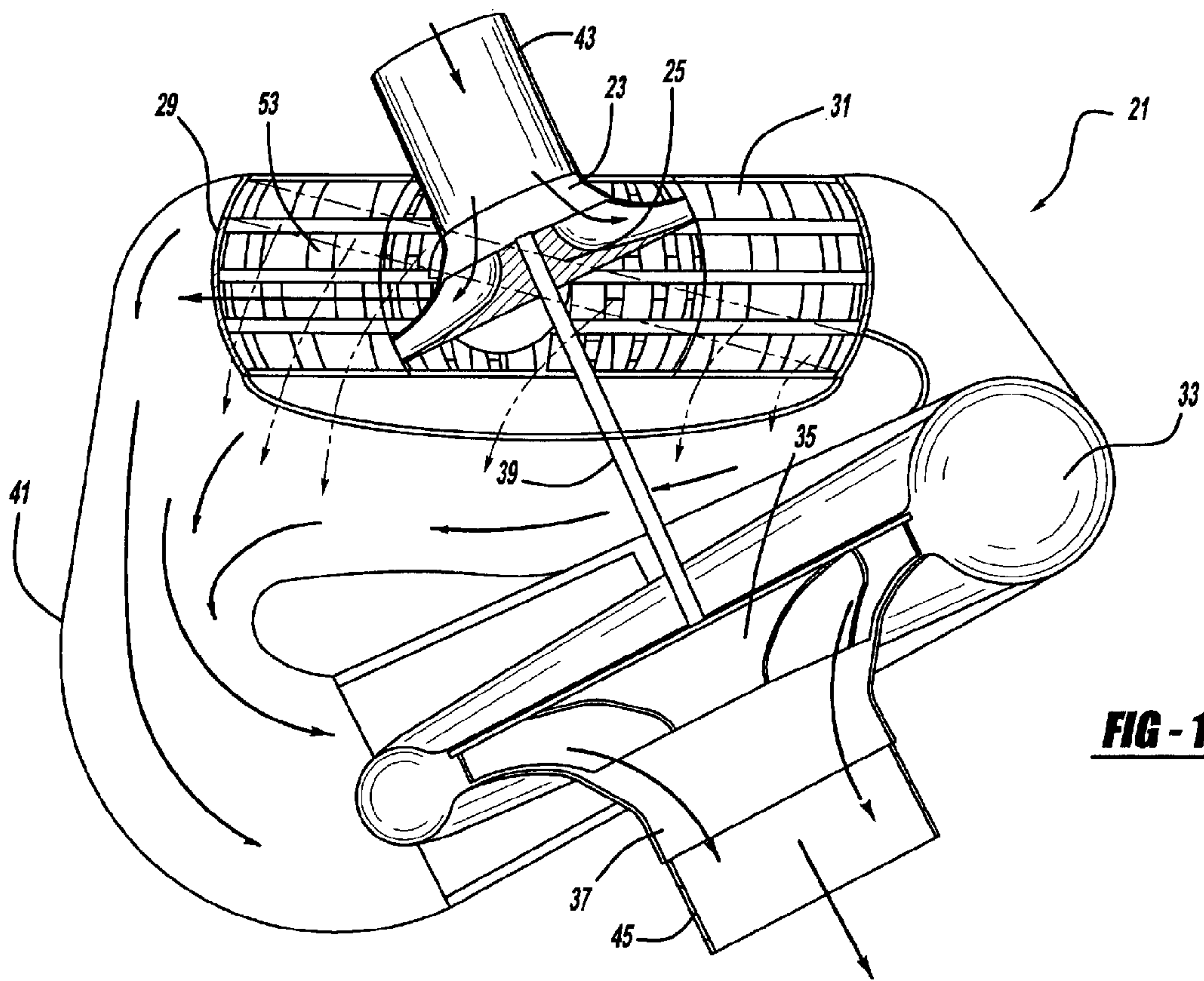
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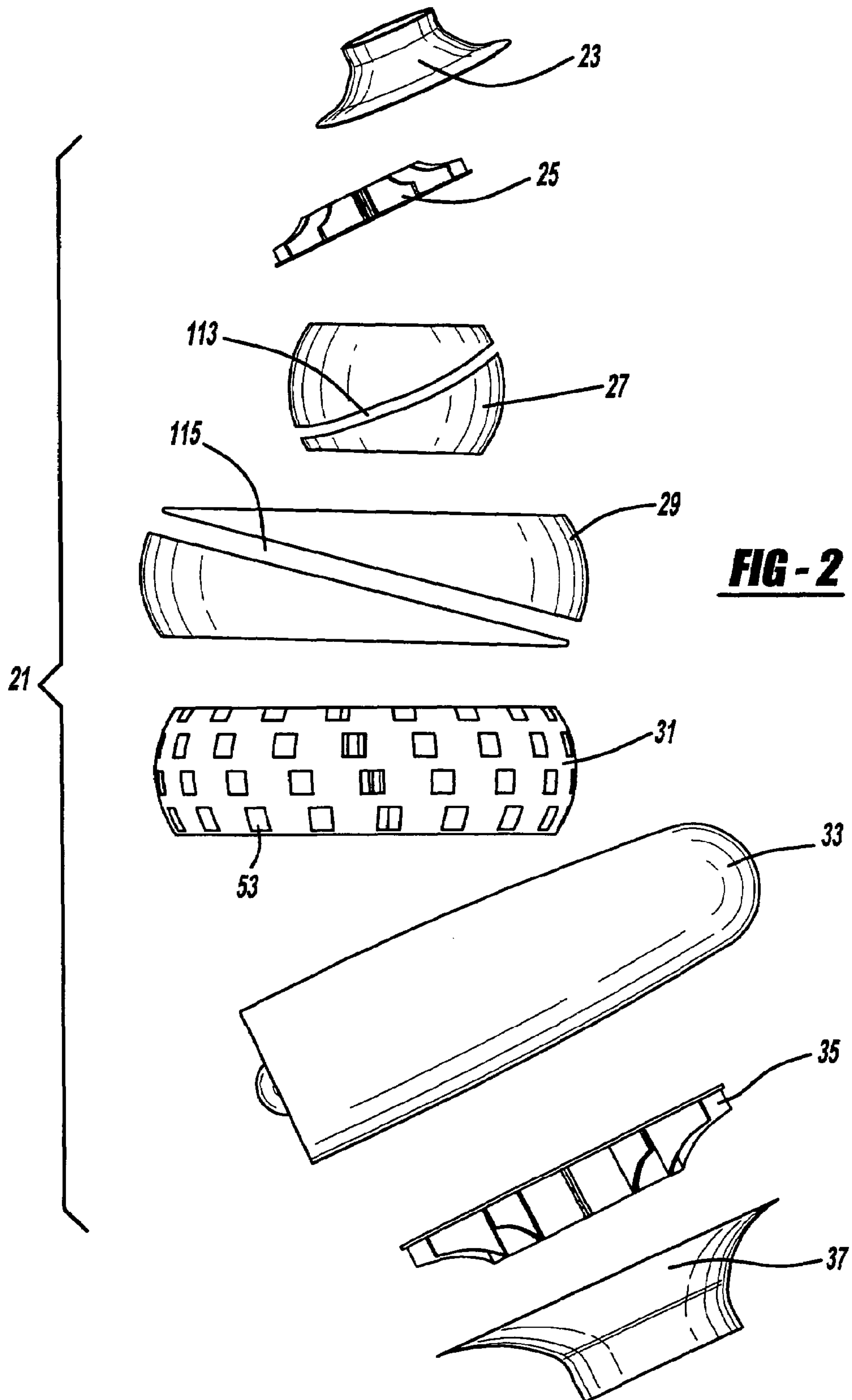
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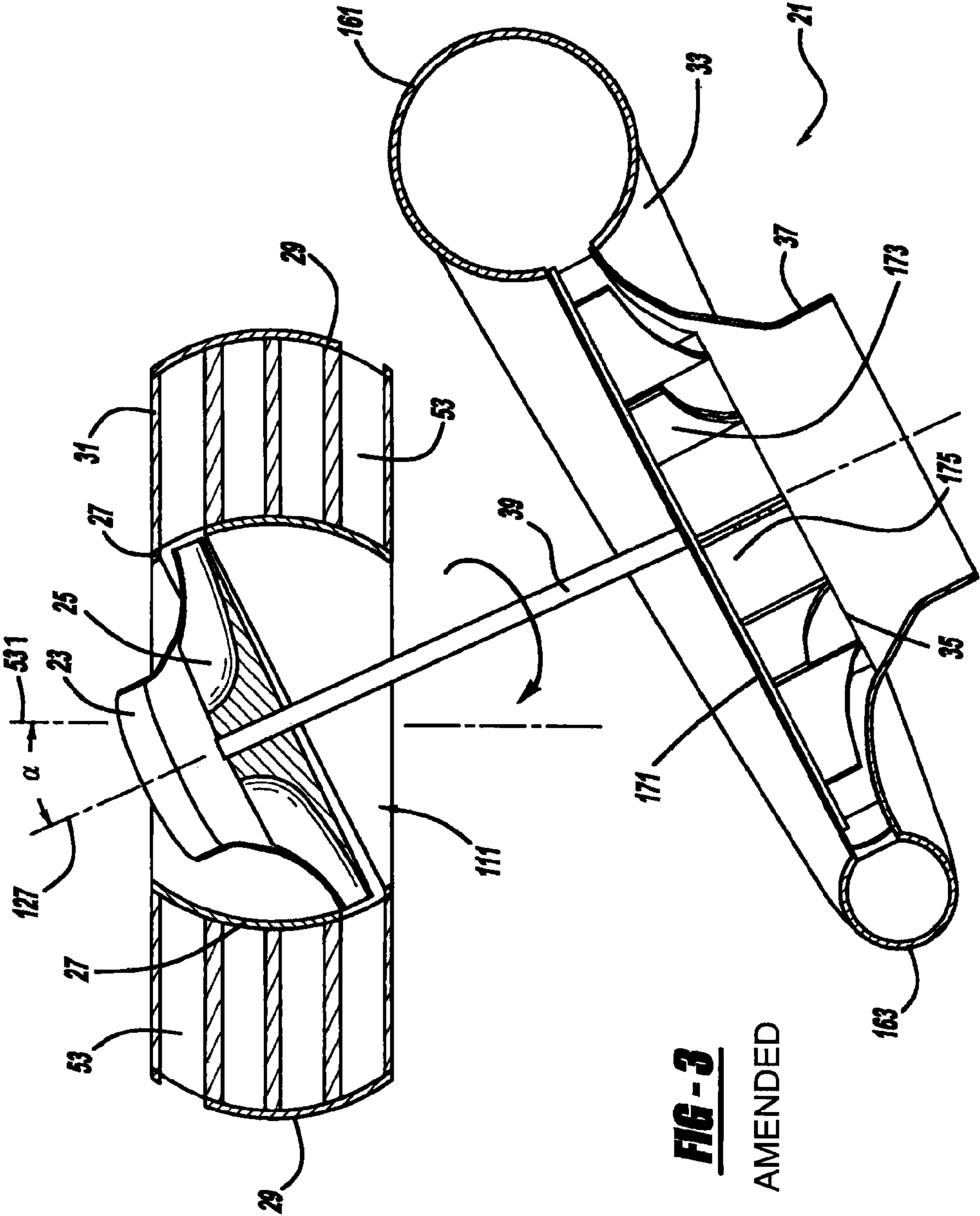
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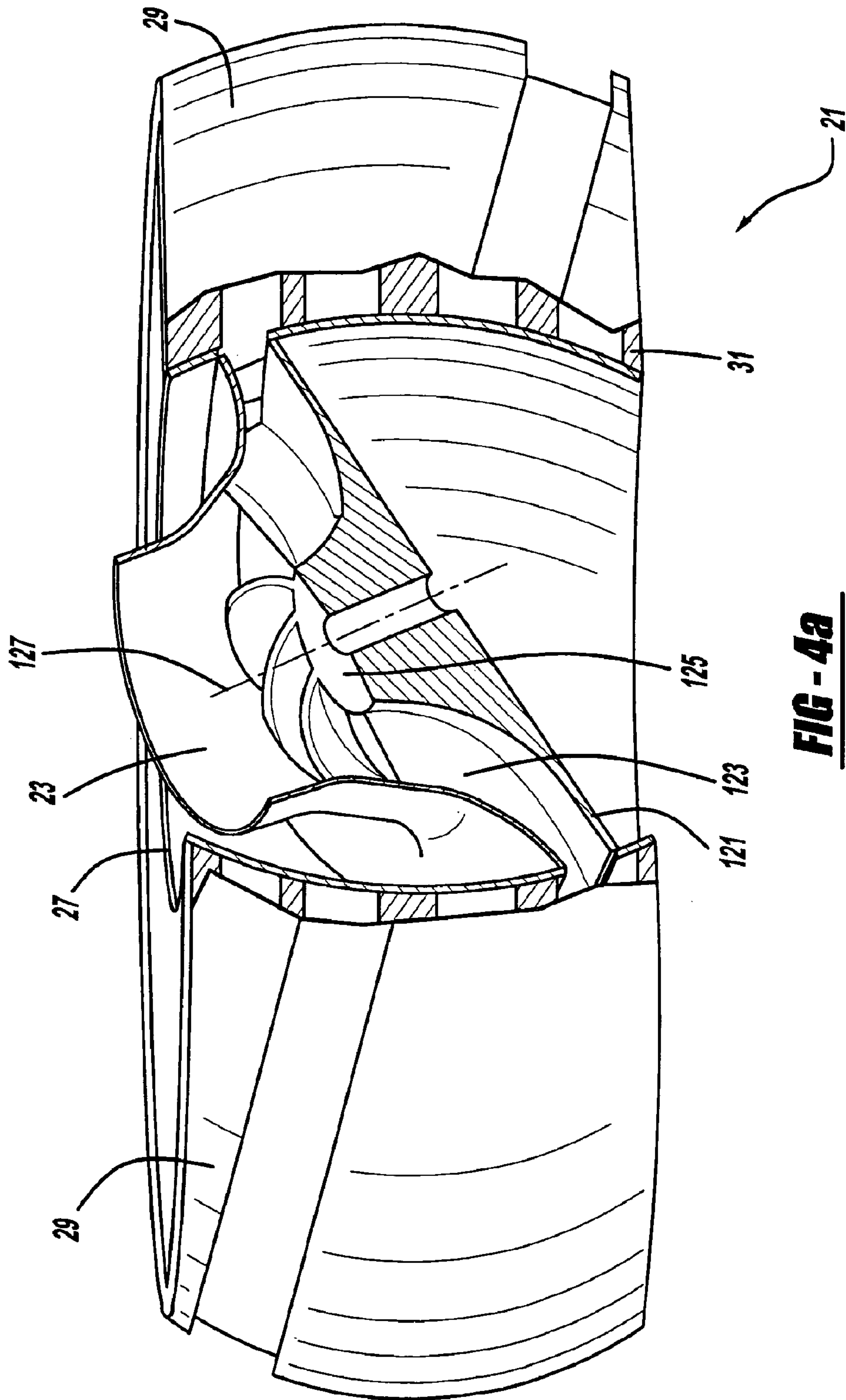




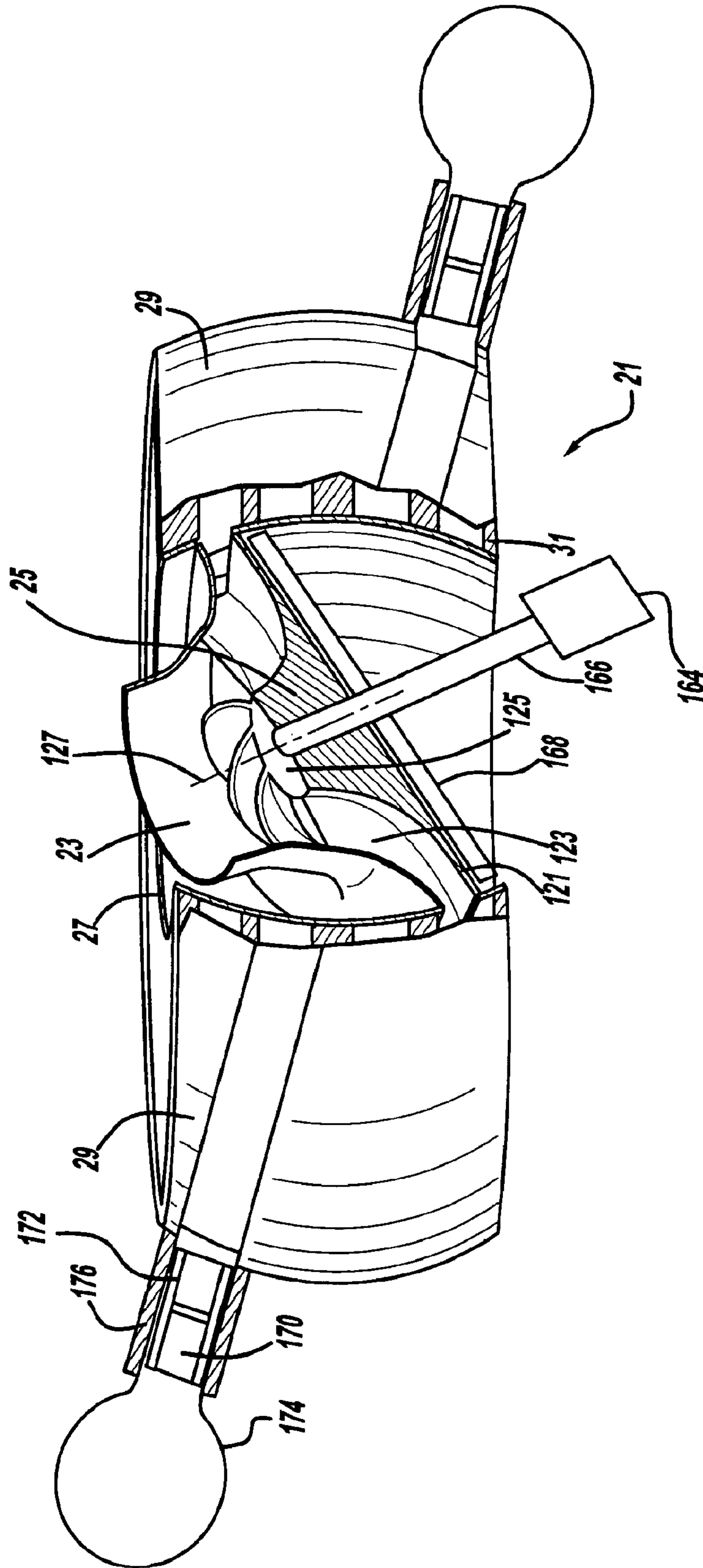




**FIG - 3**  
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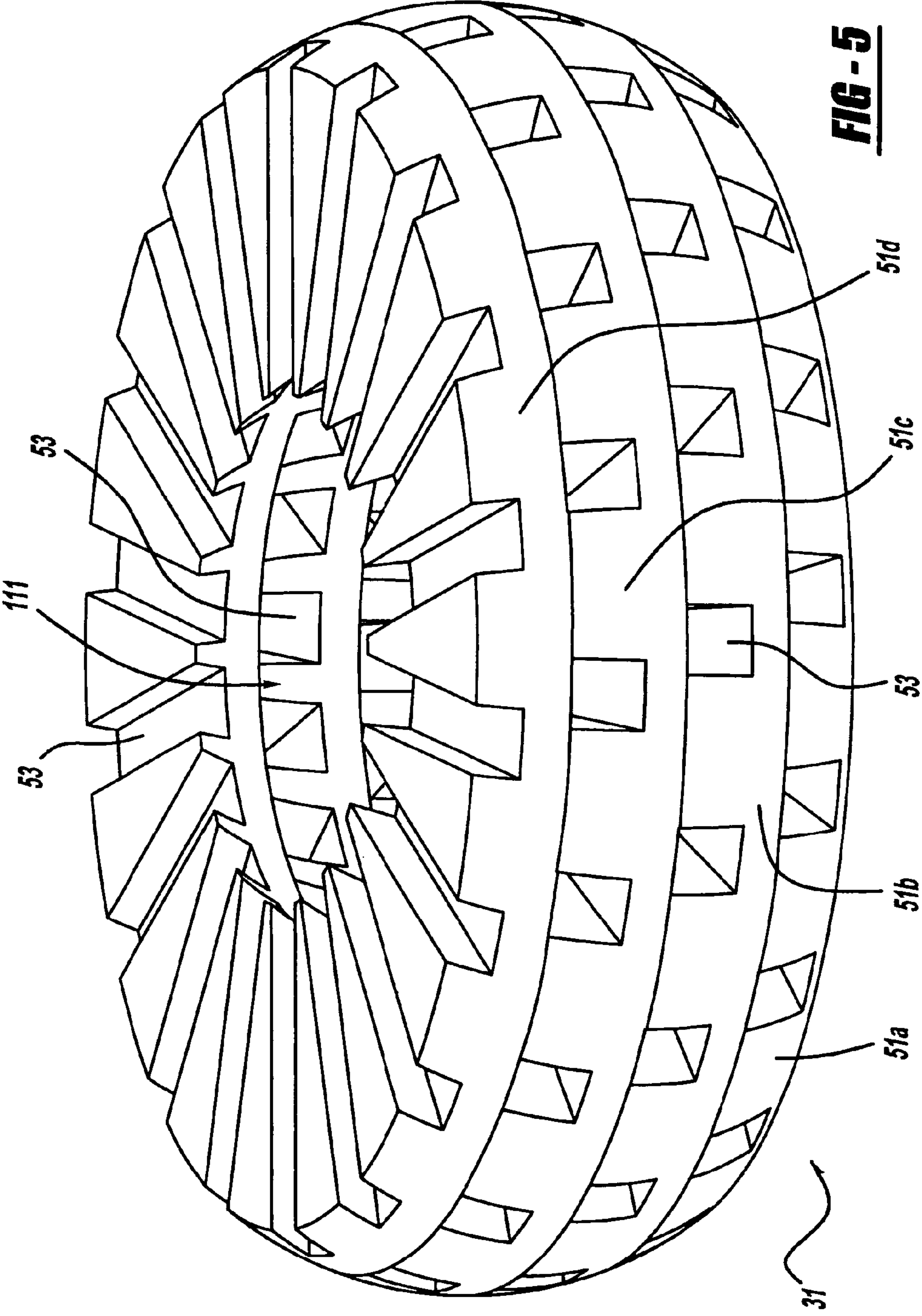


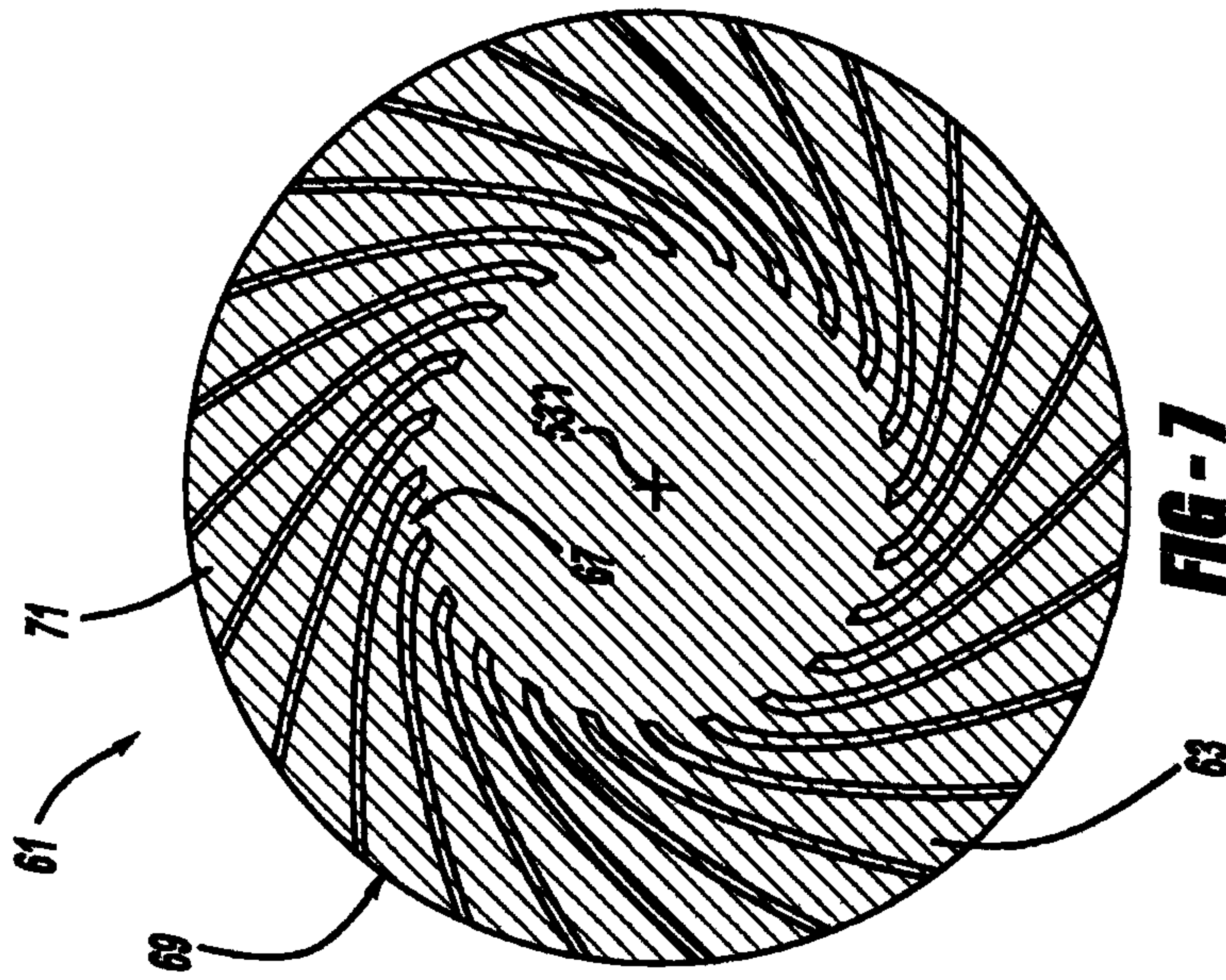
**FIG - 4a**



**FIG - 4b**

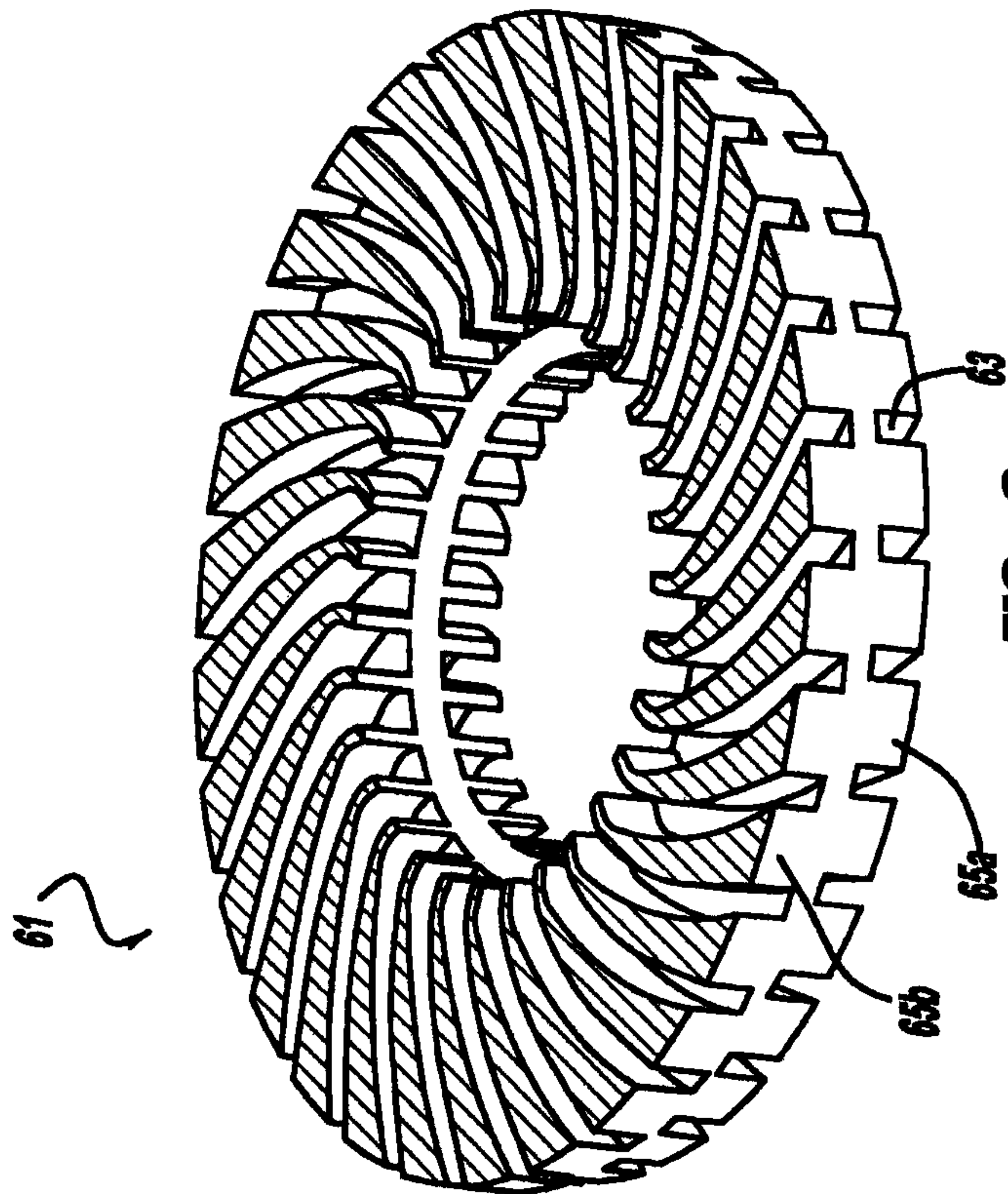






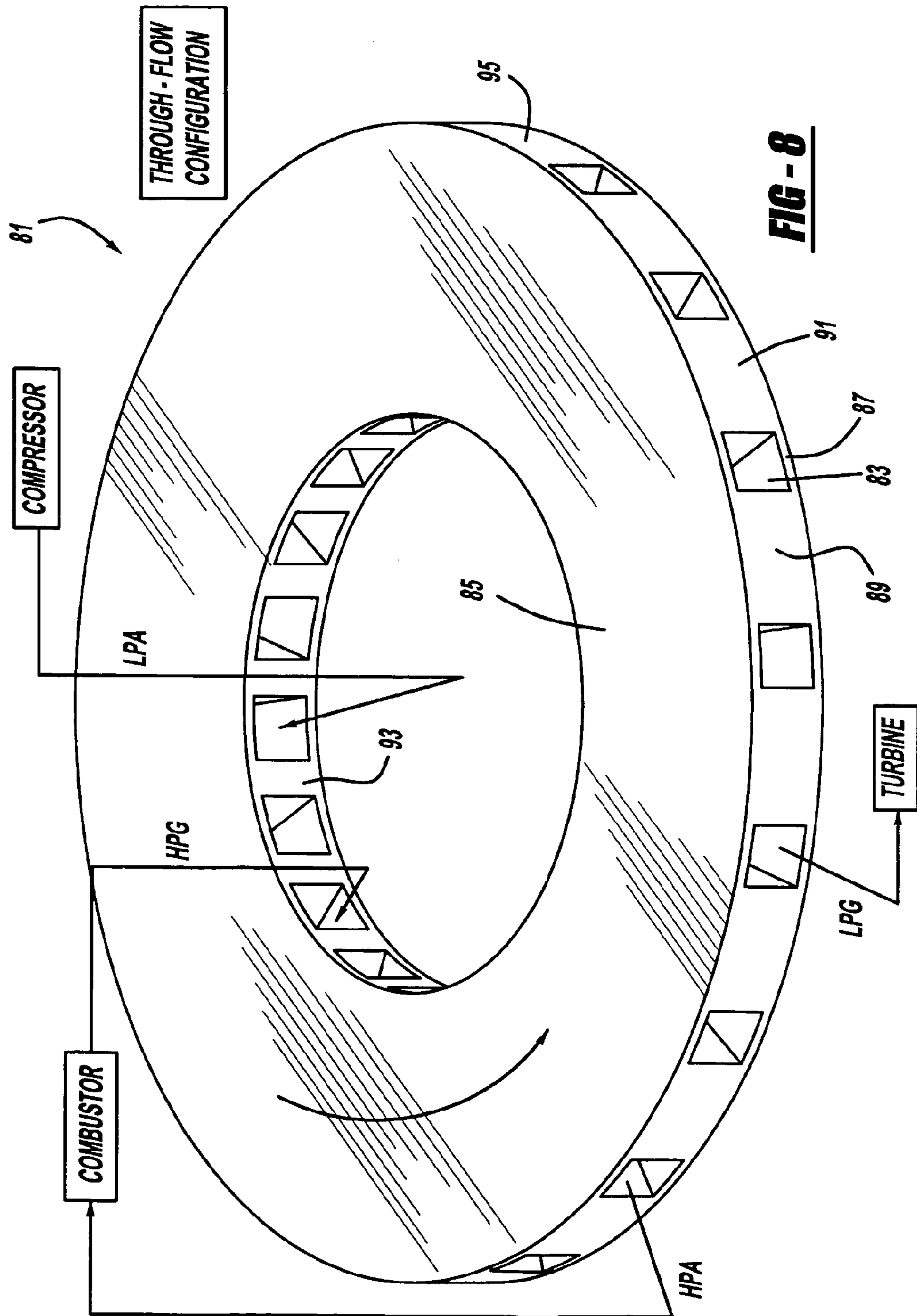
**FIG-7**

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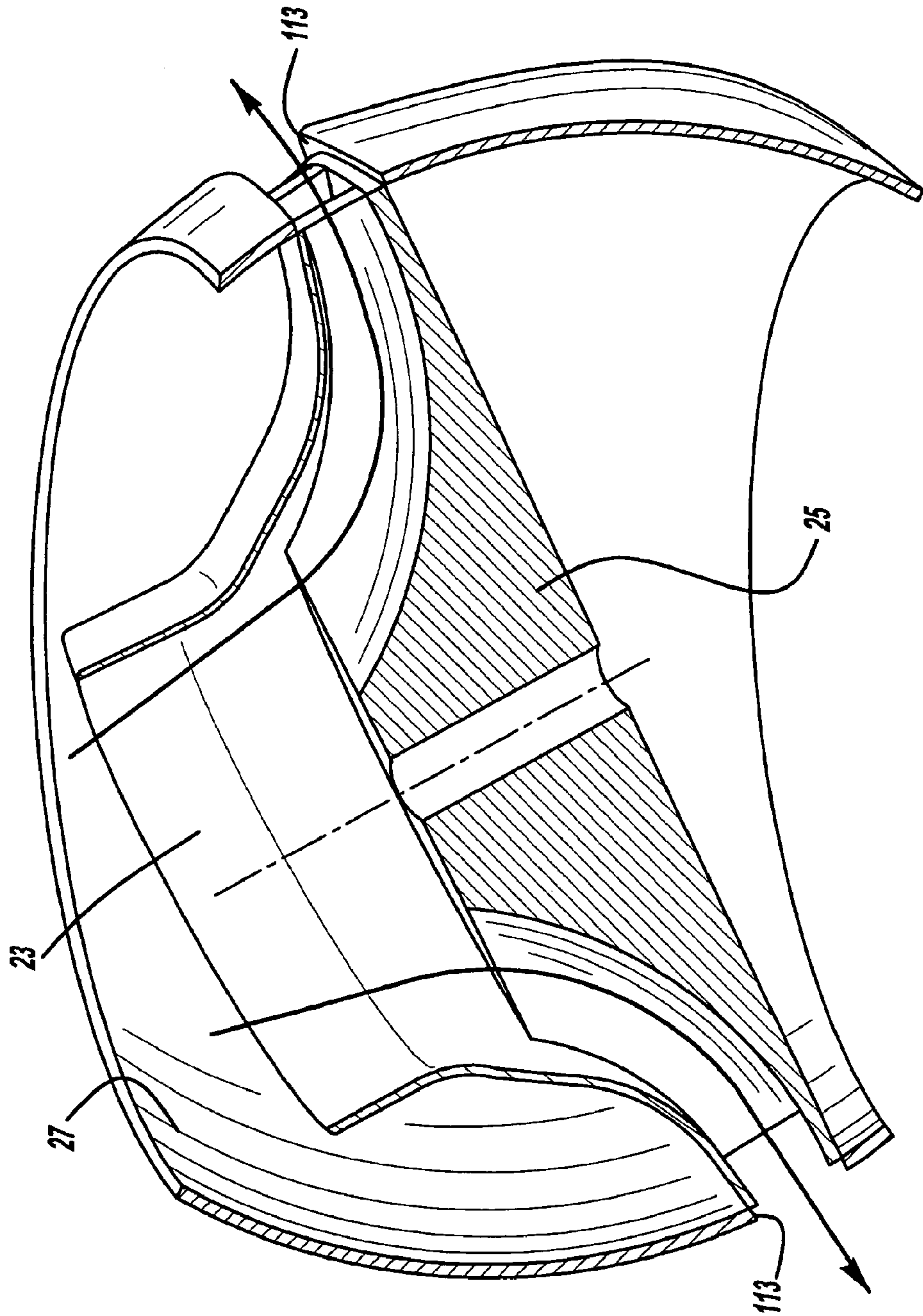


**FIG-6**

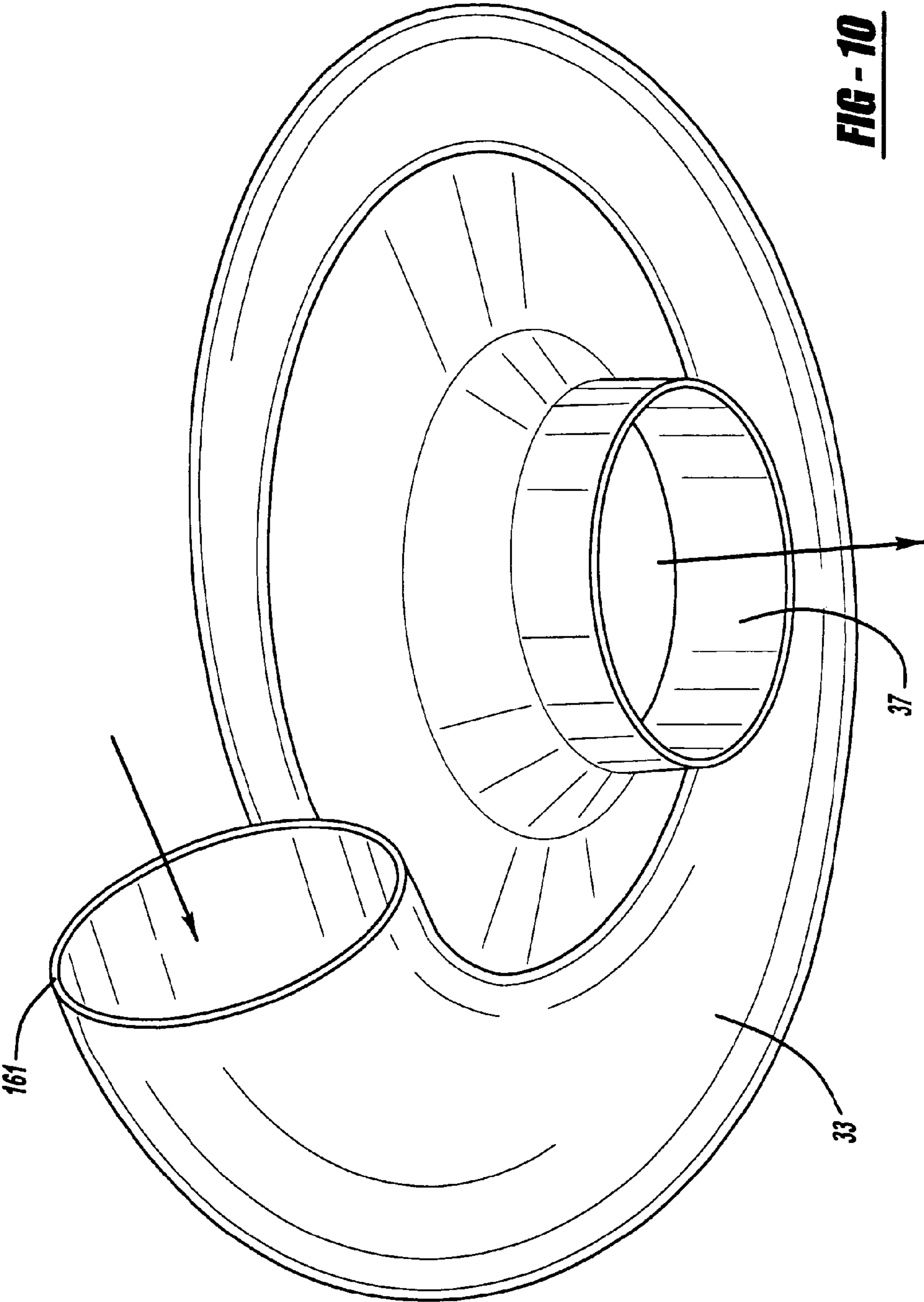
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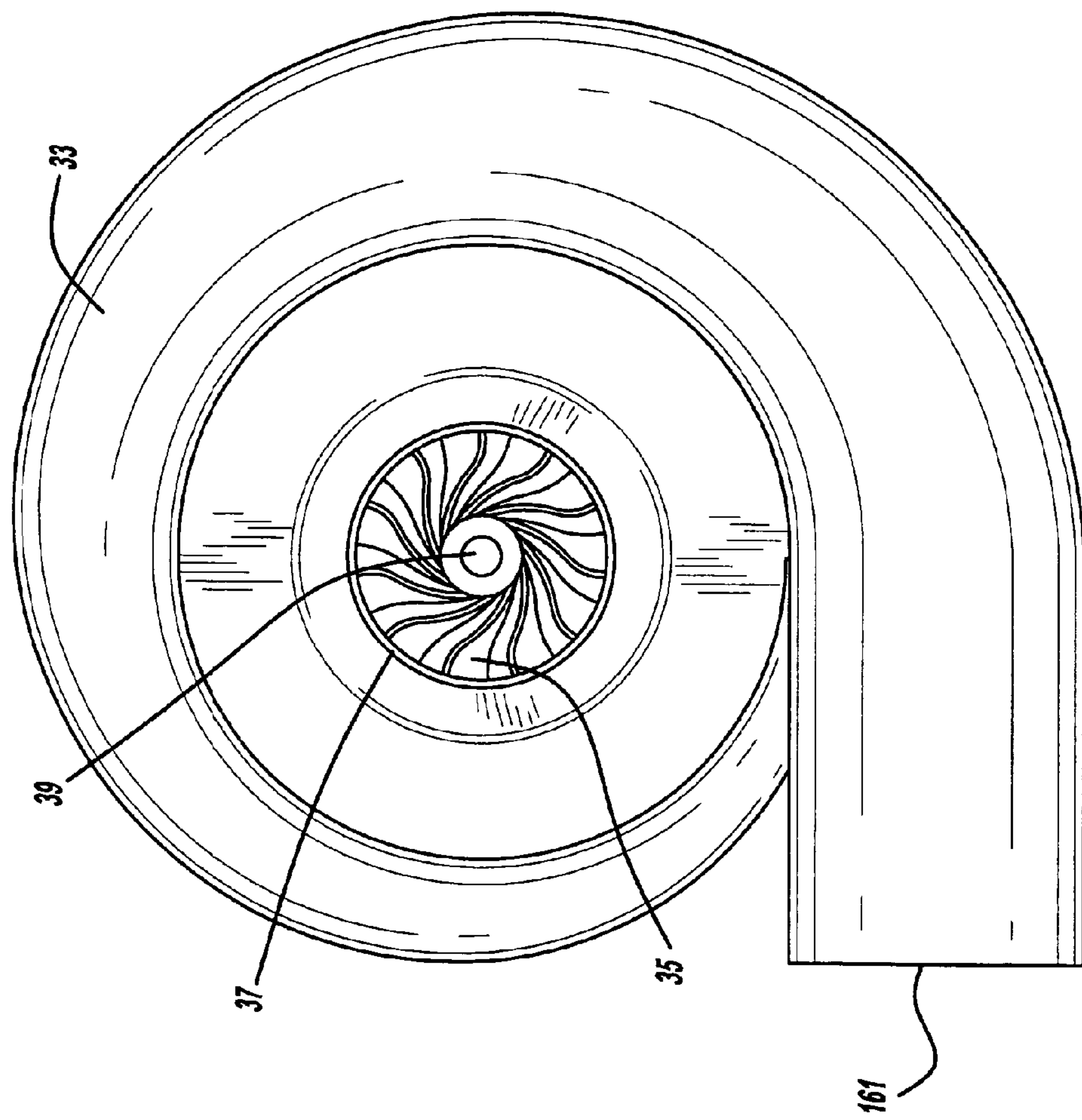




**FIG - 9**

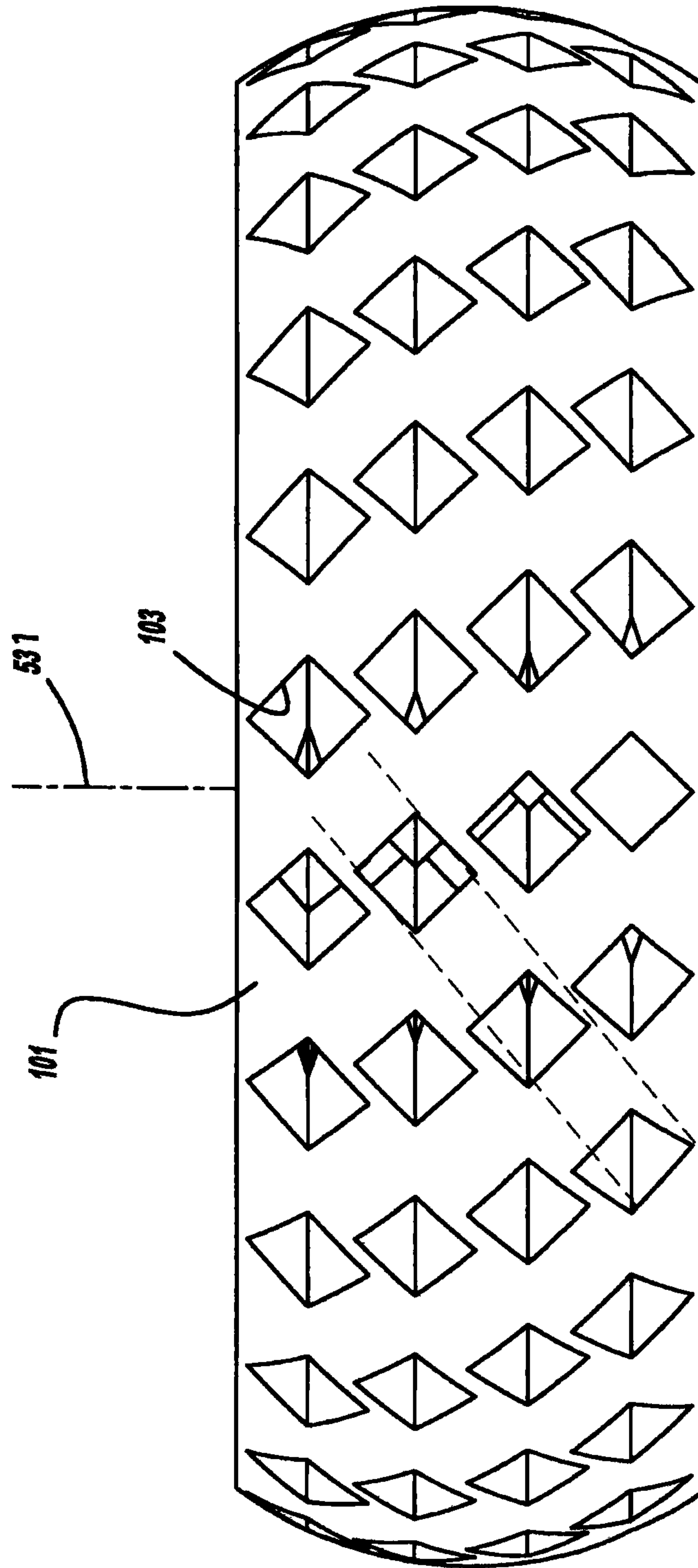


**FIG - 10**



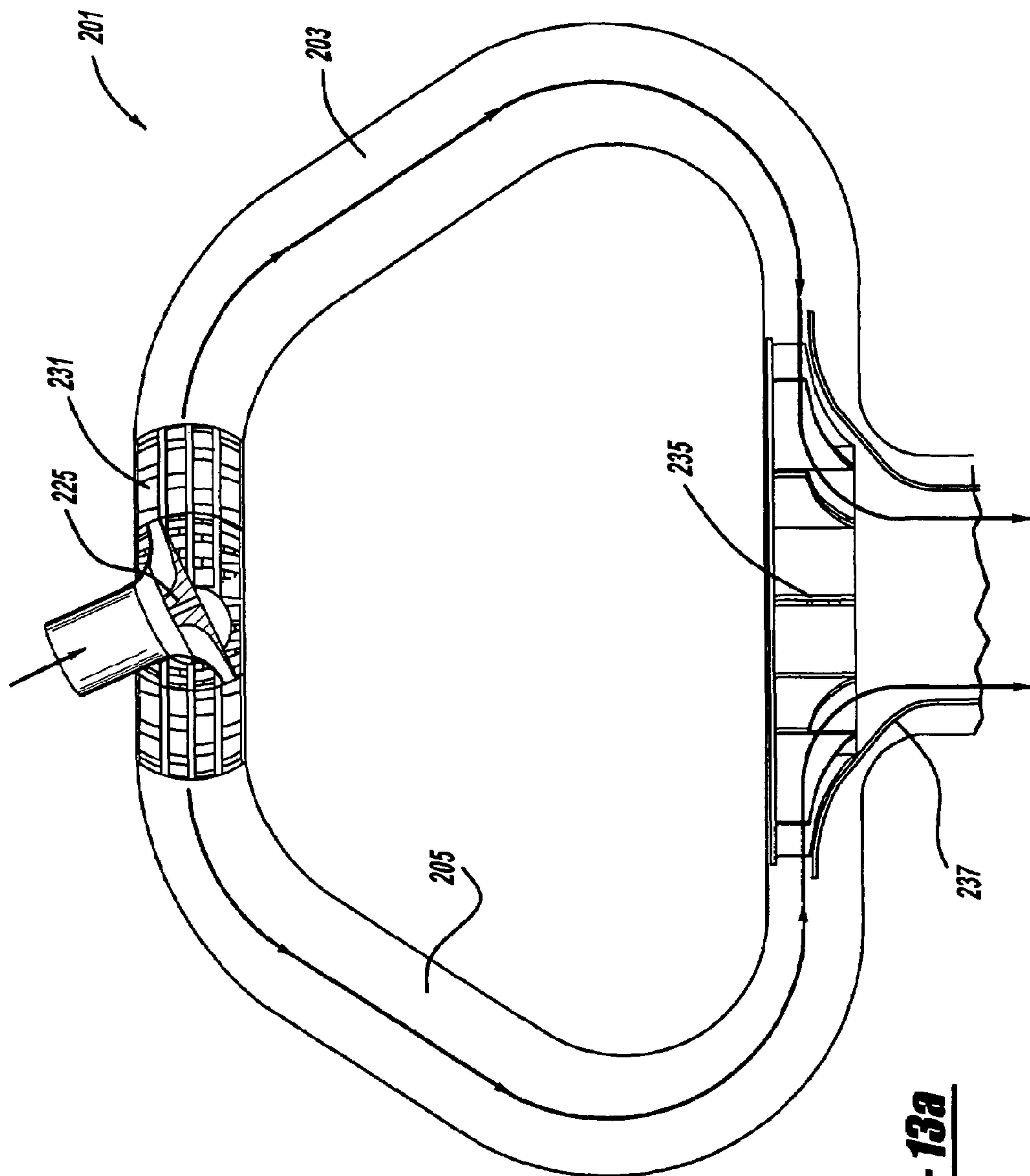
**FIG - 11**



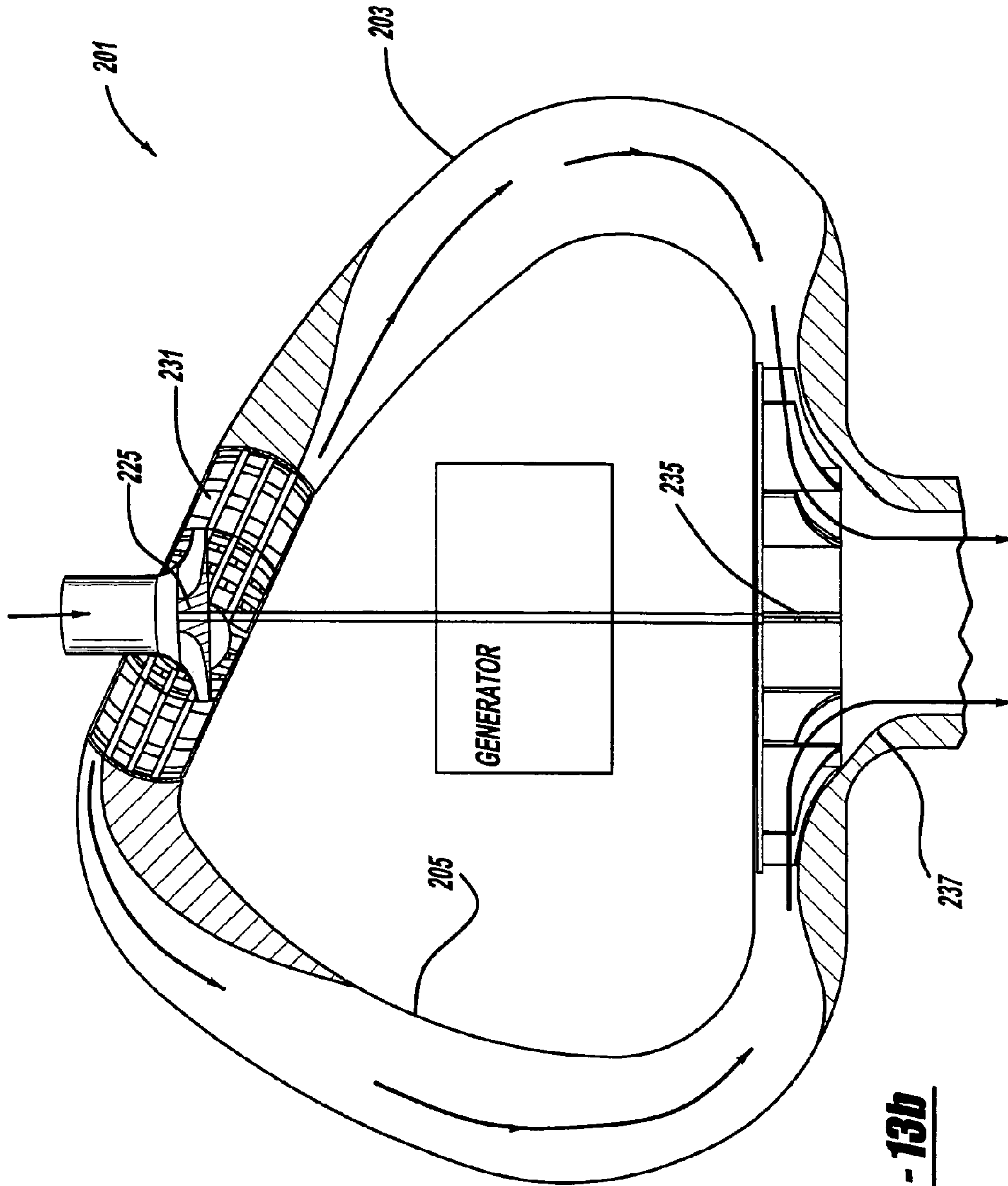


**FIG - 12**

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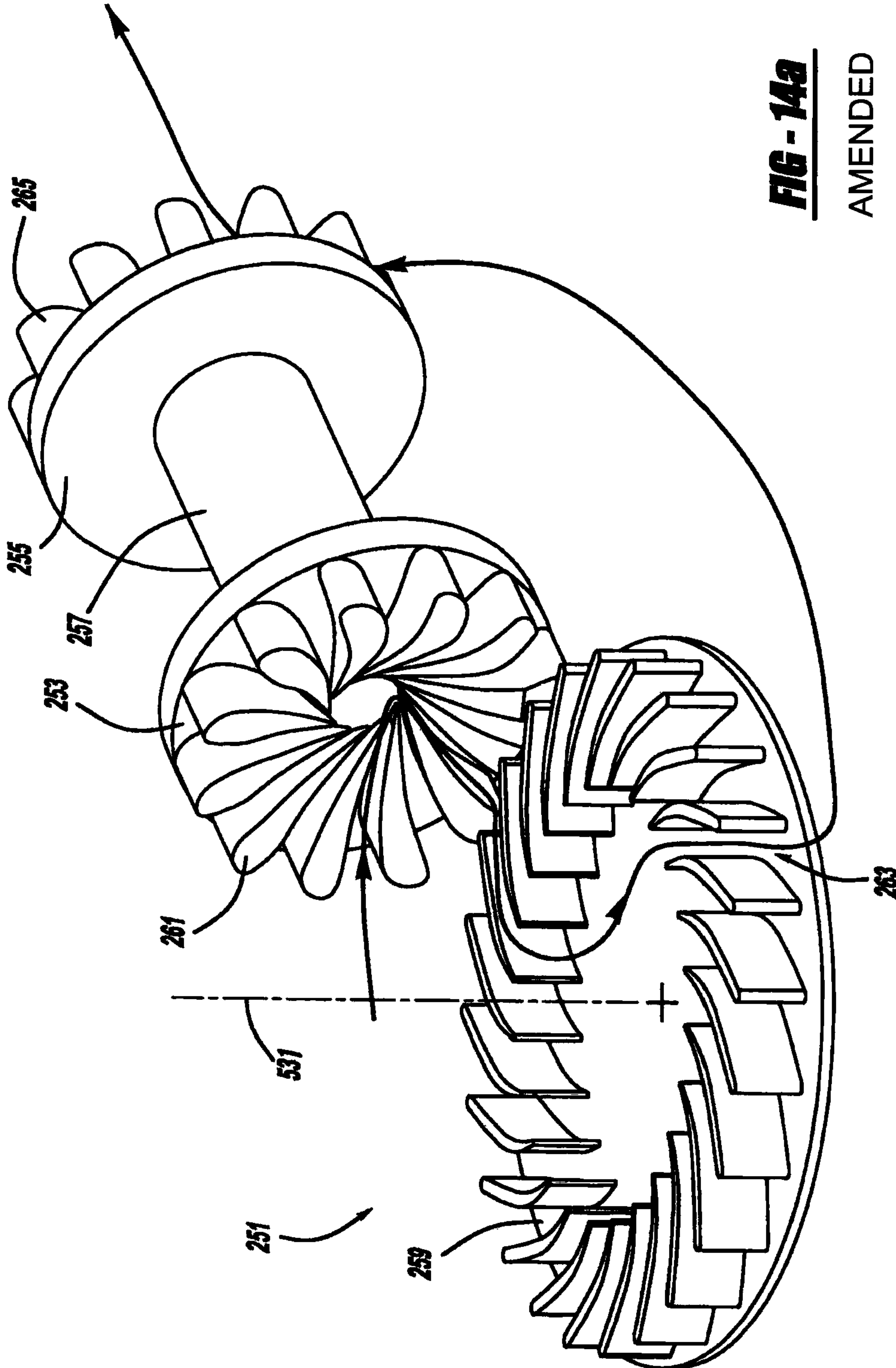


**FIG - 13a**

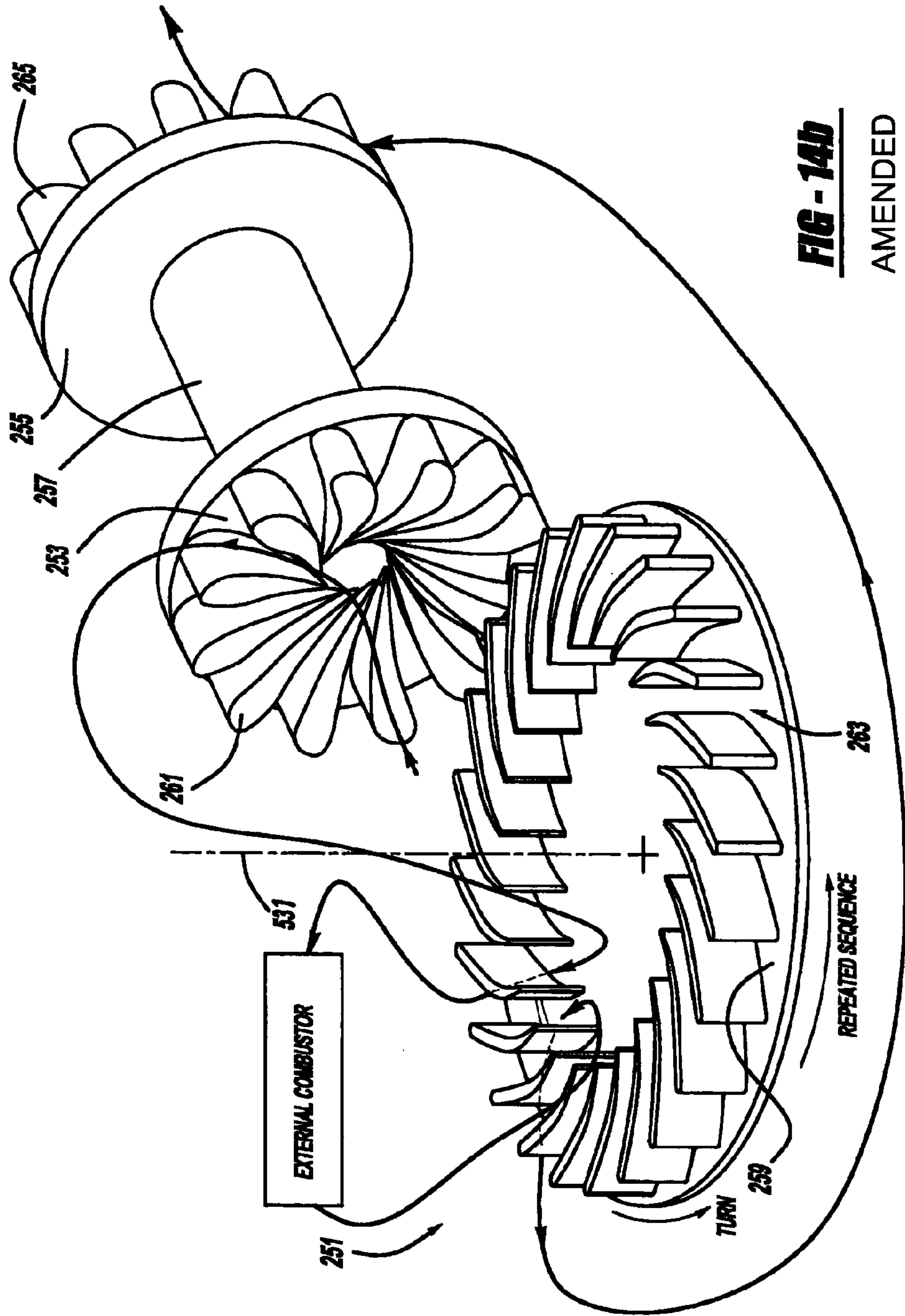


**FIG - 13b**

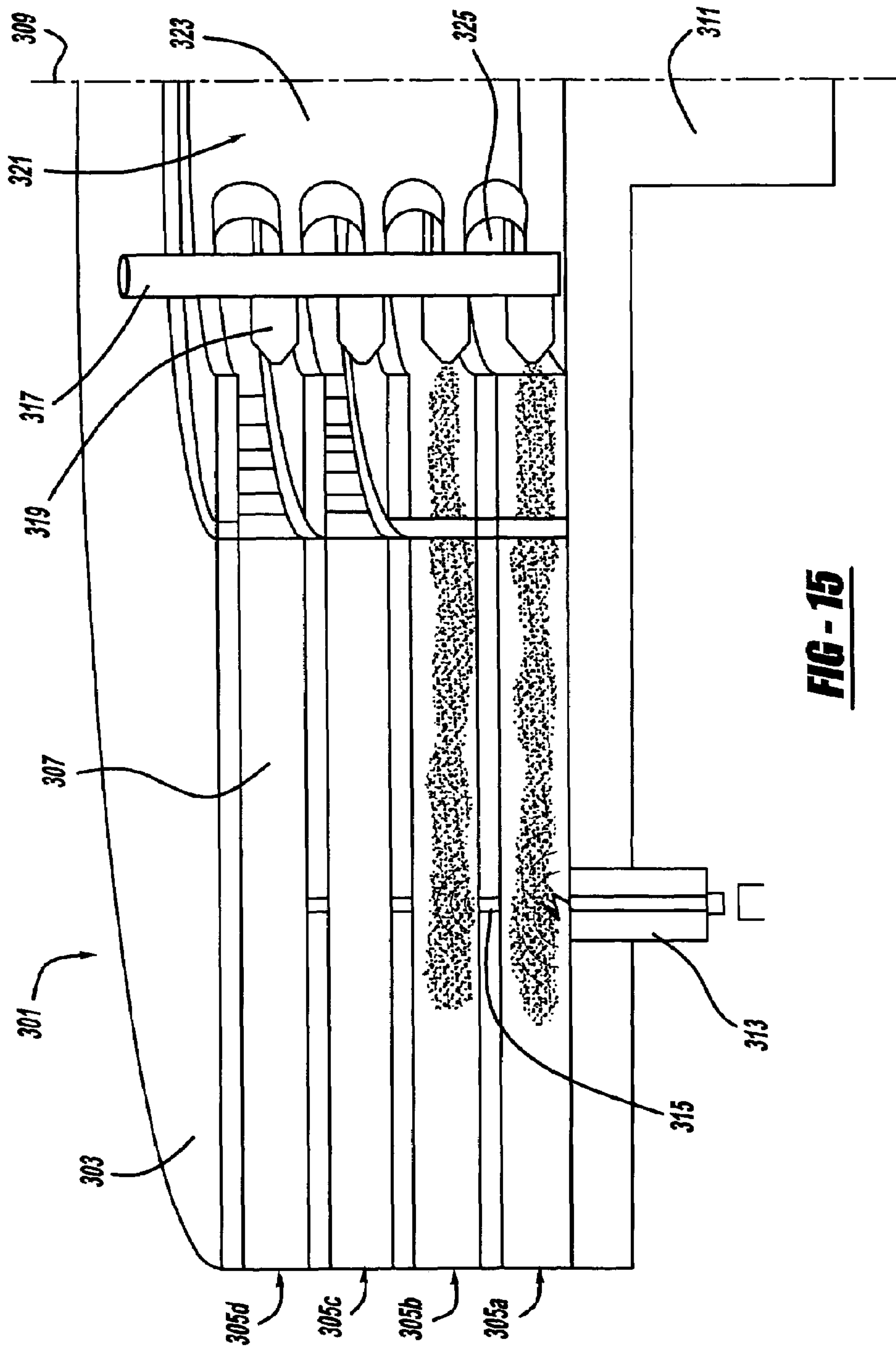




**FIG - 14a**  
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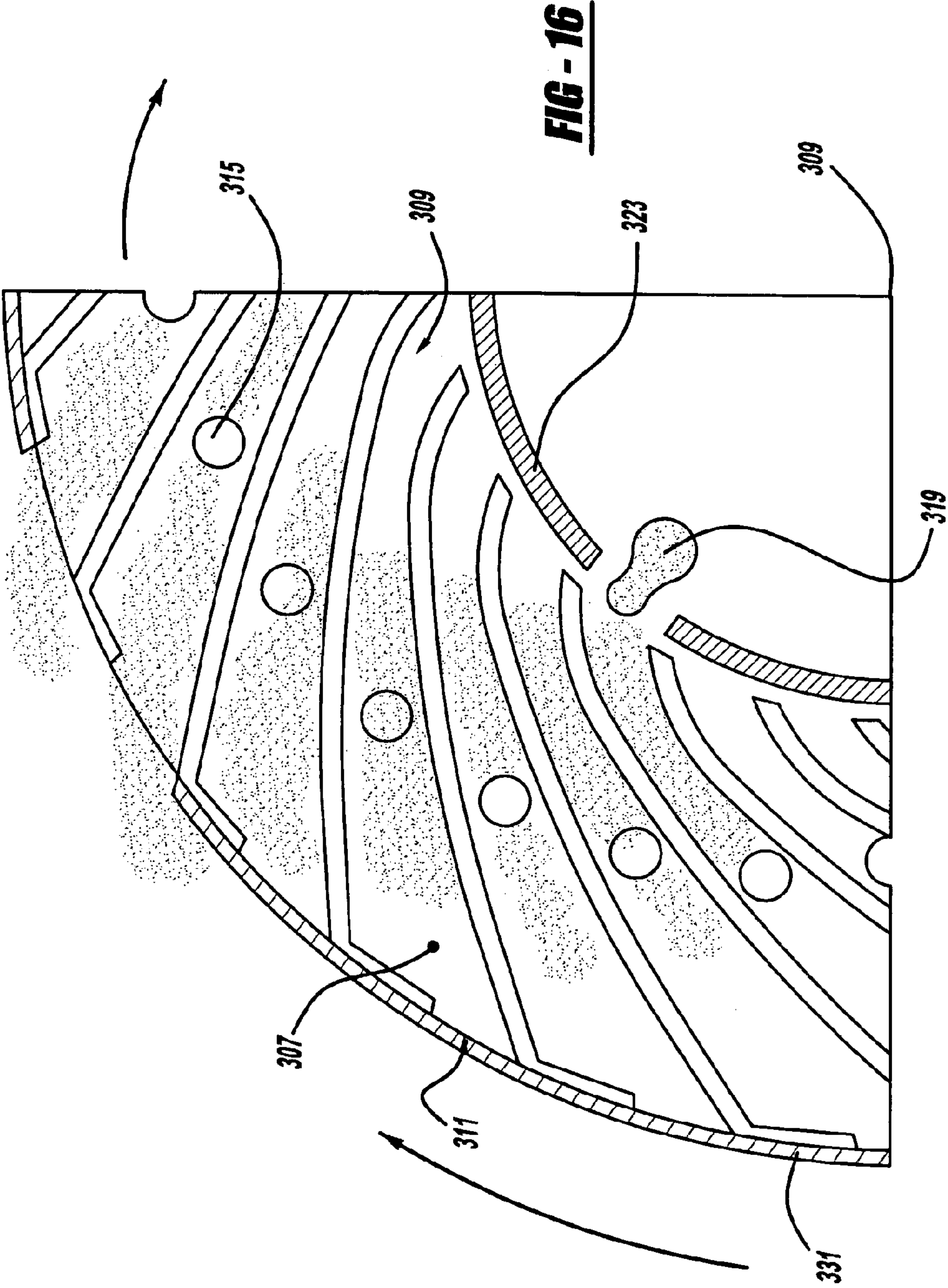


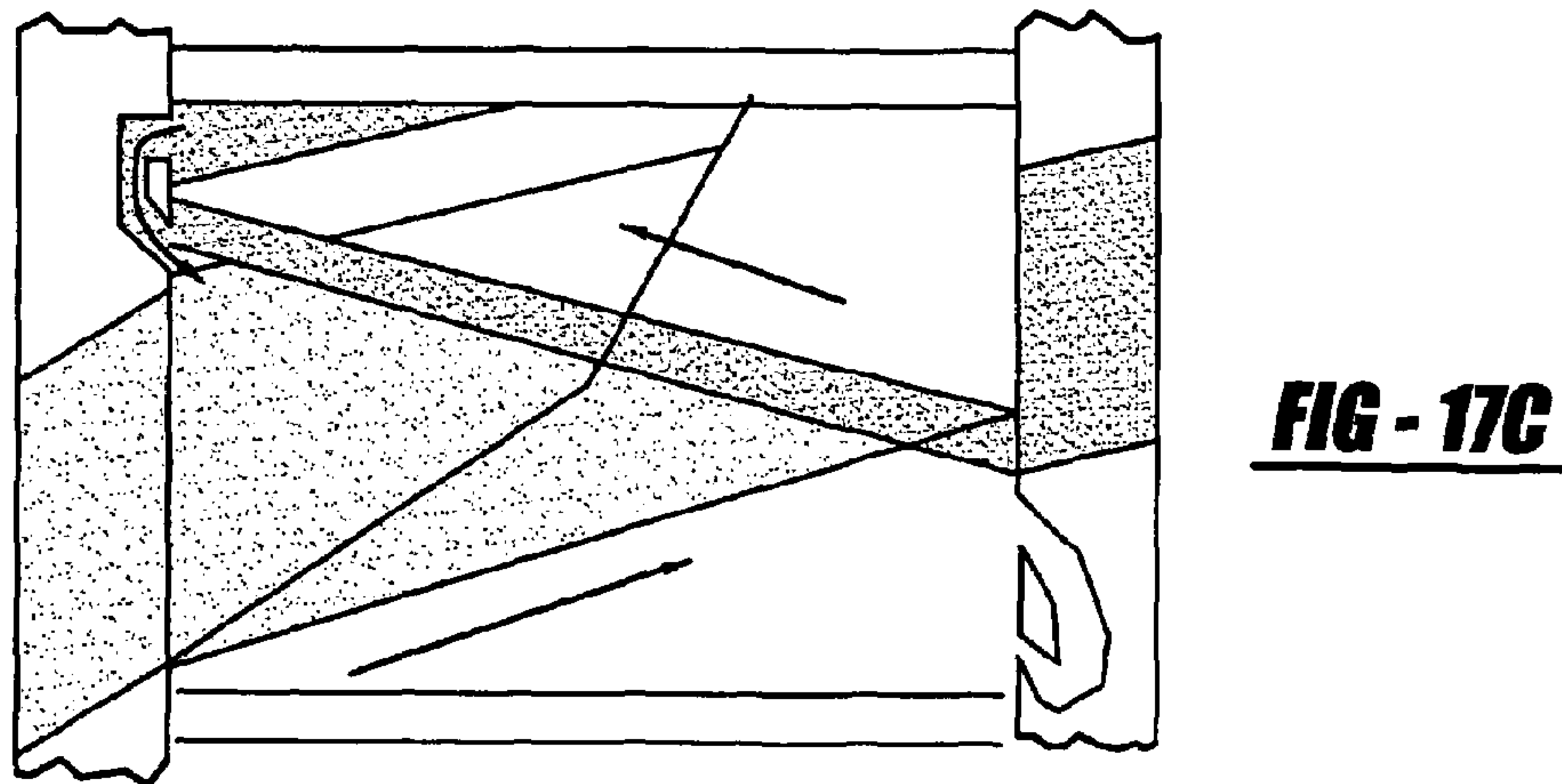
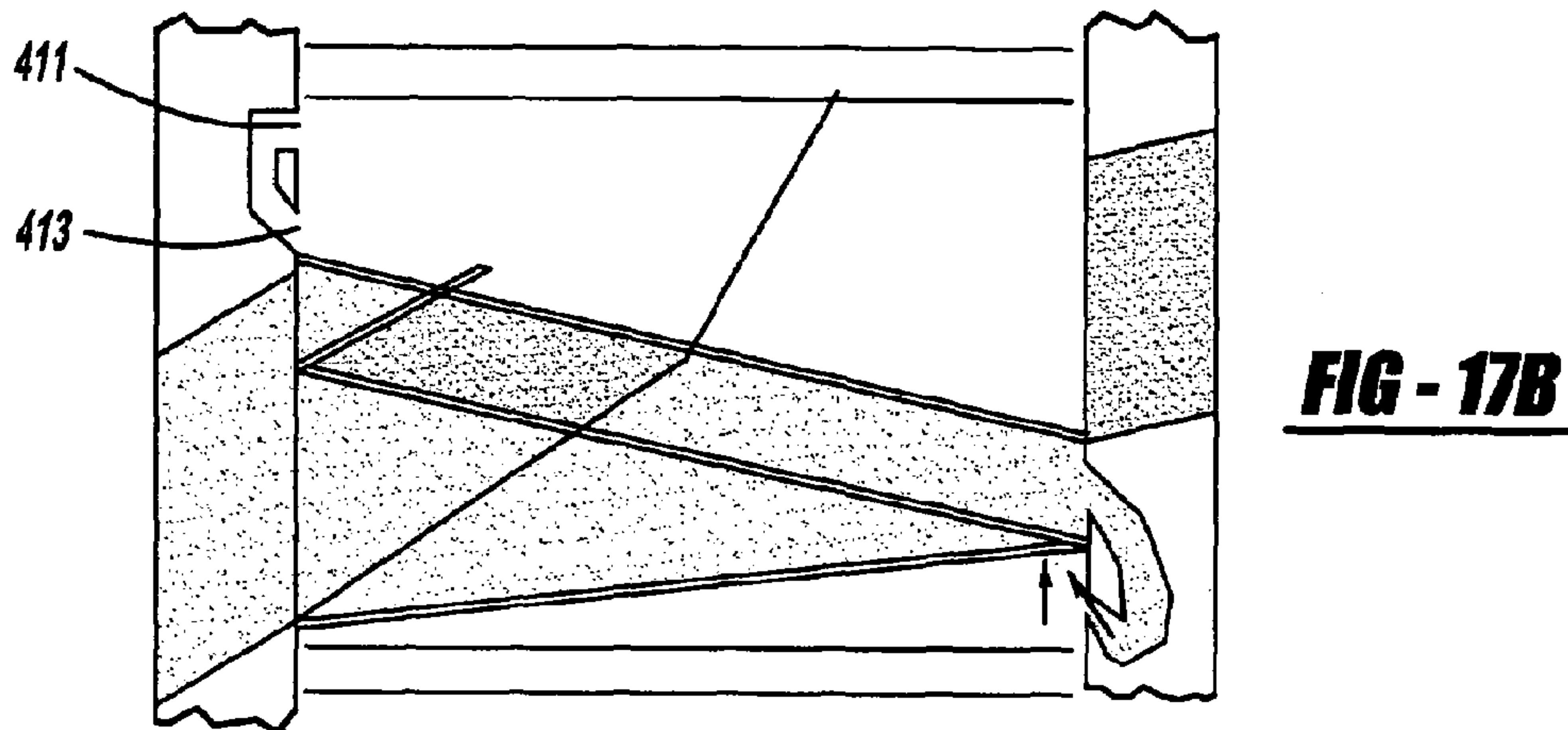
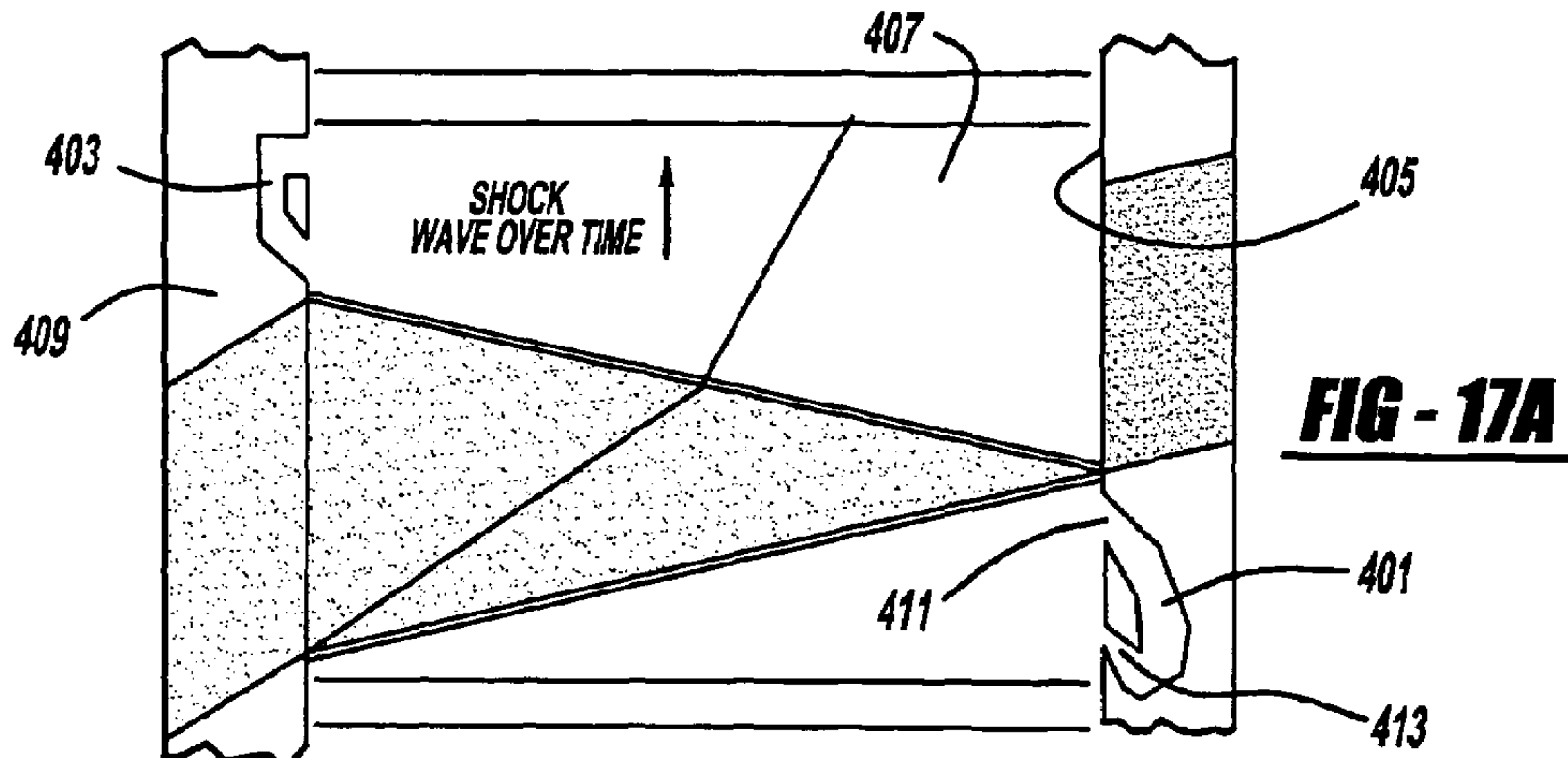
**FIG - 14b**  
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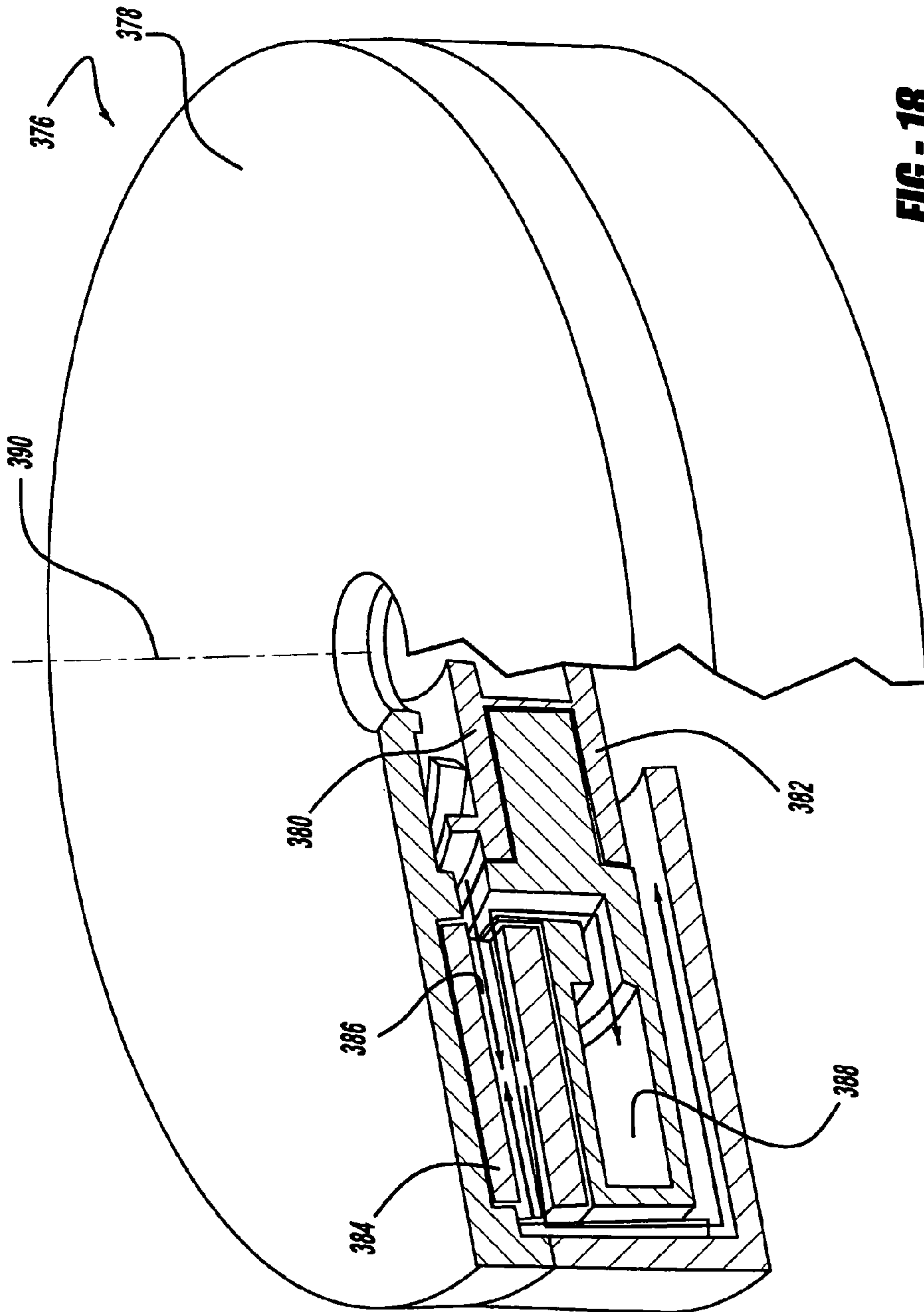


**FIG - 15**

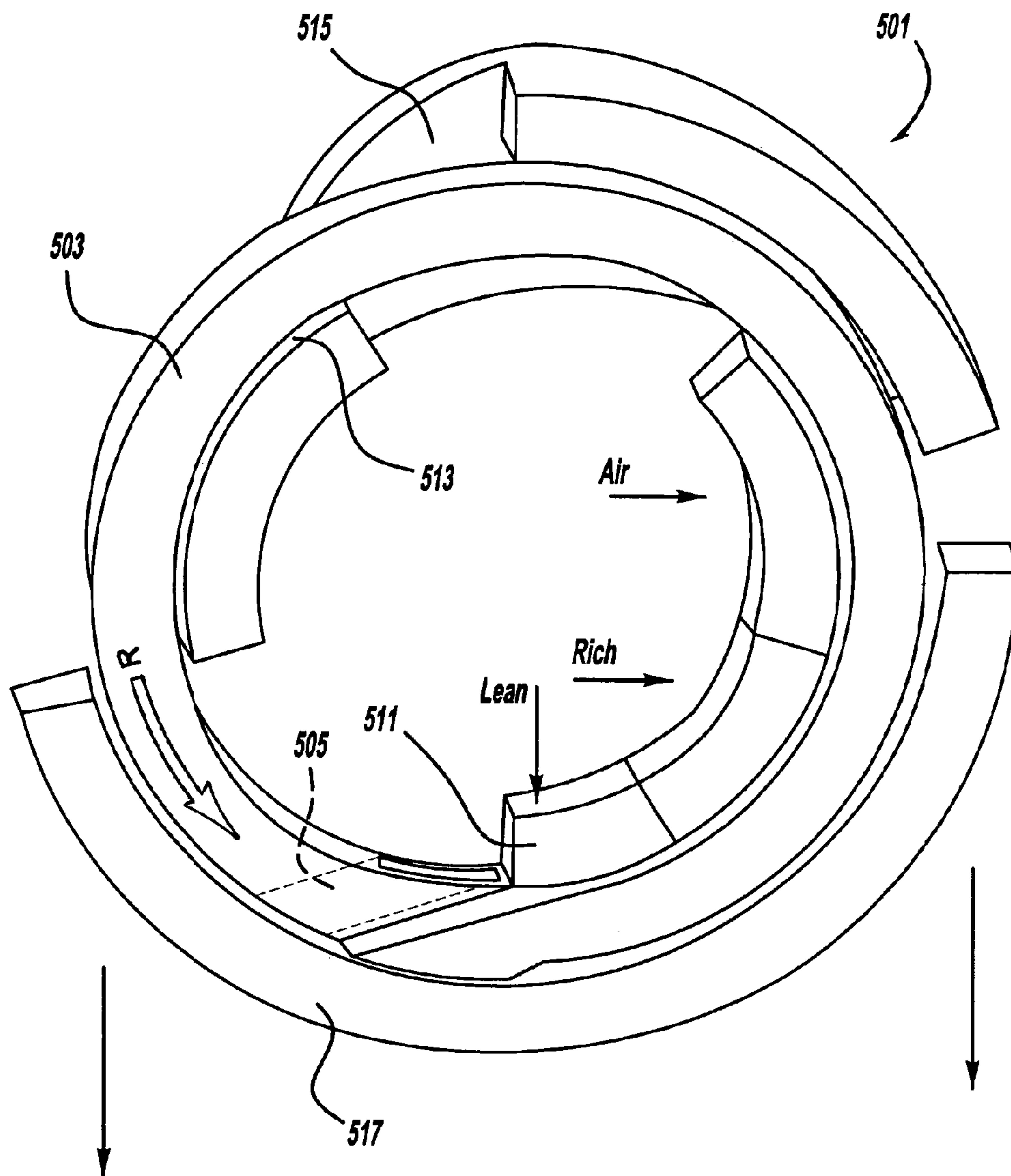




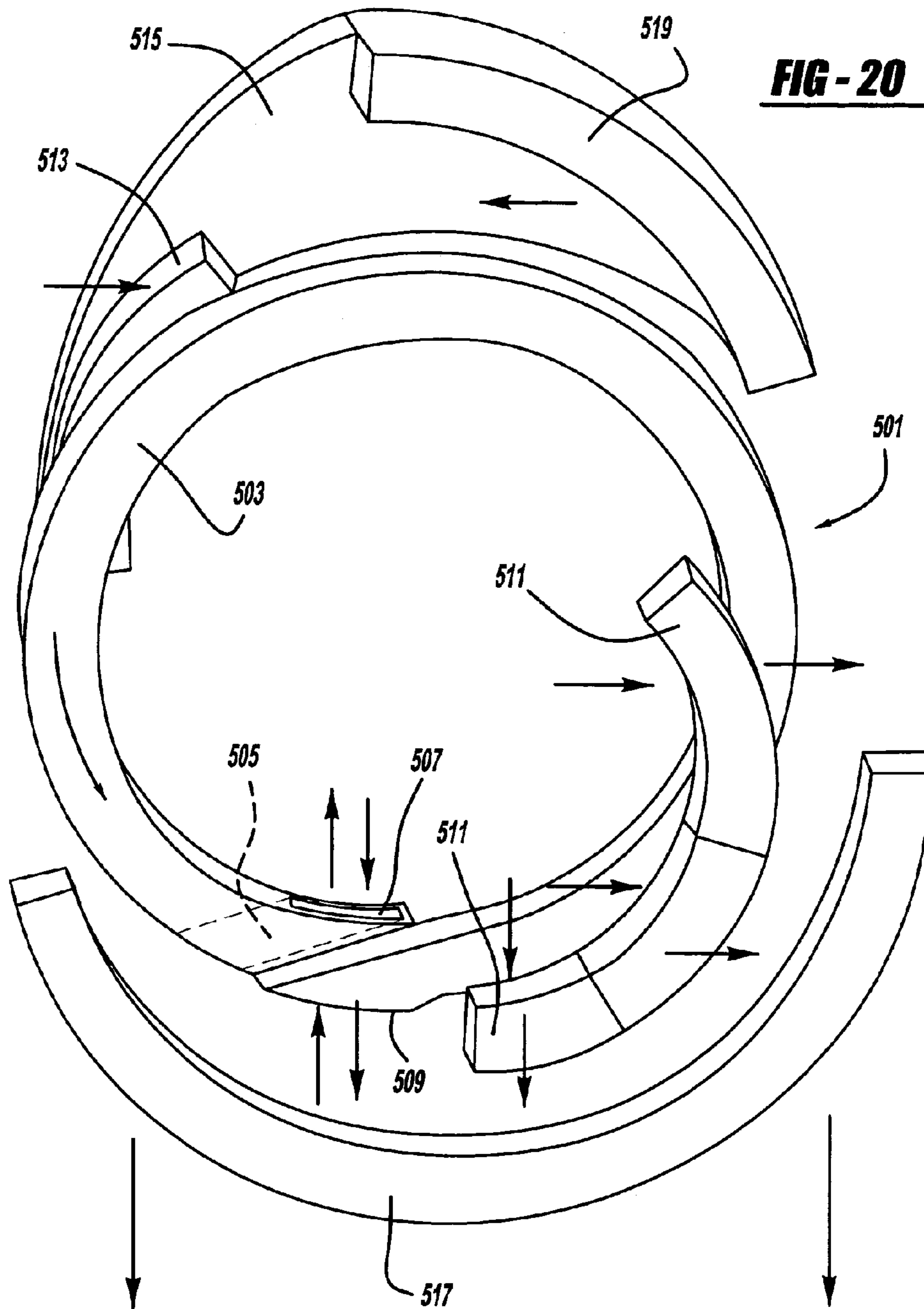


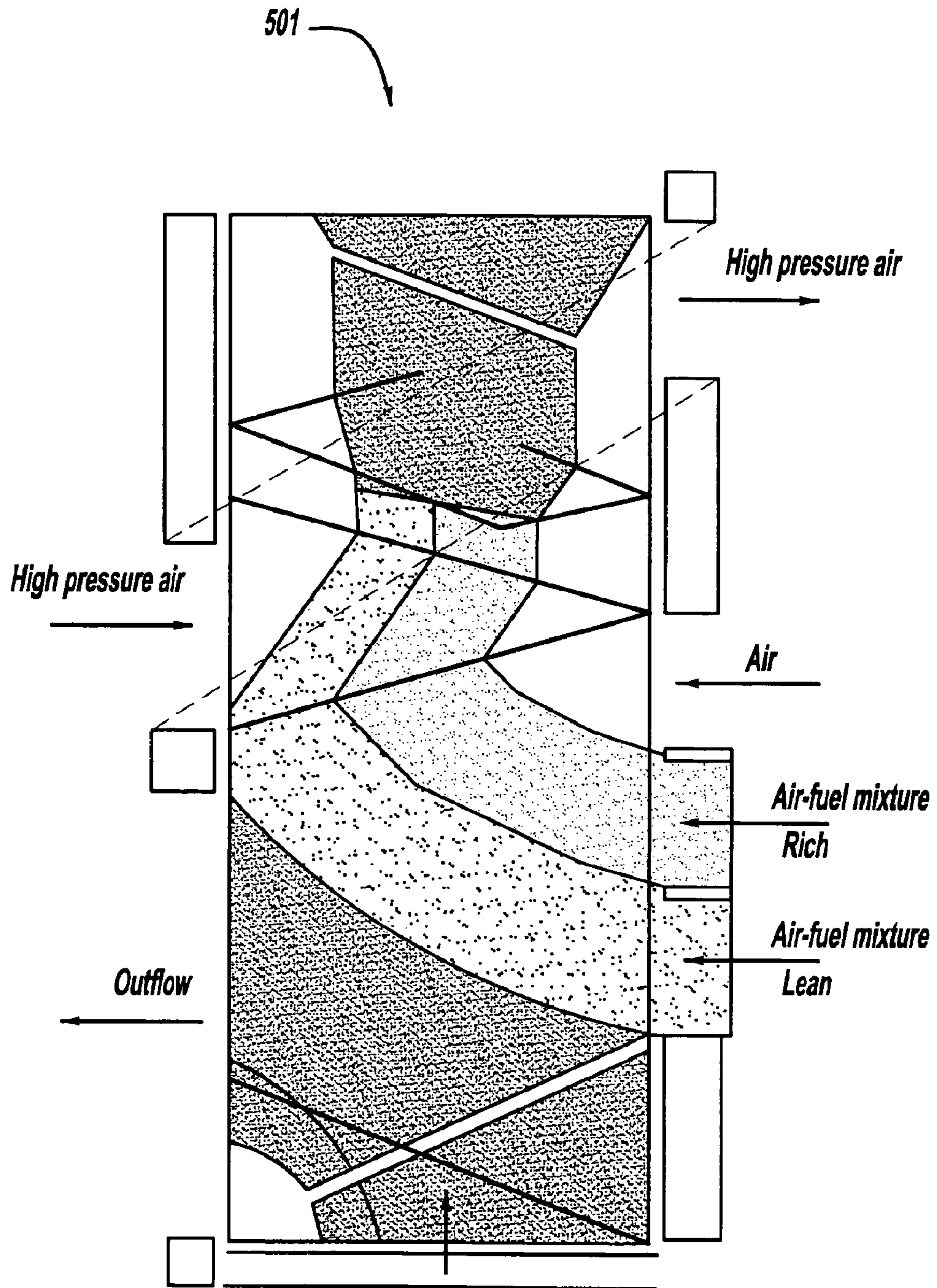




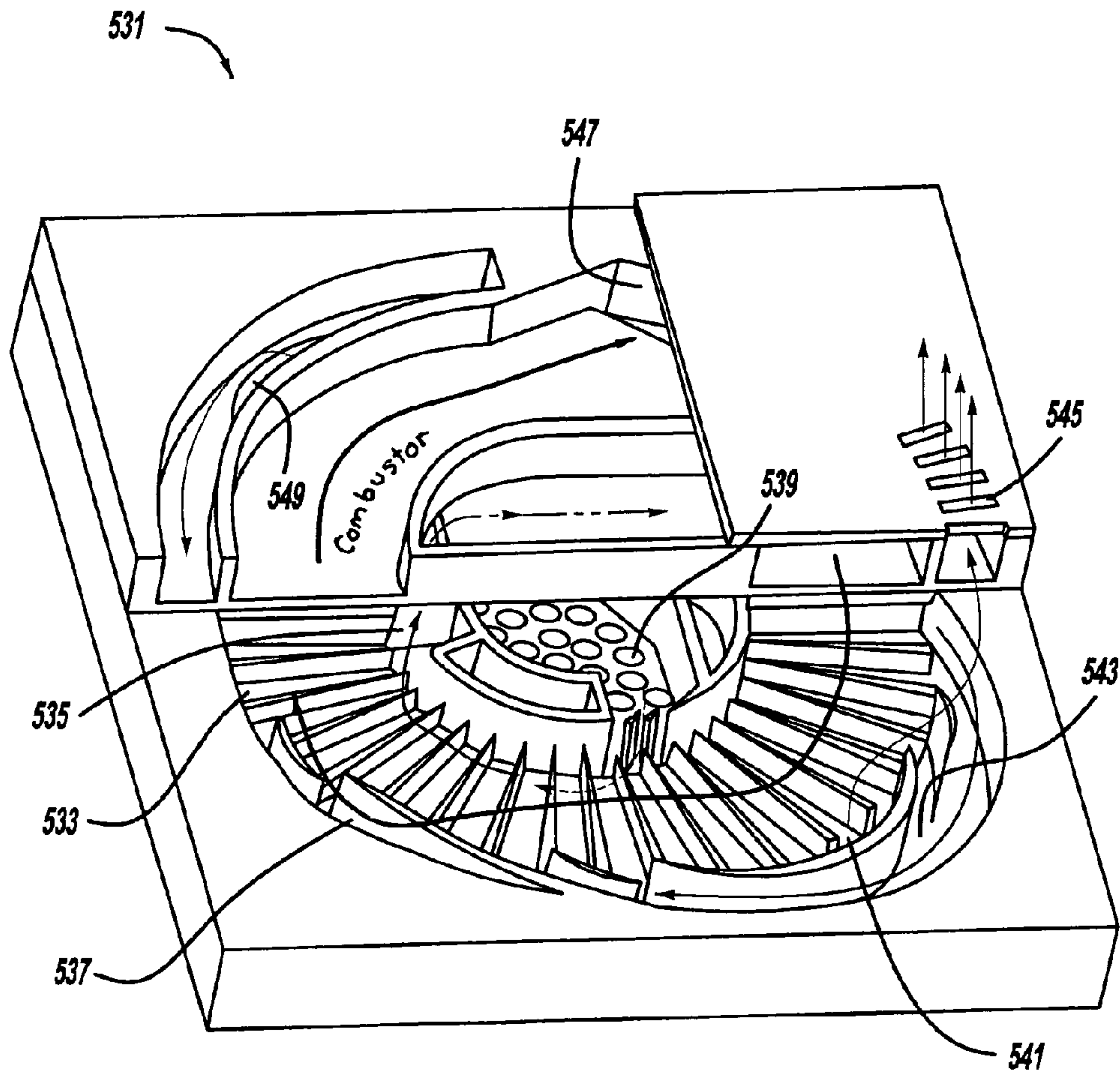


**FIG - 19**



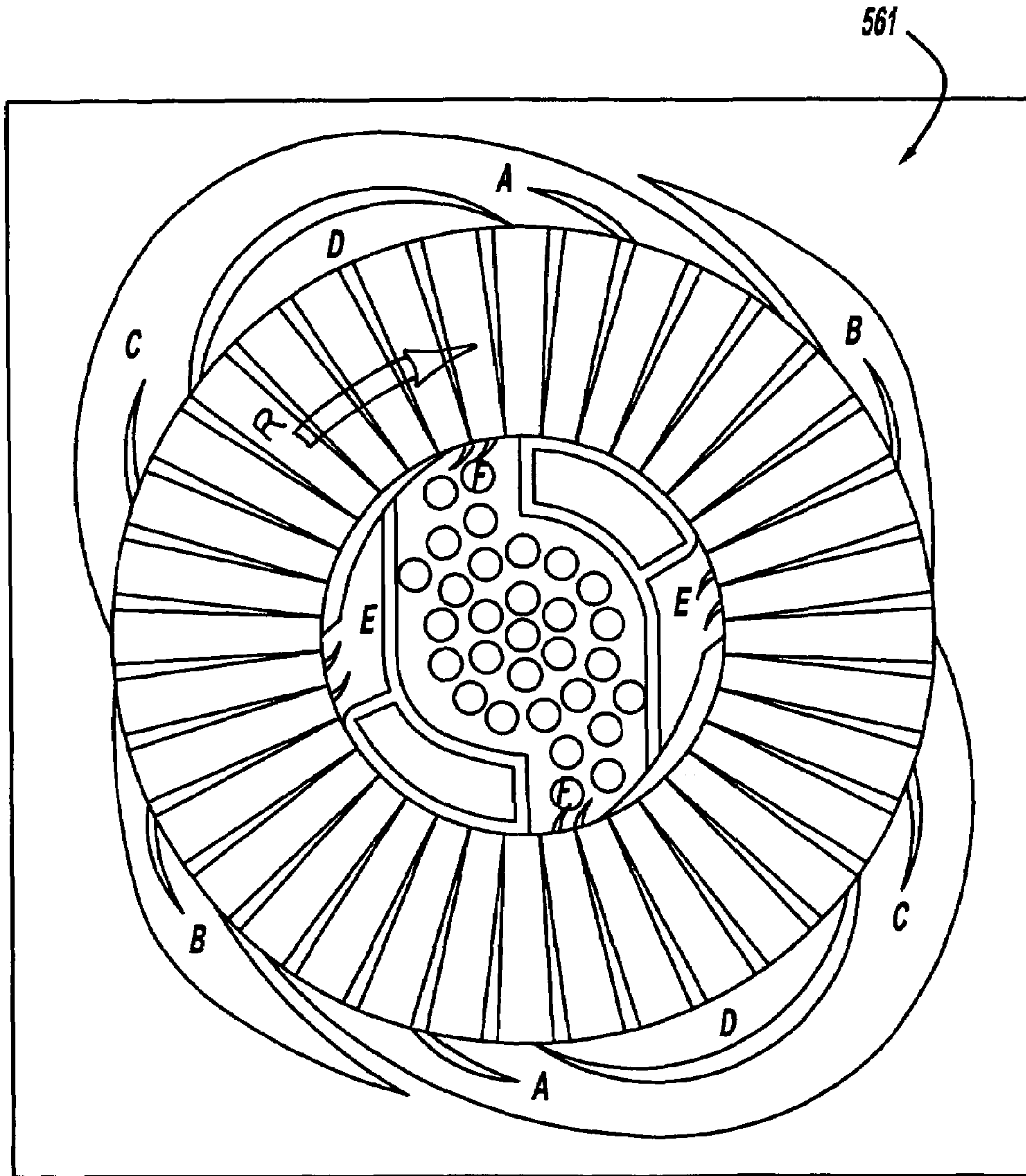


**FIG - 21**

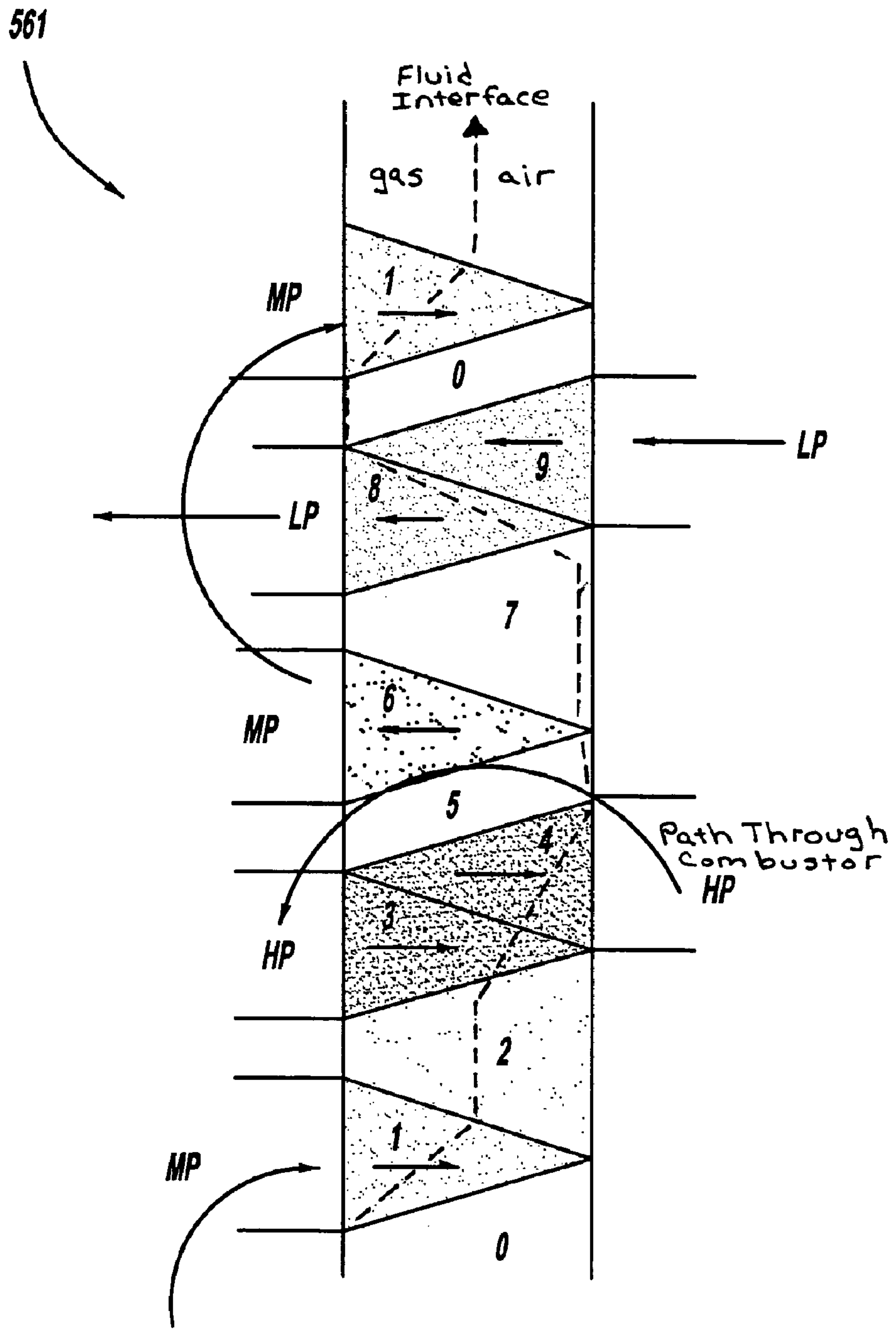


**FIG - 22**





**FIG - 23**



**FIG - 24**



## WAVE ROTOR APPARATUS

**Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.**

## CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional patent application Ser. No. 60/627,742, filed on Nov. 12, 2004, which is incorporated by reference herein.

## BACKGROUND OF THE INVENTION

The present invention relates generally to fluid power devices and more particularly to a wave rotor apparatus.

It is known to use an axial wave rotor as a supercharger in internal combustion engines for automotive vehicles. This conventional device is described in P. Akbari and N. Müller, "Gas Dynamic Design Analyses of Charging Zone for Reverse-Flow Pressure Wave Superchargers," ICES 2003-690, ASME (May 11-14, 2003). Wave rotors have also been proposed for use in propulsive jet engines and power turbines as disclosed in U.S. Pat. No. 6,584,764 entitled "Propulsion Module" which issued to Baker on Jul. 1, 2003; and U.S. Pat. No. 5,894,719 entitled "Method and Apparatus for Cold Gas Reinjection in Through-Flow and Reverse-Flow Wave Rotors" which issued to Nalim et al. on Apr. 20, 1999; both of which are incorporated by reference herein. Various attempts have also been made to cancel an expansion wave generated by a wave rotor. Such a configuration is taught in U.S. Pat. No. 5,267,432 entitled "System and Method for Cancelling Expansion Waves in a Wave Rotor" which issued to Paxson on Dec. 7, 1993, and is incorporated by reference herein. Traditional attempts to use depressions or pockets to control wave reflections of off-design operation undesirably, reduce the sensitivity of axial wave rotors to engine speed changes. Nevertheless, there still exists a need to improve the performance and reduce the size of traditional wave rotors to enhance their commercial viability or adapt a different geometry for more convenient implementation.

## SUMMARY OF THE INVENTION

In accordance with the present invention, a wave rotor apparatus is provided. In another aspect of the present invention, a radial wave rotor includes fluid passageways oriented in a direction offset from its rotational axis. A further aspect of the present invention employs stacked layers of generally radial channels in a wave rotor. Moreover, turbomachinery is located internal and/or external to a wave rotor in yet another aspect of the present invention. In another aspect of the present invention, a radial wave rotor has an igniter and fuel injector. Correctional passages are employed in still another aspect of the present invention wave rotor.

The radial wave rotor of the present invention is advantageous over conventional devices since the present invention should produce higher power densities, an improved efficiency, a smaller frontal area, and a smaller size compared to known axial wave rotors. The centrifugal forces of the fluid, created by the present invention, advantageously improve flow scavenging and compression. The offset or generally

radial passageways of the wave rotor of the present invention are also easier and less expensive to manufacture as compared to many traditional, axial wave rotors, especially if incorporated into a layered arrangement. The stacked configuration and/or shapes of channels employed in the present invention further provide advantageous variations in cycle timing.

Moreover, performance of the radial wave rotor of the present invention is simpler to model, predict and analyze in the design stage than traditional wave rotors. Placing turbomachinery in the presently disclosed locations also reduces undesirable pressure losses caused by conventional collectors and/or diffusers. Additionally, the correctional passageways of the present invention advantageously achieve directed and self-actuated aerodynamic control of the internal flow and shock wave pattern. Scavenging processes are also improved by the present invention's use of centrifugal forces. Additional advantages and features of the present invention will become apparent from the following description and appended claims, taken in conjunction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatic side view showing a first preferred embodiment of a wave rotor apparatus of the present invention;

FIG. 2 is an exploded, side elevational view showing the first preferred embodiment of the wave rotor apparatus;

FIG. 3 is a partially fragmented and diagrammatic, side elevational view, showing the first preferred embodiment of the wave rotor apparatus;

FIG. 4a is a partially fragmented side view, showing the first preferred embodiment of the wave rotor apparatus;

FIG. 4b is a partially fragmented side view showing variations to the wave rotor apparatus of FIG. 4a;

FIG. 5 is a perspective view showing a radial wave rotor employed in the first preferred embodiment of the wave rotor apparatus;

FIG. 6 is a partially fragmented, perspective view showing one and one-half layers of a radial wave rotor employed in a second preferred embodiment of the wave rotor apparatus;

FIG. 7 is a diagrammatic top view showing one layer of the radial wave rotor employed in the second preferred embodiment of the wave rotor apparatus;

FIG. 8 is a perspective view showing one layer of a radial wave rotor employed in a third preferred embodiment of the wave rotor apparatus;

FIG. 9 is a cross-sectional view showing an inlet and compressor assembly employed in the first preferred embodiment of the wave rotor apparatus;

FIG. 10 is a perspective view showing a turbine volute employed in the first preferred embodiment of the wave rotor apparatus;

FIG. 11 is a top elevational view showing the turbine volute employed in the first preferred embodiment wave rotor apparatus;

FIG. 12 is a side elevational view showing a radial wave rotor employed in a first alternate embodiment wave rotor apparatus;

FIGS. 13a and 13b are diagrammatic side views showing variations of a fourth preferred embodiment wave rotor apparatus;

FIGS. 14a and 14b are diagrammatic and perspective views showing variations of a second alternate embodiment wave rotor apparatus;



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FIG. 15 is a fragmented, diagrammatic and perspective view showing a quarter of a third alternate embodiment wave rotor apparatus;

FIG. 16 is a diagrammatic, fragmentary and top view showing a quarter of the third alternate embodiment wave rotor apparatus of FIG. 15;

FIGS. 17A-17C are a series of diagrams showing correctional passageways preferably employed in any wave rotor apparatuses;

FIG. 18 is a fragmentary perspective view showing a fourth preferred embodiment wave rotor apparatus employed with a microfabricated gas turbine;

FIG. 19 is a perspective view showing a fourth alternate embodiment wave rotor apparatus;

FIG. 20 is an exploded view showing the fourth alternate embodiment wave rotor apparatus;

FIG. 21 is a wave diagram showing expected operation of the fourth alternate embodiment wave rotor apparatus of FIGS. 19 and 20;

FIG. 22 is a fragmentary, perspective view showing a fifth alternate embodiment wave rotor apparatus, in a two step compression wave engine variation;

FIG. 23 is a diagrammatic top view showing the fifth alternate embodiment wave rotor apparatus; and

FIG. 24 is a wave diagram showing expected operation of the fifth alternate embodiment wave rotor apparatus of FIGS. 22 and 23.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A wave rotor is a machine in which a fluid is pressurized by generally unsteady shock or compression waves and expanded by expansion waves. As a general principle for wave rotors used in a gas turbine engines, a wave rotor provides a pressure gain additional to that provided by a compressor. It also enables higher combustion end temperatures without raising a turbine inlet temperature since a portion of the energy of the burning gas exiting a combustion chamber is used in the shock compression to increase the pressure and temperature of the fresh air before it enters the combustion chamber. Accordingly, the pre-expanded burned gas is scavenged toward a turbine and channels of the wave rotor are reconnected to the compressor outlet, allowing fresh, pre-compressed air to flow into the wave rotor channels. Thus, wave rotors utilize a high-pressure fluid to transfer its energy directly to a low-pressure fluid when two fluids with different thermodynamic properties are brought into direct contact for a very short time, wherein pressure exchange occurs faster than mixing.

A first preferred embodiment of a wave rotor apparatus 21 is shown in FIGS. 1-5 and 9-11. More specifically, FIGS. 1-3 illustrate wave rotor apparatus 21 including a compressor inlet port 23, a radial impeller or compressor 25, an internal end plate 27, an external end plate 29, a radial wave rotor 31, a turbine volute 33, a turbine exit port 37, a driving shaft 39, a housing 41, an inlet duct 43 and an outlet duct 45. Radial wave rotor 31 is preferably made from multiple, annularly shaped discs or layers 51 which each have multiple channels or passageways radially extending outward from a rotational rotor centerline axis 531 toward a peripheral surface. Channels 53 are created, for example, by simple welding, soldering, gluing channel walls on discs, a milling machine, an electrical discharge machine, chemical etching or the like in a metal or ceramic material. Four such layers 51a, 51b, 51c and 51d are disclosed, however, greater or fewer layers can be employed. The layers are stacked upon each other in a coaxial

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manner after machining and can be permanently fixed together through electric current welding, structural adhesives, bolts or the like. Alternatively discs with channels can be manufactured altogether in one manufacturing process like casting. Each channel 53 of the first preferred embodiment has a straight configuration in an elongated radial direction and a constant rectangular cross-sectional area from its inlet, closest to rotor axis 531, to its peripheral outlet. Furthermore, the channels of each layer can be circumferentially offset from the adjacent layers thereby forming a diagonal or oblique configuration to allow for different timing of fluid entry and exiting of the channels. The stacked layer construction provides a modular wave rotor that can have one or more easily interchanged layers for different mass flow rates. The subdivision of channels further advantageously allows for acoustic noise reduction. The internal surface and periphery of the stacked layers of wave rotor 31 have partially spherical shapes to improve fluid flow characteristics from compressor 25 and through the ported end plates, reducing losses otherwise appearing in ducting and collectors.

FIGS. 6 and 7 illustrate a second preferred embodiment of a radial wave rotor 61 wherein multiple channels 63 in each of exemplary layers 65a and 65b have a curved configuration between each inlet 67 and outlet 69. In the embodiment shown, the cross-sectional area between inlet 67 and outlet 69 also varies with the curve radius being more severe adjacent to the inlet and gradually expanding adjacent the outlet. Solid partition portions 71 are transversely disposed between each set of channels 63, much like that illustrated in FIG. 5. Layer-by-layer manufacturing is ideally suited for the curved channel configuration, allowing non-die locked or free from undercut access to all of the channels within a single layer at the same time as viewed in Figure curved or otherwise angled configuration is ideally suited for a "free-running" wave rotor where the impulse of entering or exiting fluid or the change of angular momentum of the internal flow self-drives the rotation of the wave rotor. The curved flow path of channels 63 of the second preferred embodiment advantageously provides a longer flow path given the same rotor diameter and packaging size thereby modulating the effect of radial forces on the flow to improve scavenging and acceleration/deceleration of the flowing fluid. This also advantageously allows for tuning of the design by changing shapes and flow lengths also in each layer differently, without affecting packaging size, thus changing wave travel timing. With the curved channels, angles can be easily varied in the design stage which will modulate the flow direction and acting accelerating/decelerating centrifugal force while also allowing the inlet and outlet angles to be independently varied.

Referring to FIG. 8, a third preferred embodiment of a radial wave rotor 81 employs multiple straight channels 83 with each having its square cross-sectional area completely bordered by an upper wall section 85, a lower wall section 87, a left wall section 89 and a right wall section 91 (in the orientation shown). This embodiment enhances structural rigidity of each layer and employs completely circular-cylindrical internal and external surfaces, respectively 93 and 95, thereby reduced manufacturing costs and modularized interchangeability of the multiple layers (only one of which is shown) when assembled. The geometric complexity and manufacturing costs of the associated end plates are also reduced. If applied with a gas turbine, the high pressure air ("HPA") and high pressure burned gas ("HPG") flow to and from combustor (burner) and the low pressure fresh air ("LPA") from the compressor to wave rotor 81, and the low pressure mixed gas ("LPG") to the turbine, are also schematically illustrated.



It should alternately be appreciated that multiple layers of channels can be created within a single piece, radial wave rotor which does not require subsequent layer assembly; such an arrangement is shown in FIG. 12. This single piece, radial wave rotor **101** is constructed to have multiple sets of fluid carrying channels **103** with each having a diamond-shape in cross-section, relative to rotational rotor axis **531**. The diagonal or oblique offset of adjacent channel openings can be observed between different rows or layers. The diamond-shape allows for more abrupt opening and closing as full channel inlet and outlet-to-end plate porting alignment is achieved during operation, especially given the preferred end plate ports disclosed hereinafter. It should also be appreciated that other channel shapes can be used and that small fillets or radii can be employed in the cross-sectional corners without significantly departing from the desired square, rectangular or diamond shapes disclosed herein.

With reference now to FIGS. 2-4a and 9, internal end plate **27** is located within a central and internal hollow cavity **111** of radial wave rotor **31**. Internal end plate **27** has a diagonally elongated port **113** which selectively and periodically aligns with opposite diagonal groups of wave rotor channels **53** when wave rotor **31** is rotated relative to the stationary internal end plate **27**. Similarly, external end plate **29** has a diagonally elongated port **115**, preferably oriented opposite to internal end plate port **113**. External end plate **29** is stationary positioned in matching registry and shape with the circumferential peripheral surface of wave rotor **31** such that, for example, diagonal groupings of outlets of wave rotor channels **53** are selectively and periodically aligned with port **115** when wave rotor **31** is operably rotated. It should be appreciated that alternate end plate shapes and orientations can be employed depending upon the wave rotor peripheral shape, channel shapes, channel spacings and flow patterns desired for different applications. End plates **27** and **29** are secured to housing **41** (see FIG. 1) or ducts by mounting brackets, welding or the like. Furthermore, bearings, seals and/or lubricants may be desired between various rotating components and members, and the adjacent stationary components, depending upon the applications within which the present invention is employed.

Compressor **25** is a rotating turbomachinery component that can be positioned inside of internal end plate **27** and cavity **111** of radial wave rotor **31**. Compressor **25** includes a base (disc) **121**, a plurality of curved, fluid-impinging vanes **123** and a central hub **125**. A rotational compressor axis **127** coaxially extends through hub **125** and vanes **123**. Compressor axis **127** is angularly offset from axis **53** of radial wave rotor **31** by an angle  $\alpha$  of between about 10-80 degrees, and more preferably by about 25 degrees. The majority of compressor inlet port **23** is also stationary disposed within internal end plate **27** and wave rotor cavity **111**. Compressor **25** is allowed to rotate independently of radial wave rotor **31** at least when no fluid is flowing and in certain potential operating conditions. When fluid is flowing, compressor **25** rotates in generally the same direction as radial wave rotor **31**, however, the angles and curves of vanes **123** of compressor **25** can be varied and/or inlet and channel angles of radial wave rotor **31** can be varied to cause opposite and/or the same rotational direction between the compressor and radial wave rotor. It should be appreciated that alternate turbomachinery members, such as turbines or the like, may be rotationally provided within an internal cavity, whether central or not, of wave rotor **31**. The angularly offset axes **53** and **127** between compressor **25** and wave rotor **31** create a continuous interface flow at the inner and outer periphery of external turbomachinery shown in FIG. 4b and the internal turbomachinery shown in FIG. 4a.

In the shown configuration, the stack of wave rotor layers **51**, also called wave disks, advantageously allows continuous outflow of fluid from the turbocompressor without need of any collecting devices that would otherwise generate unnecessary losses like pressure loss due to wall friction.

As best observed in FIGS. 1-3, 10 and 11, turbine **35** is rotatably located within a turbine volute **33**. Turbine volute **33** is stationary mounted to housing **41** and is in fluid communication with port **115** of external end plate **29** through volute openings **161** and **163** and intermediate ducts. Turbomachinery-turbine **35** can rotatably spin within volute **33** and be mechanically coupled to compressor **25** in a direct manner by way of drive shaft **39** or, alternately, through other gearing or belt arrangements which may be coaxial or offset or electrically by a generator motor arrangement (see FIG. 4b). Turbine exit port **37** is mounted to volute **33** adjacent and coaxial with turbine **35**. Shown turbine **35** has a generally flat base **171**, curved vanes **173** projecting from base **171**, and a central hub **175** aligned with drive shaft **39**. However, an axial turbine could be additionally employed with or without a volute.

Wave rotor apparatus **21**, as disclosed with the first preferred embodiment, shows the use of a radial wave rotor as a topping component for a gas turbine and is intended for use within an aircraft, jet engine, a stationary, electricity-producing power plant or for propelling other vehicles like land or water vehicles. With slight modification, the radial wave rotor apparatus of the present invention can also be used as a supercharger within an internal combustion engine, such as that employed in an automotive land vehicle, as a pressure exchanger in air or other gas refrigeration cycles, or as a condensing wave rotor, for example, in a water based refrigeration system. One such exemplary water refrigeration system is disclosed in U.S. Pat. No. 6,427,453 entitled "Vapor-Compression Evaporative Air Conditioning Systems and Components" which issued to Holtzapfel et al. on Aug. 6, 2002, and is incorporated by reference herein. Another is disclosed in Akbari, P., Kharazi, A., Müller, N., "Utilizing Wave Rotor Technology to Enhance the Turbo Compression in Power and Refrigeration Cycles," 2003 International Mechanical Engineering Conference, ASME Paper IMECE 2003-44222 (2003). Radial wave rotor **31** offers great potential and advantages for a condensing wave rotor in a vapor (phase change) refrigeration system, since it exploits the enormous density differences of gaseous and liquid fluid by the action of centrifugal forces. This greatly supports the separation of vapor and condensed fluid in the scavenging process and channel drying before refilling, which addresses a concern in handling of phase changes occurring in both directions in conventional, axial wave rotors.

FIG. 4b illustrates a first configuration employing an externally located motor or generator **164** coupled to either a turbine or compressor **25** by a coaxially aligned shaft **166**. A second configuration uses a flat and disc-like shaped generator or motor **168** coupled to compressor **25** and positioned within internal end plate **27** in an offset angular manner. Motor **168** is preferably of a permanent magnet type due to its simplicity and higher efficiency, and includes magnets that rotate with the compressor via a shaft, geared or direct coupling, and stationary electrical coils. Alternately, motor **168** may be of an induction type, and this internal cavity arrangement can alternately be employed in an axial wave rotor although some radial wave rotor advantages will not be realized. A third configuration provides a motor or generator integrated into the compressor's hub **125**. A fourth configuration locates a turbine **170** in a direct and generally radial flow path with the outlet ports of external end plate **29**, defined by a housing **172** and a volute **174**. A motor or



generator 176 is driven by turbine 170 and is attached to housing 172 in an annular manner surrounding radial wave rotor 31.

Further, a fourth preferred radial wave rotor embodiment is shown in FIG. 18 for use in conjunction with a microfabricated gas turbine like that disclosed in U.S. Pat. No. 5,932,940 which issued to Epstein, et al. on Aug. 3, 1999; and U.S. Pat. No. 6,392,313 which issued to Epstein, et al. on May 21, 2002; both of which are incorporated by reference herein. The radial wave rotor allows for incorporation of the wave rotor in the disc or wafer-based assembly without introducing additional flow bends (which would cause additional losses) like a conventional axial wave rotor would require. A MEMS micromachine engine 376 includes a housing 378, compressor 380 and turbine 382 of very small size; for example, the housing has an outer diameter less than 100 millimeters and more desirably about 12 millimeters, with a thickness of about 3 millimeters. Compressor 380 is located within an internal cavity of a radial wave rotor 354, which has radially elongated channels 386. A combustion chamber 388 is stationarily affixed to housing 378 while compressor 380, wave rotor 384 and turbine 382 are allowed to rotate about axis 390. In such a small scale, efficiency of compressor 380 and turbine 382 are traditionally very low. Also, the compression ratio is low for one step compression in traditional devices. Use of radial wave rotor 384, however, increases the total compression ratio. It is expected that the radial wave rotor advantageously rotates less than about 100 rpm while the turbine and compressor rotate at speeds reaching one million rpm, in the reverse-flow configuration shown.

The first preferred embodiment wave rotor apparatus 31 operates as follows. Fresh air enters air intake 43 and flows to compressor inlet port 23. Rotation of turbine 35 mechanically causes compressor 25 to also rotate, which, in turn, forces the intake air into the radial wave rotor channels 53 when they are aligned with port 113 of internal end plate 27. Expanded and burned gases exiting outlet duct 45 may go through supplemental conduits or ducts, or a jet nozzle (not shown). The air inserted from compressor 25 to wave rotor channels 53 is preferably of a non-supersonic flow and will generate unsteady shock waves inside channels 53 due to pressure differences between the compressor outlet and the temporarily lower pressure in channels 53. The centrifugal force additionally supports the flow in channel 53. The radial action of wave rotor 31 improves scavenging and acceleration of fluid within each channel. The fluid flowing action from compressor 25 and through wave rotor channels 53 can also serve to rotate radial wave rotor 31, after which, the burned gases exit the channels aligned with port 115 of external end plate 29. The radial wave rotor alternately may be driven by a gear and/or electrical motor. In the case of a fluid driven wave rotor, the wave rotor may extract even more energy from the fluid and drive an additional generator connected to it or integrated in it and the housing. The periodical exposure of the channels to the port openings in the end plates initiates compression and expansion waves that move through the wave rotor channels and internally generate an unsteady flow in the wave rotor. Thus, pressure is exchanged dynamically between high pressure and low pressure fluid utilizing unsteady pressure waves such that both compression and expansion are accomplished in the single component, being the wave rotor. In the preferred embodiment, combustion takes place (as shown in FIGS. 14-15) within the channels in the form of deflagration or even detonation, generating the major shock wave while further compressing the fluid before it exits toward the turbine and generates an expansion wave that draws in fresh pre-compressed air from the compressor.

The exiting pre-expanded gases flow to volute 33 and impinge upon vanes 173 of turbine 35, thereby forcing the turbine to rotate. The expanded gases are subsequently exhausted and exit from turbine exit port 37 and outlet duct 45 to atmosphere. The channel wall temperature of the wave rotor is maintained between the temperature of both fluids through the periodic exposure of the channels to both fluids between which the pressure is exchanged, thereby providing a self-cooling feature.

FIG. 13a discloses a first configuration of a fourth preferred embodiment wave rotor apparatus 201 having a radial wave rotor 231, compressor 225, internal and external end plates (not shown) and turbine 235, like that of the first preferred embodiment. Flow collectors 203 and 205 (both showing cut contours of preferably one rotational body that ducts the flow), however, are employed to direct the exiting burned and pre-expanded gas flow from wave rotor 231 and the external end plate port to turbine 235 and a turbine exit port 237. Turbine 235 is mechanically coupled in an indirect manner, through multiple shafts, gears or belts, to compressor 224. FIG. 13b shows another configuration with a direct shaft coupling, where an optional generator is mounted on the shaft.

Another alternate embodiment wave rotor apparatus 251 is illustrated in FIGS. 14a and 14b. In the exemplary embodiment of FIG. 14a, a compressor 253 is mechanically coupled to a turbine 255 by way of a drive shaft 257 or the like. Compressor 253 is located external of radial wave rotor such that flow collector conduits (not shown) are required to flow the fluid from compressor vanes 261 through entry end plate ports, through elongated channels 263 of wave rotor 259, out additional end plate ports and to vanes 265 of turbine 255. Whereas FIG. 14a shows an internal combustion wave rotor configuration, FIG. 14b shows a radial wave rotor configuration with an external combustor. While a through-flow configuration is shown, reverse-flow configurations are possible as well. One or multiple cycles can be realized per revolution with either flow pattern or configuration.

FIGS. 15 and 16 show more details of the internal combustion configurations of FIGS. 1, 2, 4a, 4b, 13a, 13b, 14a and 14b, where the wave rotor apparatus 301 serves as an internal combustion engine employing direct, radial wave rotor flow. Such a configuration can work in conjunction with turbomachinery (see FIGS. 1, 2, 4a, 4b, 13a, 13b, 14a and 14b) or alone, where the exhaust gases may be directed and utilized for jet propulsion and/or work may be extracted by momentum change of the generated radial flow, driving a shaft or generating electricity in a generator. More specifically, a radial wave rotor 303 has multiple layers 305a, 305b, 305c and 305d with each having radially elongated fluid flow passageways or channels 306. Layers 305 and channels 307 are manufactured, stacked and joined much like that explained in the first preferred embodiment, and may have a greater or lesser number of layers and channels than that shown, depending upon the actual usage situation. Each channel has an inlet opening 309, a curved and angularly offset flow path, of varying cross sectional area, and an outlet opening 311. Alternately, straight or other shaped channels can be provided, the cross-sectional area may also be constant and/or the cross-sectional shape may change. Wave rotor 303 operably rotates about a central rotor axis 309 and a stationary base platform 311.

An igniter or spark plug 313 is affixed to platform 311 and is selectively aligned with fire channel apertures 315 in each layer 305 having access to each channel 307. A fuel line 317, having a fuel injector 319 aligned with each layer 305, is stationarily mounted within a central, internal cavity 321 of



radial wave rotor **303**. An internal end plate **323** has one or more ports aligned with fuel injectors **319**. Air inlets **325** allow fresh air from ambient or pre-compressed air from a compressor (such as that of FIG. **9** or **14**) through internal end plate ports and into channels **307**, when the channels are appropriately aligned with the internal end plate ports. In addition to or instead of the fresh air inlets, a premixed fuel can be alternately employed. In operation, the fuel can be sprayed into the aligned channels **307** from injectors **319**, mixing therein with the entering fresh/pre-compressed air, and is then centrifugally compressed in the channels. This mixture is combusted through flame ignition by igniter **313** and fire channel apertures **315**. The process of burning fuel significantly increases pressure inside channel **307**. Then the burned gases can expand to exit through outlet openings **311** when aligned with ports in an external end plate **331**. The exiting gases are then directed to a turbine (such as that of FIG. **3** or **14a**) or a jet nozzle. It is possible to radially stratify the air and fuel mixture during the channel-filling process. For example, after closing channel **307** from both sides, each fuel and air mixture is trapped in the middle of the channel and ignites, while at the channel ends, a lean mixture of air is present. This keeps the channel ends cool, provides sealing and minimizes undesirable mixture leakage. In other words, the combustion process starts in the central part of the channel, where the fuel and air mixture is rich, and the flame propagates to inner and outer ends of the cell. Since heat release increases pressure inside the channel, opening the outer channel end generates an outflow of the exhaust gases. For curved channels **307**, torque is given to the disc or wave rotor **303** during the flow scavenging. This can be used for self-driven rotation or, if large enough, for external work extraction through a shaft or a generator. The outflow of the burned gases can induce an inflow of air and air-fuel mixture into channels **307**, refilling and cooling the channels before the cycle starts again. As mentioned before, this cycle also can be self-aspirating without need for external turbomachinery if the combustion is in a pulse detonation mode. This way the internal combustion, radial wave rotor **303** is also considered as an attractive propulsion system and may be used as a simple jet engine even without expensive turbomachinery. Such a jet engine propulsion device would have small and, most importantly, a flat front area.

It is alternately envisioned that fire channel apertures **315** can be either circular holes or elongated slots. Additionally, it is alternately envisioned that fuel injectors can be selectively turned off and on so that only a limited number of the multiple layers of channel sets have fuel injected therein, thereby improving fuel efficiency within the wave rotor portion of the internal combustion engine in certain vehicle operational modes, such as in an idle condition. In another alternate arrangement, rotating electrical igniters, activated only in a certain angular position of the mixture-filled channel or a fixed laser beam igniter, can be substituted for fixed igniter **313** and apertures **315**.

Correctional passages **401** and **403** can be provided in any of the previously disclosed embodiment wave rotor apparatuses or even in any axial wave rotor although some of the advantages of the present invention may not be achieved. This modification is shown in FIGS. **17a-17c**. Correctional passages **401** and **403** are created in side wall surfaces **405** defining each radial channel of a radial wave rotor **409** of any of the preceding embodiments. Alternately, correctional passages **401** and **403** can be employed in even conventional, axial wave rotors although some of the advantages of the present invention may be not realized. Each channel has an inlet opening **411** and an outlet opening **413** with an elongated

and generally enclosed intermediate section extending therebetween. The inlet and outlet openings somewhat face the same direction within the channel although the portion of each passage immediately adjacent to inlet **411** may have a different elongated flow angle than the portion of each passage immediately adjacent to outlet opening **413**. More specifically, in a preferred construction, outlet opening wall angles preferably have an internal wall angle of about 45 degrees and an external wall angle of about 20 degrees (as measured from surface **405** while the inlet internal wall angle is about 25 degrees and the inlet external wall angle is about 50 degrees, for correctional passage **401**. The angles of correctional passage **401** act to accelerate the rotor cell walls as they pass. This is in contrast to correctional passage **403**, which serves to break or decelerate the rotor cell walls as they pass the inlet, that has inlet wall angles substantially perpendicular to the adjacent portion of surface **405** while its outlet wall angles are between about 30 and 50 degrees.

The correctional passages correct the rotational speed of disk or rotor to obtain or maintain the proper position of the compression waves. In contrast to the traditional correctional pockets or open, depressions in conventional, axial wave rotors, the correctional passages of the present invention advantageously only have a noticeable effect on fluid flow if the primary and secondary compression waves hitting the end plate are not in their properly desired positions. The arrival location of the primary wave depends on the rotational speed of the wave rotor. In the tuned case, it should be at the leading edge of the compressed air port. A passage having an inlet just before the leading edge of the compressed fluid outlet port, and with an exit or outlet opening in the rotational direction, should have the primary shock wave reach the inlet opening if the rotational speed is too low. The pressure ratio across the shock wave will then induce a jet of redirected fluid to exit the outlet opening of correctional passage **401** and the rotational direction and to thereby accelerate the wave rotor with the momentum of the jet. This is shown in the operational condition of FIG. **17B**. FIG. **17C** illustrates deceleration caused by correctional passage **403**. In the situation of a reverse flow wave rotor, the secondary shock wave arriving at the opposite end plate at the trailing edge of the high pressure inlet port, enters inlet opening **411** and a jet of redirected fluid as projected from outlet opening **413** to slow down or decelerate the wave rotor. The shock wave position for an optimal rotational speed of wave rotor is shown in FIG. **17A**.

More specifically, FIG. **17A** shows aerodynamic control of the rotational speed of radial wave rotor **409**. Its purpose is to adapt the rotational speed to maintain a preferred wave pattern, however, it operates passively without any external control. However, the correcting channels also may be actuated by an active control to better maintain, alter or obtain a desired wave pattern. Special passages **401** and **403** are provided with outlet nozzles directed in and against the rotational direction to accelerate or decelerate wave rotor **409**, respectively. These passages can be arranged closely beside the tuned location where a compression wave is supposed to meet the end plate. If the wave pattern becomes off-tune, the location at which the compression wave reaches the end plate moves between the inlet and the outlet of such a passage. This results in a pressure difference between the passage inlet and outlet and generates a jet that can accelerate or decelerate the wave rotor. If the passage, such as **403**, is placed in the rotational direction after the location where the shock wave is designed to hit the end plate, its outlet is directed against the rotational direction and the jet will decelerate the rotor, retuning the compression wave to the design location. If the passage, such as **401** is placed before the design arrival location



of a compression wave and its outlet is directed in the rotational direction, it serves to retune the wave rotor by accelerating it. For proper passive control, at least one accelerating passage **401** and at least one decelerating passage **403** are needed.

FIG. **17B** shows a reverse-flow wave rotor in which the arrival of the primary wave is too early. A passage with an inlet located just before the leading edge of the compressed fluid outlet port and an exit in the rotational direction, will have the primary shock wave hit between both in the case of too low of a rotational speed. The pressure ratio across the shock wave will then induce a jet coming out of passage **401** to exit in the rotational direction and accelerate the wave rotor with its momentum. For deceleration, the same principle is applied in FIG. **17C** using a secondary shock wave that should arrive at the opposite end plate at the trailing edge of the high pressure inlet port. The outlet of passage **403** is directed against the rotational direction. This principle is envisioned more for speed control rather than for a primary drive of the radial wave rotor.

A fourth alternate embodiment wave rotor apparatus **501** is of a first variation shown in FIGS. **19-21**. Apparatus **501** includes a rotating torque ring **503**, which acts as a wave rotor disc, rotating in the direction of arrow R, and is the main part of a detonation engine. Wave rotor ring **503** is either directly attached to an output shaft or acts as a rotor in a generator. Ring **503** includes oblique and outwardly radiating (preferably in a changing curved pattern) cuts or fluid channels **505**, and two openings, a first opening **507** on an inner side and end, and a second opening **509** on an outer side and end of ring **503**. A group of air and air-fuel mixture inlets allow selective access between a stationary port assembly **511** and inside openings of ring **503**. An inlet **513** with an internal end plate for a stationary, high pressure passage **515** is selectively in communication with openings in an inner section of ring **503**. An outlet port through a stationary end plate **517** receives exhaust gases from ring **503**. A portion **519** of the high pressure passage outlet is also located adjacent an outer section of ring **503**. Two air-fuel mixture inlets are employed. The first one is for a lean air-fuel mixture and the second one is for a rich air-fuel mixture. The stratified air-fuel layers are pre-compressed by the compressed air or air-exhaust gas mixture temporarily stored in the high pressure air passage. Ignition of the rich air-fuel mixture is realized near the center part of the cut ring length, such that a shorter time period can be realized, in which the compression wave reaches both ends of the ring. The compressed air, from the ring side where the air inlet is located, is used on the opposite side in order to move the air without internal loops. This embodiment is especially desirable at small sizes, for example with a wave disc outer diameter less than or equal to about ten centimeters, where conventional turbomachinery is inefficient.

A fifth alternate embodiment wave rotor apparatus **531/561** is illustrated as a wave disc micro-engine in FIGS. **22-24**. A wave disc **533** plays the multifunctional role of an active compression-decompression unit, and an electricity and torque generator. Appropriate port geometry, with oblique blades forming the disc channels, generates torque. Apparatus **531** further includes a compressed air port **535**, a high pressure and high temperature port **537**, a fresh air inlet **539**, a low pressure exhaust gas port **541**, a middle pressure passage **543**, exhaust gas outlets **545** in a cover, an exhaust gas outlet (in a second layer) from a combustion chamber, and a low pressure exhaust gas port **549**. The fresh air arrow in FIG. **22** is shown in dashed lines, the compressed air flow arrows are shown with dot-and-dashed lines and medium thickness solid lines, and the exhaust gas flow arrows are illustrated by

thicker solid lines and by thinner solid lines at port **549** and the adjacent channel as well as between port **541** and outlet **545**. The first compression step occurs adjacent a center of the wave rotor disc and the second compression step occurs adjacent outer and intermediate portions of the wave rotor disc.

The engine disc rotates with speeds much lower than a conventional turbo-unit, thereby simplifying bearing problems and construction of the electric generator. The present wave disc geometrical configuration and porting system causes one and two stage compression-decompression processes to increase the total efficiency. Middle pressure bypass generates the torque and consequently, net power. Wave disc **533** is a radial wave rotor having curved channels. It overcomes the traditional poor scavenging problem by adding, in a controllable way, additional force (being the component of centrifugal forces) which improves the scavenging process. Further, the motor-generator can be directly integrated within the engine.

The exemplary construction of FIG. **22** is a two step compression-decompression micro-engine manufactured by MEMS technology. A double port set with two parallel operating combustion chambers is used. The engine case can be prepared as a three part set with the most complicated part containing a basic plate with all port arrangements. The second part forms combustion chambers and outflow mufflers and the third part defines the cover with air inlets and exhaust gas outlets. The wave rotor disc is formed as two parts etched together. Moreover, an electric motor-generator is imprinted in the case part containing ports and in one of parts forming a wave disc.

As can be observed in FIGS. **23** and **24**, micro-engine apparatus **561** includes a high pressure gas port (port B), two middle pressure gas ports (inlet (port A) and an outlet (port C)), connected by a passage, and a low pressure gas outflow port (port D), are all located in the radial wave rotor disc. A high pressure air port (port E) and a low pressure fresh air port (port F) are located at the inner side of the wave disc. Generally this flow arrangement can be classified as the reversed flow configuration. Centrifugal forces are believed to improve the flow during the scavenging and to slightly disturb the compression process. Enough energy exists during the compression process to overcome the negative influence of centrifugal forces. During the end of traditional scavenging processes, there exists a lack of energy to completely remove exhaust gases from cells. In contrast, centrifugal forces of the present invention act to improve the scavenging process. Predicted two-step compression micro-engine efficiency is 13-16% in the stable operational area. In the case of a single compression step wave engine, estimated efficiency is about 6%. In the simplified wave diagram of FIG. **24**, fresh air is indicated at area **2**, compressed air is indicated at areas **1, 6, 8** and **9**, and exhaust gases are indicated at areas **3** and **4**. The compression and expansion flow parameters in the areas on the wave diagram, separated by waves, are constant.

Various embodiments have been disclosed, however, variations can be made which fall within the scope of the present invention. For example, the wave rotor can be stationary with the end plates rotating, although centrifugal flow advantages may not be fully realized. Further, it is envisioned that an electric motor actuator or the like may drive the wave rotor. Reverse-flow or through-flow wave rotor channels can be employed. Various aspects of the ultra-micro devices and methods disclosed in PCT Serial No. PCT/US05/24290, filed on Jul. 7, 2005, entitled "Ultra Micro Gas Turbine" and invented by Muller et al., which is incorporated by reference herein, can be used with the radial wave rotor of the present invention. Additionally, it is envisioned that the present inven-



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tion pertains to the internal location of compressors or other rotatable members within an internal cavity of otherwise conventional axial wave rotors, although many of the advantages of the radial wave rotor may not be achieved. It is further envisioned that two or more radial wave rotors can be coaxially aligned and used together, preferably rotating at the same speed, or alternately, at different speeds. While various materials, quantities and shapes have been disclosed, it should be appreciated that various other materials, quantities and shapes can be employed. It is intended by the following claims to cover these and any other departures from the disclosed embodiments which fall within the true spirit of this invention.

The invention claimed is:

1. An apparatus comprising: a wave rotor operably rotating about a rotor axis; the wave rotor including a first set of channels located substantially on a first plane, a second set of channels located substantially on a second plane and at least a third set of channels located substantially on at least a third plane, the first, second, and third sets of channels each being in a stacked relationship offset along the rotor axis; [and] at least the majority of the channels having elongated flow directions outwardly radiating relative to the rotor axis, *and certain sets of the channels operate in a different timing scheme.*

2. The apparatus of claim 1 further comprising multiple channels located substantially on a fourth plane, the planes being substantially parallel to each other, openings of the channels on the first plane being circumferentially offset from those on the second plane.

3. The apparatus of claim 1 wherein at least a majority of the channels are radially offset from the rotor axis, and the first, second and third planes are substantially parallel.

4. The apparatus of claim 1 wherein all of the channels are substantially perpendicular to the rotor axis.

5. The apparatus of claim 1 wherein at least a majority of the channels have a straight elongated orientation.

6. The apparatus of claim 1 wherein at least a majority of the channels have a curved elongated orientation.

7. The apparatus of claim 1 wherein the channels on the first plane are made as a separate layer from the channels on the second plane, the layers being stacked upon each other and joined together in a coaxial manner.

8. The apparatus of claim 1 further comprising a fuel injector and igniter aligned with at least one of the channels in at least one operating position, wherein the wave rotor utilizes shock waves to exchange energy from a high energy fluid to a low energy fluid, increasing both temperature and pressure of the low energy fluid, in an internal combustion engine.

9. An apparatus comprising:

a wave rotor having a plurality of fluid passageways, the wave rotor being rotatable about a rotor axis, the wave rotor having an internal surface defining an internal cavity; and

a rotatable member located inside the internal cavity of the wave rotor, the member further comprising a plurality of fluid-impinging vanes rotatable about a member axis independent of the fluid passageways.

10. The apparatus of claim 9 wherein the member is a fluid compressor.

11. The apparatus of claim 9 wherein the member axis is angularly offset from the rotor axis.

12. The apparatus of claim 9 wherein the member axis is offset from the rotor axis by about 20-50 degrees, the vanes of the member being oriented in an outwardly radiating manner relative to the member axis.

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13. The apparatus of claim 9 wherein the wave rotor is a radial wave rotor with its passageways being elongated in an orientation substantially radially offset relative to the rotor axis.

14. The apparatus of claim 9 further comprising:

an internal end plate having at least one port, the internal end plate being located between the internal surface of the wave rotor and the member; and

an external end plate having at least one port, the external end plate being located around an exterior surface of the wave rotor substantially coaxial with the rotor axis;

the ports of the internal and external end plates selectively aligning with the wave rotor passageways depending upon the positioning of the wave rotor; and

other portions of the internal and external end plates selectively blocking fluid entry and exit of the wave rotor passageways depending upon the positions of the wave rotor.

15. The apparatus of claim 9 further comprising:

a rotatable turbine mechanically coupled to the member; and

a turbine volute surrounding at least a portion of the turbine;

wherein fluid first flows to the member, radially outward through the wave rotor passages, through the turbine volute and subsequently to the turbine.

16. The apparatus of claim 9 further comprising a fuel injector and igniter aligned with at least one of the passageways in at least one operating position, wherein the wave rotor utilizes shock waves to exchange energy from a high energy fluid to a low energy fluid, increasing both temperature and pressure of the low energy fluid, in an internal combustion engine.

17. An apparatus comprising:

a radial wave rotor including a rotational axis and multiple fluid carrying channels angularly offset from the axis in a substantially radial manner;

a radial compressor selectively in fluid communication with and being located inside the radial wave rotor; and a turbine;

the compressor and radial wave rotor operably utilizing fluid to exchange energy from a high energy fluid state to a low energy fluid state, increasing both temperature and pressure of the low energy fluid state during fluid flow from the compressor to the radial wave rotor and then to the turbine, free of a collector and free of a diffuser.

18. The apparatus of claim 17 further comprising a mechanical coupling attaching the turbine to the radial compressor.

19. The apparatus of claim 18 further comprising a turbine volute surrounding at least a majority of the turbine.

20. The apparatus of claim 17 wherein the radial wave rotor includes some of the channels being located on a first plane which are a separate layer from some of the channels being located on a second plane, the layers being stacked upon each other in a coaxial manner.

21. An apparatus comprising a radial wave rotor including a rotational rotor axis and fluid carrying channels having fluid flow directions oriented substantially radial to the rotor axis, the radial wave rotor operably creating a compressed fluid-pressure wave, and a plurality of groups of channels adjacent each other being in a stacked relationship, the groups of channels being offset from each other along the rotor axis, *and a fuel injector and igniter aligned with at least one of the channels in at least one operating position, wherein the wave rotor utilizes shock waves to exchange energy from a high*



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*energy fluid to a low energy fluid, increasing both temperature and pressure of the low energy fluid, in an internal combustion engine.*

22. The apparatus of claim 21 further comprising a compressor located internal to the radial wave rotor, the compressor operably rotating around a compressor axis.

23. The apparatus of claim 22 wherein the compressor axis is angularly offset from the rotor axis.

24. The apparatus of claim 21 wherein at least a majority of the channels have a straight elongated orientation.

25. The apparatus of claim 21 wherein at least a majority of the channels have a curved elongated orientation.

26. The apparatus of claim 21 wherein an opening of each of the channels has a substantially square shape relative to the rotor axis.

27. [The apparatus of claim 21 wherein] *An apparatus comprising a radial wave rotor including a rotational rotor axis and fluid carrying channels having fluid flow directions oriented substantially radial to the rotor axis, the radial wave rotor operably creating a compressed fluid-pressure wave, and a plurality of groups of channels adjacent each other being in a stacked relationship, the groups of channels being offset from each other along the rotor axis, and an opening of each of the channels [has] having a substantially diamond shape relative to the rotor axis.*

[28. The apparatus of claim 21 further comprising a fuel injector and igniter aligned with at least one of the channels in at least one operating position, wherein the wave rotor utilizes shock waves to exchange energy from a high energy fluid to a low energy fluid, increasing both temperature and pressure of the low energy fluid, in an internal combustion engine.]

29. The apparatus of claim 21 further comprising:

a compressor;

an internal end plate having at least one port, the internal end plate being located between an internal surface of the wave rotor and the compressor; and

an external end plate having at least one port, the external end plate being located around an exterior surface of the wave rotor substantially coaxial with the rotor axis;

the ports of the internal and external end plates selectively aligning with the wave rotor channels depending upon the positioning of the wave rotor.

30. The apparatus of claim 21 wherein fluid flows into the wave rotor at a subsonic speed.

31. The apparatus of claim 21 wherein the wave rotor acts as a refrigeration condenser.

32. The apparatus of claim 21 wherein the wave rotor is part of an aircraft jet engine.

33. The apparatus of claim 21 [further comprising] *wherein the wave rotor acts as an active compression-decompression wave engine using centrifugal forces acting on fluid in the wave rotor to improve scavenging therein, the wave rotor generating torque during operation.*

34. An apparatus comprising:

a wave rotor having fluid flow paths, the wave rotor being rotatable about a rotor axis; and

a compressor including fluid-contacting structures rotatable about a compressor axis;

the compressor axis being angularly offset from the rotor axis, and the compressor operably supplying fluid to the wave rotor; and

*the wave rotor being a radial wave rotor with its paths being elongated in an orientation substantially radially offset relative to the rotor axis.*

[35. The apparatus of claim 34 wherein the wave rotor is a radial wave rotor with its paths being elongated in an orientation substantially radially offset relative to the rotor axis.]

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36. The apparatus of claim 34 wherein the compressor axis is offset from the rotor axis by about 20-50 degrees.

37. The apparatus of claim 34 further comprising:

an internal end plate having at least one port, the internal end plate being located between an internal surface of the wave rotor, defining an internal cavity, and the compressor; and

an external end plate having at least one port, the external end plate being located around an exterior surface of the wave rotor substantially coaxial with the rotor axis;

the ports of the internal and external end plates selectively aligning with the wave rotor paths depending upon the positioning of the wave rotor.

38. The apparatus of claim 34 wherein the compressor is rotatably located inside an internal cavity of the wave rotor.

39. A wave rotor apparatus comprising a surface defining an elongated channel being rotated around an axis, a shock wave of a flowing fluid moving through the channel, and a correctional passage located in the surface, the correctional passage being elongated and enclosed between an inlet and an outlet of the [passage] channel, the correctional passage operably receiving a portion of the flowing fluid and changing flow characteristics of the shock wave in at least one operating condition;

wherein the channel is part of a radial wave rotor, the channel being radially elongated in a direction offset from the axis.

40. The apparatus of claim 39 wherein the inlet and outlet of the correctional passage substantially face the same direction, and the correctional passage operably varies a rotational speed of the wave rotor to obtain a proper position of the shock wave.

41. An apparatus comprising:

a wave rotor including multiple fluid-carrying passageways, each of the passageways having an inlet opening and an outlet opening; [and]

at least one end plate including a fluid blocking section, and the end plate further including an elongated and diagonally angled port being in periodic alignment with at least one of the passageways to allow fluid flow between the port and aligned passageway, the port being elongated and diagonally angled across a peripheral surface of the end plate, the elongation direction of the port being angularly offset from a rotational axis of the wave rotor;

*a fluid compressor;*

*a rotatable turbine mechanically coupled to the compressor; and*

*a turbine volute surrounding at least a portion of the turbine;*

*wherein fluid first flows to the compressor, radially outward through the wave rotor passages, through the turbine volute and subsequently to the turbine.*

42. An apparatus comprising:

a wave rotor including multiple fluid-carrying passageways, each of the passageways having an inlet opening and an outlet opening; and

at least one end plate including a fluid blocking section, and the end plate further including a port defined by an edge at an internal face of the end plate, the edge of the port being elongated and diagonally angled [port], the port being in periodic alignment with at least one of the passageways to allow fluid flow between the port and aligned passageway;

wherein the passageways of the wave rotor are elongated in an outwardly radiating direction relative to a rotational axis of the wave rotor; and



wherein the diagonally angled port is elongated larger than the corresponding opening of the wave rotor passageways and a section of the diagonally angled port is offset from the corresponding opening in all operating conditions.

43. The apparatus of claim 41 wherein fluid flows into the wave rotor at a subsonic speed and the passageways have a curve in their elongated directions.

44. An apparatus comprising:

a radial wave rotor having a plurality of fluid passageways, the wave rotor being rotatable about a rotor axis with the passageways being elongated in an orientation substantially radially offset relative to the rotor axis, the wave rotor having an internal surface defining an internal cavity; and

an electromagnetic generator located inside the cavity of the wave rotor.

[45. The apparatus of claim 44 wherein the device is an electric motor.]

46. An apparatus comprising:

a wave rotor having a plurality of fluid passageways, the wave rotor being rotatable about a rotor axis, the wave rotor having an internal surface defining an internal cavity; and

an electromagnetic device located inside the cavity of the wave rotor;

wherein a central axis of the device is angularly offset from the rotor axis.

47. The apparatus of claim 46 wherein the wave rotor is a radial wave rotor with its passageways being elongated in an orientation substantially radially offset relative to the rotor axis.

48. The apparatus of claim [44] 46 wherein the device is an electric generator.

[49. The apparatus of claim 1 wherein certain sets of the channels operate in a different timing scheme.]

50. The apparatus of claim 21 [further comprising] wherein the radial wave rotor acts as an active compression-decompression wave engine using centrifugal forces acting on fluid in the wave rotor to improve compression therein, the wave rotor generating torque during operation.

51. The apparatus of claim 21 [further comprising] wherein the radial wave rotor acts as an active compression-decompression wave engine using the radial channel orientation in the wave rotor to improve scavenging therein, the wave rotor generating torque during operation.

52. A method of manufacturing a power generation assembly comprising:

(a) creating a first member to include outwardly radiating fluid passageways and an internal cavity;

(b) creating a second member to include fluid-contacting vanes;

(c) orienting the second member substantially inside the cavity of the first member;

(d) providing selective fluid communication between the first and second members;

(e) allowing the first and second members to rotate independently of each other in at least one condition; and

(f) utilizing shock waves inside the passageways of the first member to transfer energy from a high energy fluid to a low energy fluid, increasing both temperature and pressure of the low energy fluid.

53. The method of claim 52 wherein the first member is a radial wave rotor and the second member is a compressor.

54. The method of claim 52 wherein the first member is a radial wave rotor with internal combustion.

55. The method of claim 52 further comprising aligning an internal combustion engine fuel injector and an igniter with at least one of the passageways.

56. The method of claim 52 further comprising connecting a rotatable turbine to the second member and flowing fluid to the members and thereafter to the turbine.

57. The method of claim 52 further comprising making the first member with stacked layers, with at least some of the layers each including an outwardly radiating set of the passageways, such that the outwardly radiating passageways are located on different parallel planes substantially perpendicular to a rotational axis of the first member.

58. [The apparatus of claim 41 further comprising] An apparatus comprising:

a wave rotor including multiple fluid-carrying passageways, each of the passageways having an inlet opening and an outlet opening;

at least one end plate including a fluid blocking section, and the end plate further including an elongated and diagonally angled port being in periodic alignment with at least one of the passageways to allow fluid flow between the port and aligned passageway, the port being elongated and diagonally angled across a peripheral surface of the end plate, the elongation direction of the port being angularly offset from a rotational axis of the wave rotor; and

a fuel injector and igniter aligned with at least one of the passageways in at least one operating position, wherein the wave rotor utilizes shock waves to exchange energy from a high energy fluid to a low energy fluid, increasing both temperature and pressure of the low energy fluid, in an internal combustion engine.

59. The apparatus of claim 41 wherein at least a majority of the passageways have a straight elongated orientation.

60. The apparatus of claim 41 [further comprising] wherein the at least one end plate comprises an external end plate having a port which is elongated and diagonally angled across an internal surface of the external end plate, the wave rotor operably rotating between the external end [plates] plate and an internal end plate.

[61. The apparatus of claim 41 further comprising:

a fluid compressor;

a rotatable turbine mechanically coupled to the compressor; and

a turbine volute surrounding at least a portion of the turbine;

wherein fluid first flows to the compressor, radially outward through the wave rotor passages, through the turbine volute and subsequently to the turbine.]

62. The apparatus of claim 42 further comprising a fuel injector and igniter aligned with at least one of the passageways in at least one operating position, wherein the wave rotor utilizes shock waves to exchange energy from a high energy fluid to a low energy fluid, increasing both temperature and pressure of the low energy fluid, in an internal combustion engine.

63. The apparatus of claim 42 wherein at least a majority of the passageways have a straight elongated orientation.

64. The apparatus of claim 42 [further comprising] wherein the at least one end plate comprises an external end plate having a port which is elongated and diagonally angled across an internal surface of the external end plate, the wave rotor operably rotating between the external end [plates] plate and an internal end plate.



65. The apparatus of claim 42 further comprising:  
 a fluid compressor;  
 a rotatable turbine mechanically coupled to the compressor; and  
 a turbine volute surrounding at least a portion of the turbine;  
 wherein fluid first flows to the compressor, radially outward through the wave rotor passages, through the turbine volute and subsequently to the turbine.
66. *An apparatus comprising:*  
 a wave rotor including a rotational axis and fluid passageways each being elongated in a substantially radial manner away from the axis;  
 a fuel injector operably supplying fuel into the passageways;  
 an igniter operably having access to the passageways to ignite the fuel therein; and  
 at least one air inlet port located in an internal end plate operably allowing air to enter the passageways when aligned, an inlet port quantity being less than a quantity of the passageways.
67. *The apparatus of claim 66 wherein the igniter is a spark plug elongated substantially parallel to the rotational axis.*
68. *The apparatus of claim 66 further comprising an electrical generator, each of the passageways having a curved segment to create torque to the wave rotor during flow scavenging which drives the generator.*
69. *The apparatus of claim 66 further comprising an external end plate including at least one port through which burned gases exit when the port is aligned with at least one of the passageways within which a fuel and air mixture is combusted, the internal and external end plates having annular walls between which the passageways rotate, the annular walls being concentric with each other and coaxial with the rotational axis, and the inlet and exit ports being located through the respective annular walls.*
70. *The apparatus of claim 66 further comprising at least a second wave rotor including a plurality of fluid passageways each being elongated in a substantially radial manner away from the rotational axis, one of the wave rotors being coaxially and longitudinally stacked on top of the other and both of the wave rotors rotating when there is combustion of the fuel therein.*
71. *The apparatus of claim 66, further comprising an automotive land vehicle at least partially powered by the wave rotor.*
72. *The apparatus of claim 66 wherein rotation of the wave rotor about the axis causes centrifugal force to act upon a combusted fuel and air mixture therein to improve scavenging and acceleration of fluid with each passageway.*
73. *An apparatus comprising:*  
 a radial wave rotor including substantially radially elongated channels each having a non-linear elongated configuration;  
 an automotive land vehicle at least partially powered by the radial wave rotor;  
 combusted fluid exiting an outer end of at least one of the channels while the radial wave rotor rotates; and  
 an igniter operably having access to at least one of the channels, a quantity of the channels being greater than an ignitor quantity.
74. *The apparatus of claim 73 wherein the ignitor is a laser beam ignitor.*
75. *The apparatus of claim 73 wherein rotation of the wave rotor about an axis causes centrifugal force to act upon a combusted fuel and air mixture therein to improve scavenging and acceleration of fluid with each channel.*

76. *An apparatus comprising:*  
 a radial wave rotor including substantially radially elongated channels each having a non-linear elongated configuration;  
 an automotive land vehicle at least partially powered by the radial wave rotor;  
 combusted fluid exiting an outer end of at least one of the channels while the radial wave rotor rotates; and  
 an external end plate including at least one port through which the combusted fluid exits when the port is aligned with at least one of the channels within which a fuel and air mixture is combusted, and an internal end plate having at least one entry port therethrough, the internal and external end plates having annular walls between which the channels rotate, the annular walls being coaxial with a rotational axis and the entry and exit ports being located through the respective annular walls.
77. *The apparatus of claim 73 further comprising at least a second wave rotor including a plurality of fluid channels each being elongated in a substantially radial manner away from a rotational axis, one of the wave rotors being coaxially and longitudinally stacked on top of the other, and the wave rotors rotating during combustion of fuel therein.*
78. *The apparatus of claim 73 wherein the non-linear configuration is a curved shape in the elongated direction.*
79. *The apparatus of claim 73 further comprising an electric generator rotated by the radial wave rotor.*
80. *The apparatus of claim 73 wherein the wave rotor is a ceramic material.*
81. *The apparatus of claim 73 further comprising an internal end plate and an external end plate, each of the end plates including ports which are periodically aligned with the channels rotating therebetween, the port-to-channel alignment controlling fluid flow through the channels.*
82. *The apparatus of claim 73 further comprising a fresh air inlet centrally located adjacent a rotational axis of the radial wave rotor, upstanding stationary walls adjacent the inlet and internal to the wave rotor assisting in guiding the fresh air from the inlet to at least one entry port periodically aligned with inner ends of the channels.*
83. *The apparatus of claim 73 wherein the radial wave rotor acts as a supercharger for an internal combustion engine.*
84. *The apparatus of claim 73 further comprising a compressor, fluidly connected to the wave rotor, being rotated by a shaft.*
85. *An apparatus comprising:*  
 a radial wave rotor including a rotational axis and fluid passageways radially extending on a plane located perpendicular to the rotational axis, the passageways having a curved shape when viewed in a true view to the plane;  
 an internal end plate and an external end plate, each of the end plates including ports which are periodically aligned with the passageways operably rotating therebetween, port-to-passageway alignment controlling fluid flow through the passageways; and  
 a fuel injector operably injecting fuel directly into the passageways.
86. *The apparatus of claim 85 wherein the injector is adjacent the rotational axis.*
87. *The apparatus of claim 86 further comprising a spark plug emitting a spark into a hole in communication with at least one of the passageways, the spark plug being spaced away from the fuel injector.*
88. *The apparatus of claim 85 wherein the wave rotor is an automotive vehicle supercharger.*



89. The apparatus of claim 85 further comprising an electrical generator rotated by the wave rotor.

90. The apparatus of claim 85 further comprising an automotive land vehicle at least partially powered by the wave rotor.

91. The apparatus of claim 85 further comprising at least a second wave rotor including a plurality of fluid passageways each being elongated in a substantially radial manner away from the axis, one of the wave rotors being coaxially and longitudinally stacked on top of the other of the wave rotors, and the wave rotors operably rotating during combustion of fuel therein.

92. The apparatus of claim 85 wherein burned gases exit the port in the external end plate when it is aligned with at least one of the passageways within which fuel and air mixture is combusted, the internal and external end plates having annular walls between which the passageways rotate, the annular walls being coaxial with the rotational axis, and the inlet and exit ports being located through the respective annular walls.

93. The apparatus of claim 85 wherein rotation of the wave rotor about the axis causes centrifugal force to act upon a combusted fuel and air mixture therein to improve scavenging and acceleration of fluid with each passageway.

94. The apparatus of claim 85 further comprising an external combustor in communication with at least one of the passageways of the radial wave rotor.

95. The apparatus of claim 85 further comprising a compressor in fluid communication with the passageways of the radial wave rotor.

96. The apparatus of claim 85 further comprising a fresh air inlet centrally located adjacent the rotational axis, and upstanding stationary walls located within the internal end plate assisting in guiding the fresh air from the inlet to at least one of the ports adjacent inner ends of the passageways.

97. An apparatus comprising:

a wave rotor having an axis, the wave rotor further comprising at least two stacked layers of channels rotating about the axis;

at least one inlet port located adjacent an end of each of the channels of at least one of the layers;

at least one outlet port located adjacent an opposite end of each of the channels of at least one of the layers;

pressure waves of combusted fluid moving toward ends of the channels containing the fluid adjacent the outlet port in at least one operating condition; and

a wall between a channel in one of the layers and a channel in another of the layers including an aperture to allow access between the channels associated therewith.

98. The apparatus of claim 97 further comprising an ignitor accessible to at least some of the channels and causing combustion of the fluid in the channels, the aperture being a fire channel to assist with combustion between the associated channels connected by the aperture.

99. The apparatus of claim 97 wherein the wave rotor is a radial wave rotor with the channels each having a direction of elongation substantially radially extending away from the axis.

100. The apparatus of claim 97 further comprising an automotive vehicle powered by the wave rotor.

101. The apparatus of claim 97 wherein the aperture is an elongated slot and the wall is on a plane perpendicular to the axis.

102. An apparatus comprising a wave rotor including an axis and fluid carrying channels rotating about the axis, at least one of the channels comprising an elongated curved configuration between an inlet end and an outlet end, and the

at least one of the channels further comprising an offset angled wall configuration adjacent the outlet end, a flat wall having a circular periphery, a plurality of the channels each having an internal surface defined by the flat wall, side walls each separating adjacent pairs of the channels and including the curved and offset configurations, the side walls upstanding from the flat wall and the walls rotating about the axis.

103. The apparatus of claim 102 wherein rotation of the wave rotor about the axis causes centrifugal force to act upon a combusted fuel and air mixture therein to improve scavenging and acceleration of fluid with each channel, and the wave rotor is a radial wave rotor that is part of an automotive vehicular engine.

104. An apparatus comprising:

a first radial wave rotor including multiple fluid carrying channels; and

at least a second radial wave rotor including multiple fluid carrying channels;

the radial wave rotors being coaxially aligned and rotating at different speeds in at least one operating condition.

105. The apparatus of claim 104 wherein the channels of at least one of the radial wave rotors each have a curved elongated configuration.

106. The apparatus of claim 104 further comprising an electrical generator rotated by at least one of the wave rotors.

107. The apparatus of claim 104 further comprising an automotive land vehicle at least partially powered by at least one of the wave rotors.

108. The apparatus of claim 104 further comprising an internal end plate including at least one inlet port intermittently aligned with the channels of the first radial wave rotor, and an external end plate including at least one outlet port intermittently aligned with the channels of the first radial wave rotor, and centrifugal force acting on a combusted fuel and air mixture in the channels of the first radial wave rotor improving scavenging and acceleration of the mixture therein.

109. A method of using a radial wave rotor, the method comprising:

(a) rotating the radial wave rotor around an axis;

(b) flowing air to at least one inlet port;

(c) outwardly flowing the air into elongated channels outwardly extending in a substantially radial direction relative to the axis, only when the channels are aligned with the at least one inlet port;

(d) supplying fuel directly into the channels;

(e) igniting the fuel inside the channels;

(f) generating waves inside the channels due to pressure differences therein;

(g) using centrifugal force to improve scavenging of the combusted air/fuel mixture within each channel; and

(h) rotating an electric generator with rotation of the radial wave rotor.

110. The method of claim 109 further comprising rotating the electric generator by rotating the radial wave rotor connected to it, and the radial wave rotor is part of an automotive vehicular engine.

111. The method of claim 109 further comprising periodically exposing the channels to outlet and the at least one inlet ports to initiate compression and expansion waves that move through the channels, and dynamically exchanging pressure between high pressure and low pressure fluid utilizing unsteady pressure waves such that both compression and expansion are accomplished in the radial wave rotor.

112. The method of claim 109 further comprising rotating the channels along a plane perpendicular to the axis.



113. The method of claim 109 further comprising self-rotating the radial wave rotor by flowing the fluid therein against curved side walls defining each of the channels.

114. The method of claim 109 further comprising using metal material for the wave rotor and ducting burned gas from the wave rotor through an elongated duct.

115. A method of using a radial wave rotor, the method comprising:

- (a) rotating the radial wave rotor around an axis;
- (b) causing elongated channels of the radial wave rotor to rotate along a plane perpendicular to the axis;
- (c) using centrifugal force to improve outward scavenging of fluid within each channel;
- (d) periodically exposing the channels to outlet and inlet ports to initiate compression and expansion waves that move through the channels, and dynamically exchanging pressure between high pressure and low pressure fluid utilizing unsteady pressure waves such that both compression and expansion are accomplished in the radial wave rotor; and
- (e) using internal combustion of the fluid inside the channels of the radial wave rotor.

116. The method of claim 115 further comprising rotating a second radial wave rotor around the axis, the radial wave rotors being coaxially stacked against each other.

117. The method of claim 115 further comprising at least partially powering an automotive land vehicle by rotation of the radial wave rotor.

118. The method of claim 115 further comprising rotating an electric generator by rotating the radial wave rotor.

119. The method of claim 115 further comprising using the radial wave rotor as a vehicular supercharger.

120. The method of claim 115 further comprising injecting fuel directly into the channels.

121. The method of claim 115 further comprising compressing the fluid before it enters the radial wave rotor.

122. A method of using a wave rotor, the method comprising:

- (a) rotating the wave rotor about an axis so as to outwardly move combusting fluid between an inlet port and an outlet port within a rotating channel which is elongated perpendicular to the axis;
- (b) using centrifugal force to scavenge the combusting fluid within the rotating channel;
- (c) periodically exposing the rotating channel to the inlet and outlet ports to cause compression and expansion waves that move through the channel; and
- (d) supplying power to a land vehicle with the wave rotor.

123. The method of claim 122 further comprising providing electrical power with the wave rotor.

124. The method of claim 122 further comprising providing supercharger power with the wave rotor.

125. The method of claim 122 wherein the wave rotor comprises multiples of the channel which are each radially elongated perpendicular to the rotational axis of the wave rotor and on a common plane, and at least one of the channels having a curved elongated shape, and aligning an ignitor with at least one of the rotating channels.

126. The method of claim 122 wherein the channel is part of a first set of wave rotor channels, further comprising rotating a second set of wave rotor channels coaxially mounted in a stacked manner relative to the first set of channels, and injecting fuel directly into at least one of the rotating channels.

\* \* \* \* \*

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

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APPLICATION NO. : 13/023568  
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INVENTOR(S) : Norbert Muller et al.

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification:

Column 1, Line 18, insert:

--GOVERNMENT FUNDING

This invention was made with government support under DE-AR0000004 awarded by the U.S. Department of Energy. The government has certain rights in the invention.--

Signed and Sealed this  
Twelfth Day of January, 2016



Michelle K. Lee  
*Director of the United States Patent and Trademark Office*