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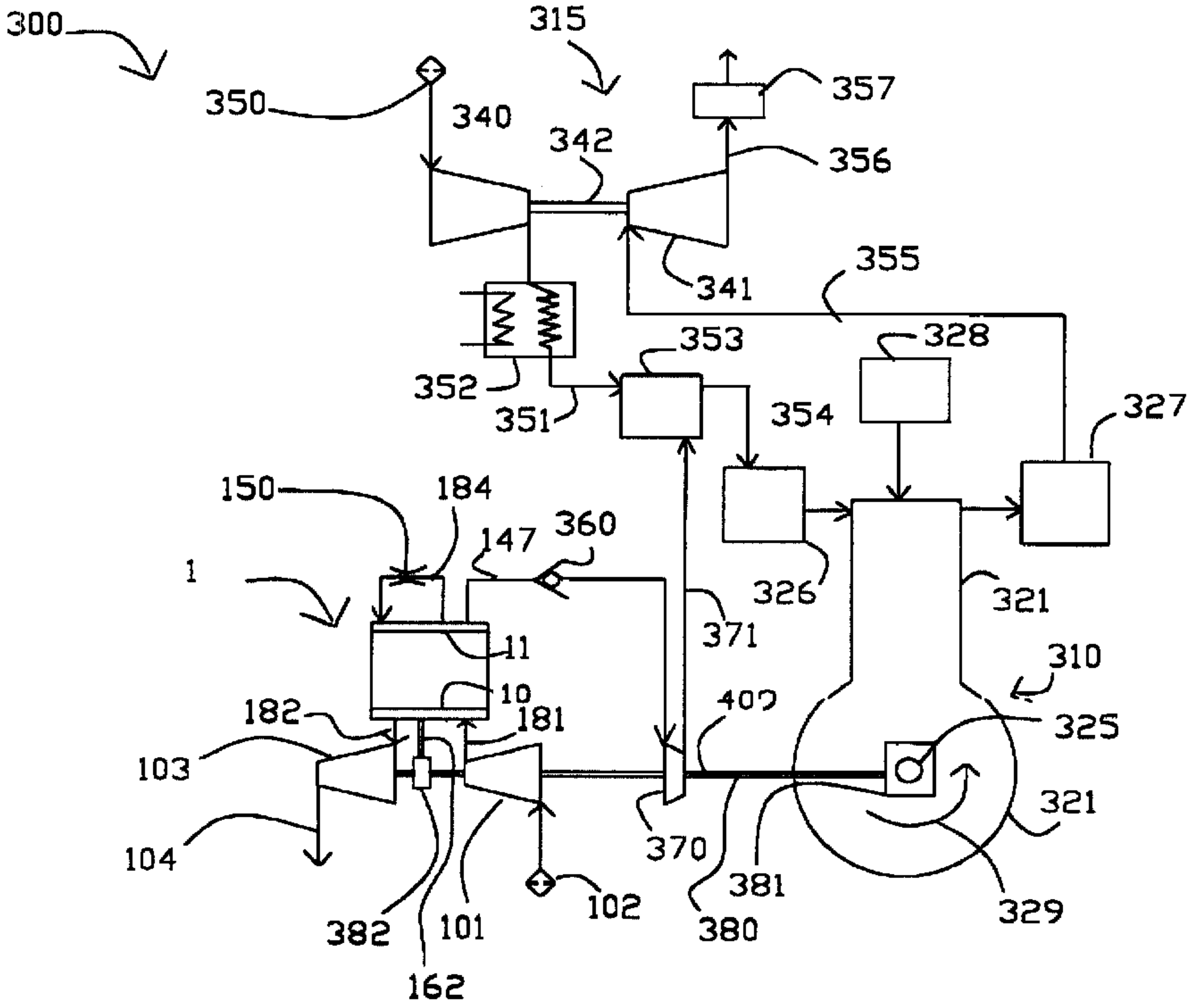

(57) Abrégé/Abstract:

A compact and efficient rotary pressure swing adsorption (PSA) apparatus with laminated sheet adsorbers is used to supply enriched oxygen and/or nitrogen streams to an internal combustion engine, allowing for reduced noxious emissions and enhanced engine performance.

Abstract

A compact and efficient rotary pressure swing adsorption (PSA) apparatus with laminated sheet adsorbers is used to supply enriched oxygen and/or nitrogen streams to an internal combustion engine, allowing for reduced noxious emissions and enhanced engine performance.

OXYGEN ENRICHMENT IN DIESEL ENGINES

FIELD OF THE INVENTION

The invention relates to oxygen and/or nitrogen enrichment in diesel engines and other internal combustion engines, providing for a reduction in noxious emissions and in some embodiments for enhanced engine performance. The invention provides a compact and efficient air separation apparatus based on pressure swing adsorption (PSA) with a high frequency cycle.

BACKGROUND OF THE INVENTION

While diesel engines are highly efficient, they are severely challenged by the urgent need to meet clean air requirements for greatly reduced emissions of unburned hydrocarbons, carbon monoxide, obnoxious and potentially carcinogenic particulate smoke, and NOx. Typically, mitigation measures to reduce NOx tend to increase the emissions of incomplete fuel combustion, while measures to achieve more complete combustion tend to increase NOx. Mitigation techniques in use or under development include use of cleaner burning fuels, exhaust gas recirculation (EGR), particulate traps, improved after-treatment catalysts, and advanced after-treatment technologies including non-thermal plasma or corona discharge devices.

Some attention has been devoted over many years to the possibility of improving engine performance and addressing emissions problems by modifying the oxygen and nitrogen concentrations of air supplied to diesel and other internal combustion engines.

Oxygen enrichment can greatly reduce emissions of unburned hydrocarbons, CO and particulate smoke, although at the risk of worsening NOx emissions. Some investigators have found that oxygen enrichment may significantly improve engine power density and gross thermal efficiency (before allowing for the parasitic power load of air separation). It has also been found that the tendency toward worsened NOx emissions may be offset in compression ignition engines by retarding the timing of fuel injection, thus achieving with modest oxygen enrichment (e.g. to 25% or less O_2) an attractive compromise with an overall modest improvement in all emission categories of incomplete combustion and NOx.

The opposite approach of nitrogen enrichment (e.g. to reduce O_2 concentration from the normal 21% to about 19%) has also been advocated as an alternative to EGR, reducing NOx emissions while avoiding the problems of accumulating abrasive or corrosive contaminants from the exhaust.

Prior art references include Cullen et al (U.S. Patent No. 5,678,526), Yi (U.S. Patent Nos. 5,517,978; 5,553,591), Manikowski (U.S. Patent No. 5,706,675), Tsang et al (U.S. Patent No. 4,883,023), Poola et al (U.S. Patent Nos.5,636,619; 5,649,517; 6,055,808), Sekar et al (U.S. Patent No.5,526,641), Ng et al (U.S. Patent No. 5,640,845), Nemser et al (U.S. Patent No. 5,960,777) and Stutzenberger (U.S. Patent No. 5,908,023).

A further approach advanced by Chanda et al (U.S. Patent No. 6,067,973) is late cycle injection of enriched oxygen to an engine cylinder, so that oxygen admitted late during cylinder expansion may improve the completeness of combustion without raising cylinder temperature high enough to adversely affect NOx levels.

Until now, despite many studies and experimental tests, auxiliary air separation equipment for combustion engines has proved to be impracticable, because of excessive power consumption to achieve even a modest change between oxygen and nitrogen atmospheric concentrations. Furthermore, the additional equipment may be too bulky and too costly in relation to any emissions benefit provided.

Previous investigators of air separation for combustion engines have considered the several established industrial technologies for air separation, including cryogenic distillation, pressure swing adsorption, and membrane permeation. Cryogenic air separation requires large plant sizes and bulky insulation to approach its best energy efficiency, and has been rejected as completely unsuitable for mobile applications. Conventional pressure swing adsorption processes have a large adsorbent inventory in relation to their productivity, and are prohibitively bulky for mobile applications.

Polymeric membrane systems have been selected by most prior investigators as the most promising available technology, because of their simplicity and relative compactness. However, the compactness of membrane systems is seriously compromised by operation at the relatively low differential pressures that may be considered in engine applications. Power consumption of blowers and/or vacuum pumps for a membrane system is too high in relation to performance benefits expected.

The present invention is concerned with application of a high cycle frequency ultr-compact pressure swing adsorption system to air separation auxiliaries for internal combustion engines.

Gas separation by pressure swing adsorption is achieved by coordinated pressure cycling and flow reversals over an adsorber that preferentially adsorbs a more readily adsorbed component relative to a less readily adsorbed component of the mixture. The total pressure is elevated during intervals of flow in a first direction through the adsorber from a first end to a second end of the adsorber, and is reduced during intervals of flow in the reverse direction. As the cycle is repeated, the less readily adsorbed component is concentrated in the first direction, while the more readily adsorbed component is concentrated in the reverse direction.

A "light" product, depleted in the more readily adsorbed component and enriched in the less readily adsorbed component, is then delivered from the second end of the adsorber. A "heavy" product enriched in the more strongly adsorbed component is exhausted from the first end of the adsorber. The light product is usually the desired product to be purified, and the heavy product often a waste product, as in the important examples of oxygen separation over nitrogen-selective zeolite adsorbents and hydrogen purification. The heavy product (enriched in nitrogen as the more readily adsorbed component) is a desired product in the example of nitrogen separation over nitrogen-selective zeolite adsorbents. Typically, the feed is admitted to the first end of a adsorber and the light product is delivered from the second end of the adsorber when the pressure in that adsorber is elevated to a higher working pressure. The heavy product is exhausted from the first end of the adsorber at a lower working pressure. In order to achieve high purity of the light product, a fraction of the light product or gas enriched in the less readily adsorbed component is recycled back to the adsorbers as "light reflux" gas after pressure letdown, e.g. to perform purge, pressure equalization or repressurization steps.

The conventional process for gas separation by pressure swing adsorption uses two or more adsorbers in parallel, with directional valving at each end of each adsorber to connect the adsorbers in alternating sequence to pressure sources and sinks, thus establishing the changes of working pressure and flow direction. The basic pressure swing adsorption process also makes inefficient use of applied energy, because of irreversible expansion over the valves while switching the adsorbers between higher and lower pressures. More sophisticated conventional pressure swing adsorption devices achieve some improvement in efficiency by use of multiple pressure equalization steps and other process refinements, but complexity of the valve logic based on conventional 2-way valves is greatly increased. Furthermore, the cycle frequency with conventional valves and granular adsorbent cannot be greatly increased, so the adsorbent inventory is large. Conventional PSA plants are accordingly so bulky and heavy that their use to enrich oxygen or nitrogen for internal combustion engines would be quite impracticable, particularly for any vehicle applications.

By operating with high surface area laminated adsorbers, with the adsorbent supported in thin sheets separated by spacers to define flow channels between adjacent sheets, and with the adsorbers mounted in a rotor to provide the PSA process valve logic with only one moving part, a high frequency PSA cycle can be performed in an extremely compact apparatus as disclosed by Keefer et al (Canadian Patent application Nos. 2,312,506, 2,274,286 and 2,274,318). The present invention provides for the use of such compact PSA devices in conjunction with internal combustion engines to provide oxygen and/or nitrogen enrichment in order to address the problems of emissions of unburned hydrocarbons, particulate, carbon monoxide, and NOx; while also to achieve favorable power density and overall efficiency.

Increasing the oxygen flow to the engine offers the following benefits:

- Reduces particulate emissions and increases engine power output.
- Allows the use of lower-grade fuels.

Increasing the nitrogen concentration of air fed to the engine potentially reduces nitrogen oxide emissions without the problems caused by exhaust gas recirculation (engine wear, oil contamination).

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows an axial section of a rotary PSA module.

Figs. 2 through 5B show transverse sections of the module of Fig. 1.

Figure 6 shows a vacuum PSA unit applied to oxygen enrichment for a turbocharged diesel engine.

Fig. 7 shows a positive pressure PSA unit applied to oxygen enrichment for a diesel engine with energy recovery from the light reflux in order to boost the oxygen product pressure.

Fig. 8 shows a vacuum PSA unit applied to oxygen enrichment for a diesel engine with an ejector to boost the oxygen product pressure and a turbocharger as the vacuum pump.

Fig. 9 shows a PSA unit applied to nitrogen enrichment for a turbocharged diesel engine.

Fig. 10 shows a PSA unit applied to nitrogen enrichment for a turbocharged diesel engine, while the oxygen enriched product is compressed and injected late in the expansion cycle into the engine at an increased pressure.

Fig. 11 shows a PSA unit applied to nitrogen enrichment for a turbocharged diesel engine, with the enriched nitrogen blended into the feed air upstream of the turbocharger and the PSA unit.

Fig. 12 shows a PSA unit applied to nitrogen enrichment for a turbocharged diesel engine, with the enriched nitrogen blended into the feed air upstream of the turbocharger and the PSA unit.

Fig. 13 shows a multicylinder engine, in which enriched product stream or ambient air is supplied to each cylinder.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figs. 1 - 5

Fig. 1 shows a rotary PSA module 1, particularly suitable for smaller scale oxygen generation. Module 1 includes a number "N" of adsorbers 3 in adsorber housing body 4.

Each adsorber has a first end 5 and a second end 6, with a flow path there between contacting a nitrogen-selective adsorbent. The adsorbers are deployed in an axisymmetric array about axis 7 of the adsorber housing body. The housing body 4 is in relative rotary motion about axis 7 with first and second functional bodies 8 and 9, being engaged across a first valve face 10 with the first functional body 8 to which feed air is supplied and from which nitrogen-enriched air is withdrawn as the heavy product, and across a second valve face 11 with the second functional body 9 from which oxygen-enriched air is withdrawn as the light product.

In preferred embodiments as particularly depicted in Figs. 1 - 5, the adsorber housing 4 rotates and shall henceforth be referred to as the adsorber rotor 4, while the first and second functional bodies are stationary and together constitute a stator assembly 12 of the module. The first functional body shall henceforth be referred to as the first valve stator 8, and the second functional body shall henceforth be referred to as the second valve stator 9.

In the embodiment shown in Figs. 1 - 5, the flow path through the adsorbers is parallel to axis 7, so that the flow direction is axial, while the first and second valve faces are shown as flat annular discs normal to axis 7. However, more generally the flow direction in the adsorbers may be axial or radial, and the first and second valve faces may be any figure of revolution centred on axis 7. The steps of the process and the functional compartments to be defined will be in the same angular relationship regardless of a radial or axial flow direction in the adsorbers.

Figs. 2 - 5 are cross sections of module 1 in the planes defined by arrows 12 - 13, 14 - 15, and 16 - 17. Arrow 20 in each section shows the direction of rotation of the rotor 4.

Fig. 2 shows section 12 - 13 across Fig.1, which crosses the adsorber rotor. Here, "N" = 72. The adsorbers 3 are mounted between outer wall 21 and inner wall 22 of adsorber wheel 208. Each adsorber comprises a rectangular flat pack 3 of adsorbent sheets 23, with spacers 24 between the sheets to define flow channels here in the axial direction. Separators 25 are provided between the adsorbers to fill void space and prevent leakage between the adsorbers.

The adsorbent sheets comprise a reinforcement material, in preferred embodiments glass fibre, metal foil or wire mesh, to which the adsorbent material is attached with a suitable binder. For air separation to produce enriched oxygen, typical adsorbents are X, A or chabazite type zeolites, typically exchanged with lithium, calcium, strontium, magnesium and/or other cations, and with optimized silicon/aluminum ratios as well known in the art. The zeolite crystals are bound with silica, clay and other binders, or self-bound, within the adsorbent sheet matrix.

Satisfactory adsorbent sheets have been made by coating a slurry of zeolite crystals with binder constituents onto the reinforcement material, with successful examples including nonwoven fibreglass scrims, woven metal fabrics, and expanded aluminum foils. Spacers are provided by printing or embossing the adsorbent sheet with a raised pattern, or by placing a fabricated spacer between adjacent pairs of adsorbent sheets. Alternative satisfactory spacers have been provided as woven metal screens, non-woven fibreglass scrims, and metal foils with etched flow channels in a photolithographic pattern.

Typical experimental sheet thicknesses have been 150 microns, with spacer heights in the range of 100 to 150 microns, and adsorber flow channel length approximately 20 cm. Using X type zeolites, excellent performance has been achieved in oxygen separation from air at PSA cycle frequencies in the range of 30 to 150 cycles per minute.

Fig. 3 shows the porting of rotor 4 in the first and second valve faces respectively in the planes defined by arrows 14 - 15, and 16 - 17. An adsorber port 30 provides fluid communication directly from the first or second end of each adsorber to respectively the first or second valve face.

Fig. 4 shows the first stator valve face 100 of the first stator 8 in the first valve face 10, in the plane defined by arrows 14 – 15. Fluid connections are shown to a feed compressor 101 inducting feed air from inlet filter 102, and to an exhauster 103 delivering nitrogen-enriched second product to a second product delivery conduit 104. Compressor 101 and exhauster 103 are shown coupled to a drive motor 105.

Arrow 20 indicates the direction of rotation by the adsorber rotor. In the annular valve face between circumferential seals 106 and 107, the open area of first stator valve face 100 ported to the feed and exhaust compartments is indicated by clear angular segments 111 - 116 corresponding to the first functional ports communicating directly to functional compartments identified by the same reference numerals 111 - 116. The substantially closed area of valve face 100 between functional compartments is indicated by hatched sectors 118 and 119 which are slippers with zero clearance, or preferably a narrow clearance to reduce friction and wear without excessive leakage. Typical closed sector 118 provides a transition for an adsorber, between being open to compartment 114 and open to compartment 115. Gradual opening is provided by a tapering clearance channel between the slipper and the sealing face, so as to achieve gentle pressure equalization of an adsorber being opened to a new compartment. Much wider closed sectors (e.g. 119) are provided to substantially close flow to or from one end of the adsorbers when pressurization or blowdown is being performed from the other end.

The feed compressor provides feed air to feed pressurization compartments 111 and 112, and to feed production compartment 113. Compartments 111 and 112 have successively increasing working pressures, while compartment 113 is at the higher working pressure of the PSA cycle. Compressor 101 may thus be a multistage or split stream compressor system delivering the appropriate volume of feed flow to each compartment so as to achieve the pressurization of adsorbers through the intermediate pressure levels of compartments 111 and 112, and then the final pressurization and production through compartment 113. A split stream compressor system may be provided in series as a multistage compressor with interstage delivery ports; or as a plurality of compressors or compression cylinders in parallel, each delivering feed air to the working pressure of a compartment 111 to 113. Alternatively, compressor 101 may deliver all the feed air to the higher pressure, with throttling of some of that air to supply feed pressurization compartments 111 and 112 at their respective intermediate pressures.

Similar, exhauster 103 exhausts nitrogen-enriched heavy product gas from countercurrent blowdown compartments 114 and 115 at the successively decreasing working pressures of those compartments, and finally from exhaust compartment 116 which is at the lower pressure of the cycle. Similarly to compressor 101, exhauster 103 may be provided as a multistage or split stream machine, with stages in series or in parallel to accept each flow at the appropriate intermediate pressure descending to the lower pressure.

In the example embodiment of Fig. 4A, the lower pressure is ambient pressure, so exhaust compartment 116 exhaust directly to heavy product delivery conduit 104. Exhauster 103 thus provides pressure letdown with energy recovery to assist motor 105 from the countercurrrent blowdown compartments 114 and 115. For simplicity, exhauster 103 may be replaced by throttling orifices as countercurrent blowdown pressure letdown means from compartments 114 and 115.

In some preferred embodiments, the lower pressure of the PSA cycle is subatmospheric. Exhauster 103 is then provided as a vacuum pump, as shown in Fig. 4B. Again, the vacuum pump may be multistage or split stream, with separate stages in series or in parallel, to accept countercurrent blowdown streams exiting their compartments at working pressures greater than the lower pressure which is the deepest vacuum pressure. In Fig. 4B, the early countercurrent blowdown stream from compartment 114 is released at ambient pressure directly to heavy product delivery conduit 104. If for simplicity a single stage vacuum pump were used, the countercurrent blowdown stream from compartment 115 would be throttled down to the lower pressure over an orifice to join the stream from compartment 116 at the inlet of the vacuum pump.

Figs. 5A and 5B shows the second stator valve face, at section 16 – 17 of Fig. 1. Open ports of the valve face are second valve function ports communicating directly to a light product delivery compartment 121; a number of light reflux exit compartments 122, 123, 124 and 125; and the same number of light reflux return compartments 126, 127, 128 and 129 within the second stator. The second valve function ports are in the annular ring defined by circumferential seals 131 and 132. Each pair of light reflux exit and return compartments provides a stage of light reflux pressure letdown, respectively for the PSA process functions of supply to backfill, full or partial pressure equalization, and cocurrent blowdown to purge.

Illustrating the option of light reflux pressure letdown with energy recovery, a split stream light reflux expander 140 is shown in Figs. 1 and 5A to provide pressure let-down of four light reflux stages with energy recovery. The light reflux expander provides pressure let-down for each of four light reflux stages, respectively between light reflux exit and return compartments 122 and 129, 123 and 128, 124 and 127, and 125 and 126 as illustrated. The light reflux expander 140 may power a light product booster compressor 145 by drive shaft 246, which delivers the oxygen enriched light product to oxygen delivery conduit 147 and compressed to a delivery pressure above the higher pressure of the PSA cycle. Illustrating the option of light reflux pressure letdown with energy recovery, a split stream light reflux expander 240 is provided to provide pressure let-down of four light reflux stages with energy recovery. The light reflux expander serves as pressure let-down means for each of four light reflux stages, respectively between light reflux exit and return compartments 122 and 129, 123 and 128, 124 and 127, and 125 and 126 as illustrated.

Light reflux expander 240 is coupled to a light product pressure booster compressor 245 by drive shaft 246. Compressor 245 receives the light product from conduit 25, and delivers light product (compressed to a delivery pressure above the higher pressure of the PSA cycle) to delivery conduit 250. Since the light reflux and light product are both enriched oxygen streams of approximately the same purity, expander 140 and light product compressor 145 may be hermetically enclosed in a single housing which may conveniently be integrated with the second stator as shown in Fig. 1. This configuration of a "turbocompressor" oxygen booster without a separate drive motor is advantageous, as a useful pressure boost of the product oxygen can be achieved without an external motor and corresponding shaft seals, and can also be very compact when designed to operate at very high shaft speeds.

Fig. 5B shows the simpler alternative of using a throttle orifice 150 as the pressure letdown means for each of the light reflux stages.

Turning back to Fig. 1, compressed feed air is supplied to compartment 113 as indicated by arrow 125, while nitrogen enriched heavy product is exhausted from compartment 117 as indicated by arrow 126. The rotor is supported by bearing 160 with shaft seal 161 on rotor drive shaft 162 in the first stator 8, which is integrally assembled with the first and second valve stators. The adsorber rotor is driven by motor 163 as rotor drive means.

As leakage across outer circumferential seal 131 on the second valve face 11 may compromise enriched oxygen purity, and more importantly may allow ingress of atmospheric humidity into the second ends of the adsorbers which could deactivate the nitrogen-selective adsorbent, a buffer seal 170 is provided to provide more positive sealing of a buffer chamber 171 between seals 131 and 171. Even though the working pressure in some zones of the second valve face may be subatmospheric (in the case that a vacuum pump is used as exhauster 103), buffer chamber is filled with dry enriched oxygen product at a buffer pressure positively above ambient pressure. Hence, minor leakage of dry oxygen outward may take place, but humid air may not leak into the buffer chamber. In order to further minimize leakage and to reduce seal frictional torque, buffer seal 171 seals on a sealing face 172 at a much smaller diameter than the diameter of circumferential seal 131. Buffer seal 170 seals between a rotor extension 175 of adsorber rotor 4 and the sealing face 172 on the second valve stator 9, with rotor extension 175 enveloping the rear portion of second valve stator 9 to form buffer chamber 171. A stator housing member 180 is provided as structural connection between first valve stator 8 and second valve stator 9.

In the following figures of this disclosure, simplified diagrams will represent the PSA apparatus as described above. These highly simplified diagrams will indicate just a single feed conduit 181 to, and a single heavy product conduit 182 from, the first valve face 10; and the light product delivery conduit 147 and a single representative light reflux stage 184 with pressure let-down means communicating to the second valve face 11.

Fig. 6

Figure 6 shows an internal combustion engine power plant 300 including an internal combustion engine 310, a turbocharger 315, and a vacuum PSA module for oxygen enrichment of the air supply to the engine. The engine 310 is shown as a section across an engine cylinder 321, crankcase 322 and crankshaft 325. The engine has an intake manifold 326 and an exhaust manifold 327 respectively communicating by valves (not shown) to each cylinder 321. In the preferred case that the engine is a diesel or compression ignition engine, a fuel injector 328 is provided for each cylinder 321. In the alternative case that the engine is a spark ignition engine, fuel may be injected to each cylinder or alternatively may be supplied already mixed with the feed air to the intake manifold by a carburetor. The direction of rotation of crankshaft 325 is shown by arrow 329.

The engine 310 of Fig. 6 is illustrated as turbocharged by a turbocharger 315, including a compressor 340 driven by expander 341 through shaft 342. Alternatively, the engine may be supercharged by a blower 340 driven electrically or mechanically by the engine, or else may be naturally aspirated. Compressor or blower 340 receives ambient air from an air filter 350, and delivers compressed air through conduit 351 and intercooler 352 to a mixing chamber 353 communicating by conduit 354 to intake manifold 326. The engine exhaust is delivered from exhaust manifold 327 by conduit 355 to expander 341, and thence after expansion to exhaust conduit 356 and exhaust after-treatment system 357, and thence to the atmosphere. Exhaust after-treatment may include a catalytic converter, perhaps assisted by a device (e.g. corona discharge or non-thermal plasma) for further reduction of NOx.

Air is also fed to the PSA module 1 by a blower 101 drawing air though an air filter 102. Nitrogen-enriched air is withdrawn from the PSA module 1 by a vacuum pump 103, and is discharged by conduit 104 either as a useful byproduct or else as waste. The PSA module has throttle orifices 150 as pressure-letdown means for a light reflux stage 184.
Oxygen-enriched light product is delivered by conduit 147 and non-return valve 360 at a pressure slightly less than the higher pressure of the PSA cycle generated by blower 101.

An oxygen booster compressor 370 is provided if required to boost the pressure of the enriched oxygen stream to the intake manifold pressure, and the compressed stream of enriched oxygen is delivered by conduit 371 to mixing chamber 353 communicating by conduit 354 to intake manifold 326.

Some of the power developed by the diesel engine is utilized to rotate the PSA adsorber rotor through shaft 162, and to drive feed blower 101, vacuum pump 103 and oxygen booster compressor 370. These auxiliary mechanical loads may be powered electrically or by mechanical power takeoffs. Fig. 6 schematically indicates these options by showing all these loads driven by a shaft 380, in turn driven by power takeoff 381 coupled to crankshaft 325, and with a gearbox 382 driving the PSA rotor drive shaft 162.

Fig. 7

Fig. 7 shows a positive pressure PSA unit applied to oxygen enrichment for a turbocharged diesel engine with energy recovery from the light reflux in order to boost the oxygen product pressure. Here, the turbocharger compressor 340 and intercooler 352 supply compressed and cooled feed air both to the mixing chamber and to the PSA feed conduit 181. No vacuum pump or exhauster 103 is provided in this example, so instead a throttle orifice provides pressure letdown of nitrogen-enriched blowdown gas discharged as waste by conduit 182.

The enriched oxygen product is generated at a total pressure slightly less than the air feed pressure to the mixing chamber 353, so in this embodiment energy recovery from light reflux pressure letdown is used to boost the oxygen product pressure as required. Light reflux expander 140 (on at least one light reflux stage 184) directly powers oxygen booster compressor 145 in an oxygen turbocharger configuration.

Fig. 8

Fig. 8 shows a vacuum PSA unit applied to oxygen enrichment for a diesel engine with an ejector to boost the oxygen product pressure and a “turboexhauster” (similar to a conventional turbocharger) as the vacuum pump.

Fig. 8 is similar to fig. 7, but without energy recovery on the light reflux. It is a vacuum PSA system, using a turboexhauster 400 as the vacuum pump. Turboexhauster 400 includes a vacuum pump 410 driven by expander turbine 412 through shaft 414. Vacuum pump 410 may be a centrifugal compressor, while turbine 412 may be a radial inflow turbine. Nitrogen enriched exhaust recompressed by vacuum pump 410 is exhausted to atmosphere or delivered as a by-product. Both the feed turbocharger 315 and the turboexhauster 400 are powered by the engine exhaust. Fig. 8 shows a two-stage expansion process utilizing turbines 341 and 412 in series. Alternatively, turbines 341 and 412 may be connected in series to perform a single stage expansion of the appropriately divided exhaust flow.

Ejector 420 is provided for mixing enriched oxygen from conduit 147 with feed air from compressor 340 at a common pressure, with a pressure boost of the enriched oxygen to overcome pressure drop in the PSA module 1. The light product enriched oxygen is directed by conduit 147 through non-return valve 360 to suction port 422 of ejector 420. The remaining portion of the feed gas stream is introduced by nozzle 424 to entrain the enriched oxygen from port 422 into a mixed stream for pressure recovery in diffuser 426 to the correct intake pressure to the diesel engine. Fuel is injected into the cylinder 321 through injector 328.

Fig. 9

Fig. 9 shows a PSA unit applied to nitrogen enrichment for a turbocharged diesel engine, in order to reduce NOx emissions and as an alternative or supplement to EGR. The oxygen enriched light product stream is in this case a by-product or waste product. A control valve 430 is provided to maintain back-pressure in conduit 147 as the light product stream is delivered. The nitrogen-enriched heavy product is compressed by heavy product compressor 440 into conduit 104 up to the intake manifold pressure to be blended with incoming feed air in mixing chamber 353. Heavy product compressor 440 here replaces exhauster 103, and may induct the heavy product from conduit 182 at any suitable lower pressure of the PSA cycle which may be a subatmospheric pressure. As in preceding embodiments, the feed atmospheric air to the engine and to the PSA is pressurized by turbocharger 315, powered by engine exhaust energy. After mixing in chamber 353, the combined air stream is slightly nitrogen enriched, resulting in a typical oxygen concentration of 19% or 20% rather than the ambient 21%.

Fig. 10

Fig. 10 shows a PSA unit applied to modest nitrogen enrichment for a turbocharged diesel engine for reduced NOx, while the oxygen enriched product is compressed to a high pressure as required for injection into the cylinder late in the expansion phase to enhance final combustion of the fuel toward completion.

Nitrogen enriched heavy product exhausted from the PSA is delivered by conduit 104 to intake mixing chamber 450, and is there mixed with atmospheric air. The mixed stream at modest nitrogen enrichment is then compressed by turbocharger compressor 340 and cooled prior to being directed to intake manifold 326.

Atmospheric air is compressed by feed blower 101 prior to entry as feed gas to the PSA unit. First and second valve means 10 and 11 respectively operate the PSA cycle. Light product oxygen 147 (at a relatively high purity of e.g. 90% O_2) from the PSA is compressed by compressor 370 to a suitable high pressure well in excess of the highest engine working pressure within the cylinder 32, as required for rapid and efficient injection. The compressed oxygen from compressor 370 may be cooled by intercooler 460 in conduit 462 communicating to oxygen injector 464. The oxygen is injected into cylinder 321 late in the expansion cycle so as to enhance final combustion of fuel already injected into the engine by fuel injector 328. Electronic control unit 470 controls the injection timing of oxygen and fuel into the cylinder, coordinated with the piston reciprocation.

Combustion occurs during downstroke of the piston head. Oxygen produced by the PSA unit is added to the combustion chamber during this downstroke. Adding oxygen at this time helps reduce the production of NOX. An exhaust valve opens, exhausting fumes from the combustion chamber. During upstroke, a portion of an air and enriched nitrogen stream (exhausted from the PSA) is added to the combustion chamber. Due to this upward movement of the piston head, the pressure increases to a point that hot fuel and air added to the chamber ignites. This ignition forces the piston head into its downstroke or power stroke.

Meanwhile, the remainder of the air and enriched nitrogen stream is used as intake air in the PSA unit. The exhaust of the PSA is used as the air intake of a turbocharger, then directed to the combustion chamber and the PSA air intake. The oxygen produced by the PSA is, as stated previously, added to the combustion chamber during downstroke.

It will be evident that the strategy of late injection of highly enriched oxygen may be applied whether or not the nitrogen enriched stream is blended with feed air as illustrated in Fig. 106, or alternatively discarded as a separate byproduct or waste stream. Also, it will be noted that such a high level of oxygen enrichment as required for viable late injection can readily be achieved by the PSA system of the present invention, but could not be achieved by a membrane permeation device which could only with difficulty approach permeate oxygen concentrations much above 30%.

Fig 11

An alternative use of highly enriched and compressed oxygen would be for oxygen enriched precombustion of a small fraction of the fuel in a precombustion chamber 475 communicating with the cylinder 321, wherein the balance of the fuel is combusted under highly lean conditions so as to minimize NOx. Here, the fuel supply conduit 476 admits a primary fuel stream to a carburetor (or mixing chamber) 477 in air feed conduit 354 to intake manifold 326, and also delivers a secondary fuel stream to fuel injector 328 which injects fuel into the precombustion chamber 475. Oxygen injector also delivers enriched and compressed oxygen from conduit 462, preferably in approximate stoichiometry or on the fuel rich side with respect to the secondary fuel stream, into the precombustion chamber. A combined injector for fuel and oxygen may be employed. The high level of oxygen enrichment and appropriate timing of injection would facilitate compression ignition within the precombustion chamber, in turn providing an intense high temperature jet from the precombustion chamber into the main combustion chamber of cylinder to create strong mixing and vigorous ignition of the lean fuel/air mixture therein. Spark ignition may not be needed. In general, the compact and highly efficient air separation system of the present invention may be applied to stratified combustion systems in order to achieve more nearly complete fuel combustion, low NOx emission, favorable power density and low specific fuel consumption.

Fig 12

Fig. 12 shows a PSA unit applied to nitrogen enrichment for a turbocharged diesel engine, with the enriched nitrogen blended into the feed air upstream of the turbocharger and the PSA unit. In this embodiment, similar to that of Fig. 9, the PSA heavy product of enriched nitrogen is recycled and mixed with feed air. This nitrogen enriched mixture is then used as intake air to the diesel engine. Enriching the intake air with nitrogen has been found to decrease NOx emissions from a diesel engine.

Nitrogen enriched product is conveyed by conduit 104 to mixing chamber 450 upstream of compressor 340, and is there mixed with feed air accepted through the air filter 350. In this embodiment, the nitrogen enriched heavy product flow is relatively small, so that the nitrogen enrichment of the mixed stream compressed by turbocharged compressor 340 is to a very modest degree, e.g. to reduce oxygen concentration to 20% O_2. Hence, the feed gas delivered from compressor 340 to the PSA by conduit 181 is already modestly depleted in oxygen. While the efficiency of this PSA process to produce byproduct oxygen will be somewhat impaired by any depletion of feed oxygen concentration, performance in nitrogen enrichment is facilitated. The major advantage of this embodiment is the use of a single compressor 340 to compress the combined feed air and nitrogen enriched heavy product stream, rather than separate compressors as in the Fig. 9 embodiment. In Fig. 11, control valve 430 controls the release of oxygen byproduct or waste from the PSA unit. It will be evident that the oxygen product stream could be compressed as in the embodiment of Fig. 10, and injected late in the expansion cycle of the cylinder 321.

Fig. 13

Fig. 13 shows an example of other embodiments with multicylinder engines, in which ambient air or the oxygen enriched product stream or the nitrogen enriched product stream may be supplied to a first cylinder or group of cylinders 321, and ambient air or the oxygen enriched product stream or the nitrogen enriched product stream may be supplied to a second cylinder or group of cylinders 321'. The first and second cylinders (or cylinder groups) may be separate engines, but preferably would be distinct cylinders of a single engine coupled by a crankshaft connection 480.

The first cylinder or cylinder group is operated in a rich burn mode so as to produce an exhaust stream in the first exhaust manifold 327 which contains products of incomplete combustion, particularly hydrogen and carbon monoxide. The first cylinder or cylinder group may also be water injected, so as to suppress soot formation while also enhancing the concentration of hydrogen. An EGR conduit 490 is provided to convey exhaust gases from the first exhaust manifold 327 to the second intake manifold 326'. Any particulates are removed in a soot trap 492 in conduit 490. A water gas shift reactor 494 may be provided in the EGR conduit 490 to convert a portion of the carbon monoxide to hydrogen. If desired, a fuel cell 496 may be included in EGR conduit 490 to obtain auxiliary electrical power by oxidation of a portion of the hydrogen and/or carbon monoxide. Residual hydrogen reaching the second intake manifold 326' will be beneficial for a low emission combustion process in the second group of cylinders 321', which operate in a lean burn mode.

In the specific example of Fig. 12, oxygen enrichment to the second group of cylinders enables more complete combustion, enhanced power density and higher thermal efficiency from the lean burn section which is already achieving low NOx thanks to the EGR and hydrogen transfer from the rich burn section of the engine. Oxygen enrichment to the first cylinder or cylinder group might also be considered to increase power density with reduced nitrogen diluent load through the entire engine. Alternatively, nitrogen enrichment to the first cylinder or cylinder group may be considered in order to moderate combustion and cylinder liner temperatures there, or to the second cylinder or cylinder group in order to further enhance the dilution effect of EGR for a lower maximum cylinder temperature and consequently even further reduced NOx.

Fig. 1

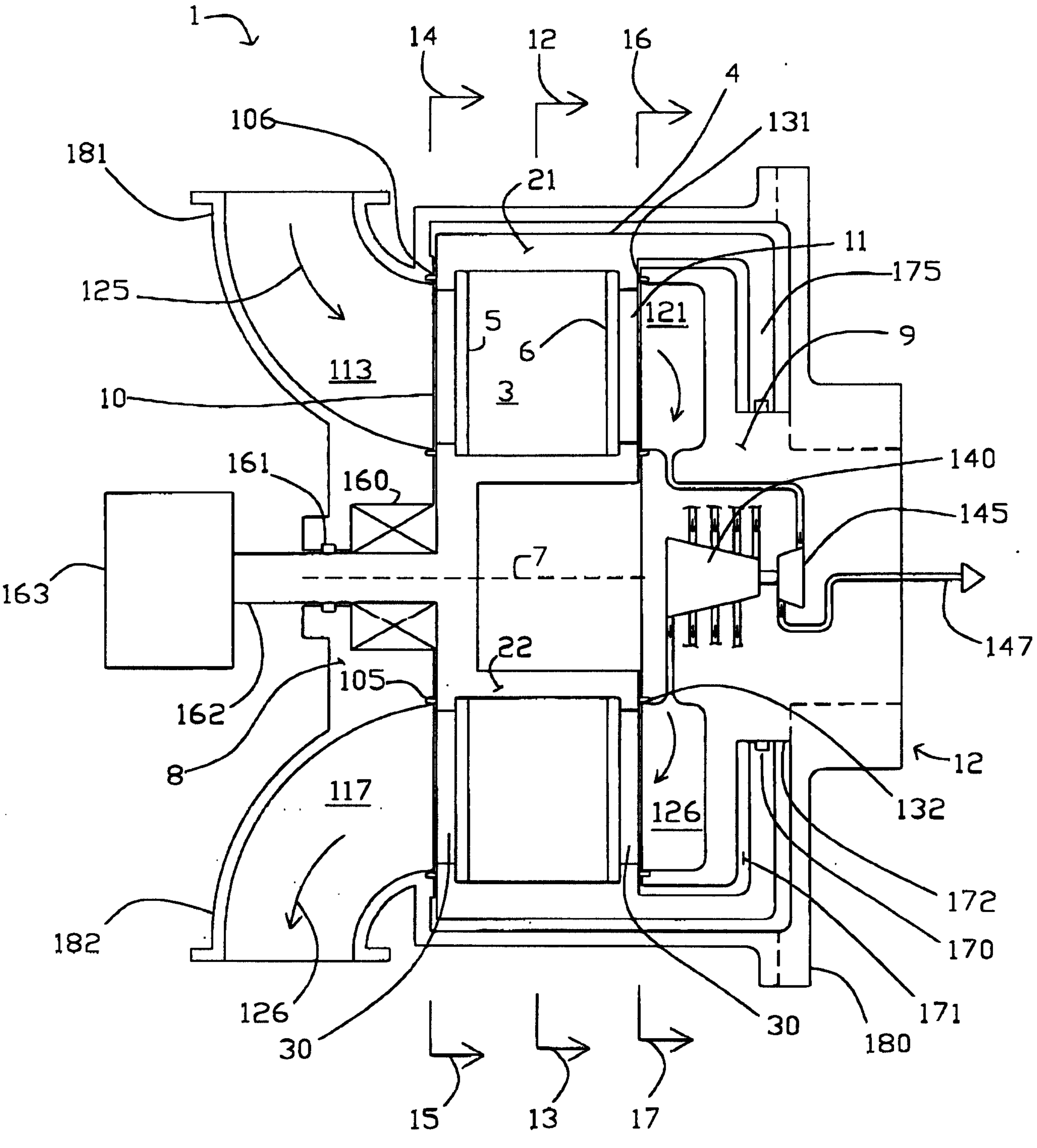
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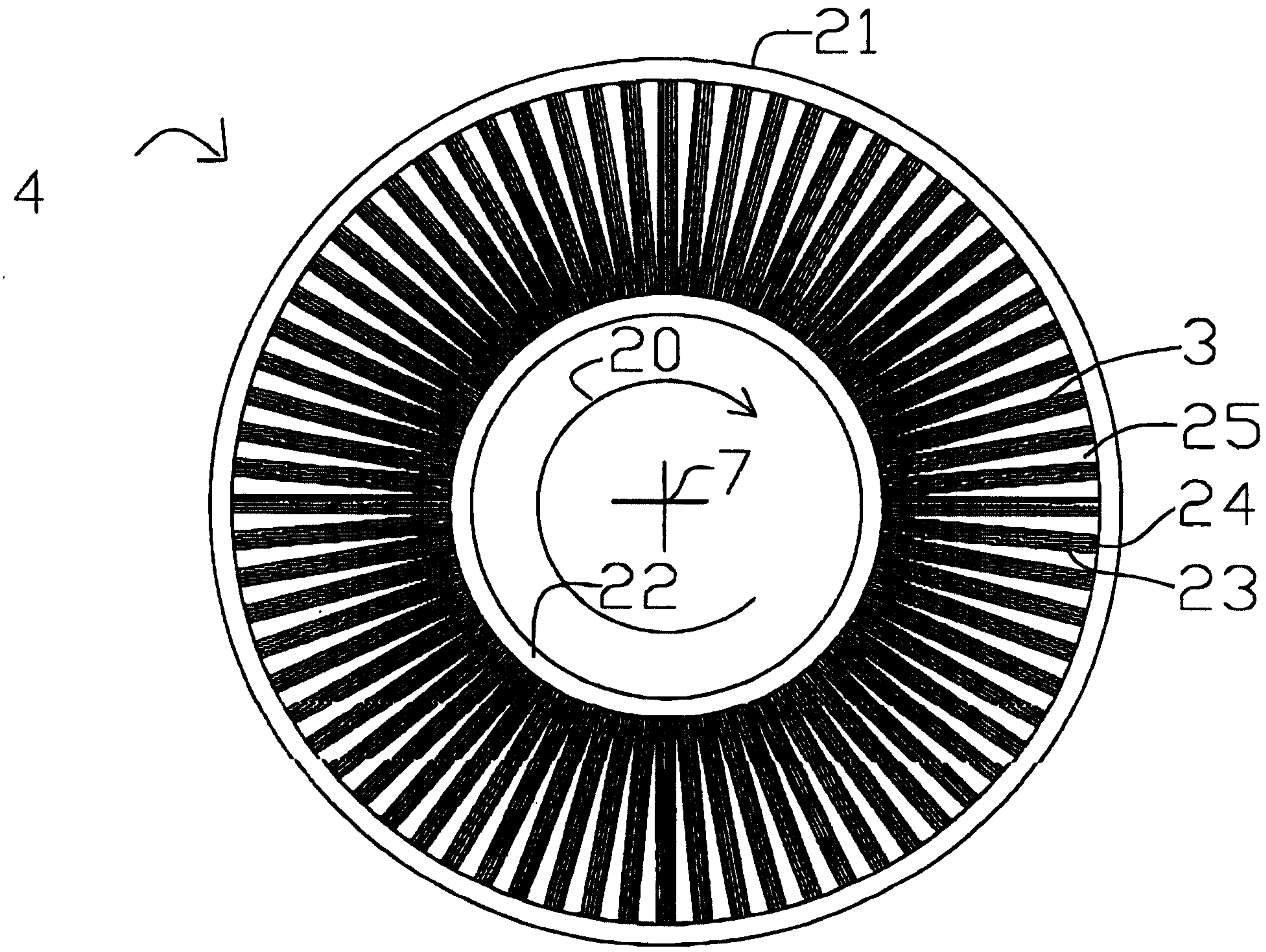
Fig. 2



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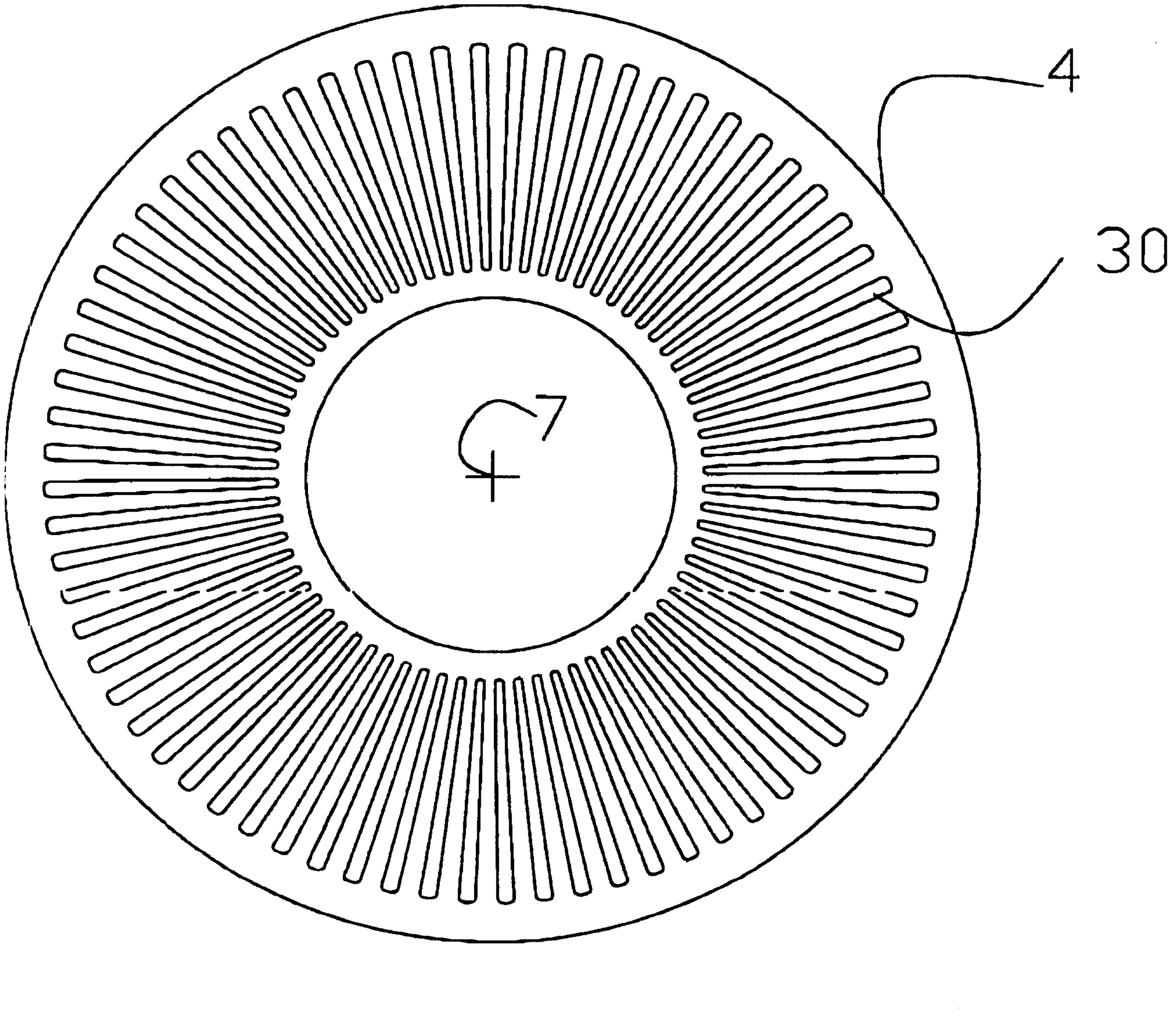

Fig. 4A

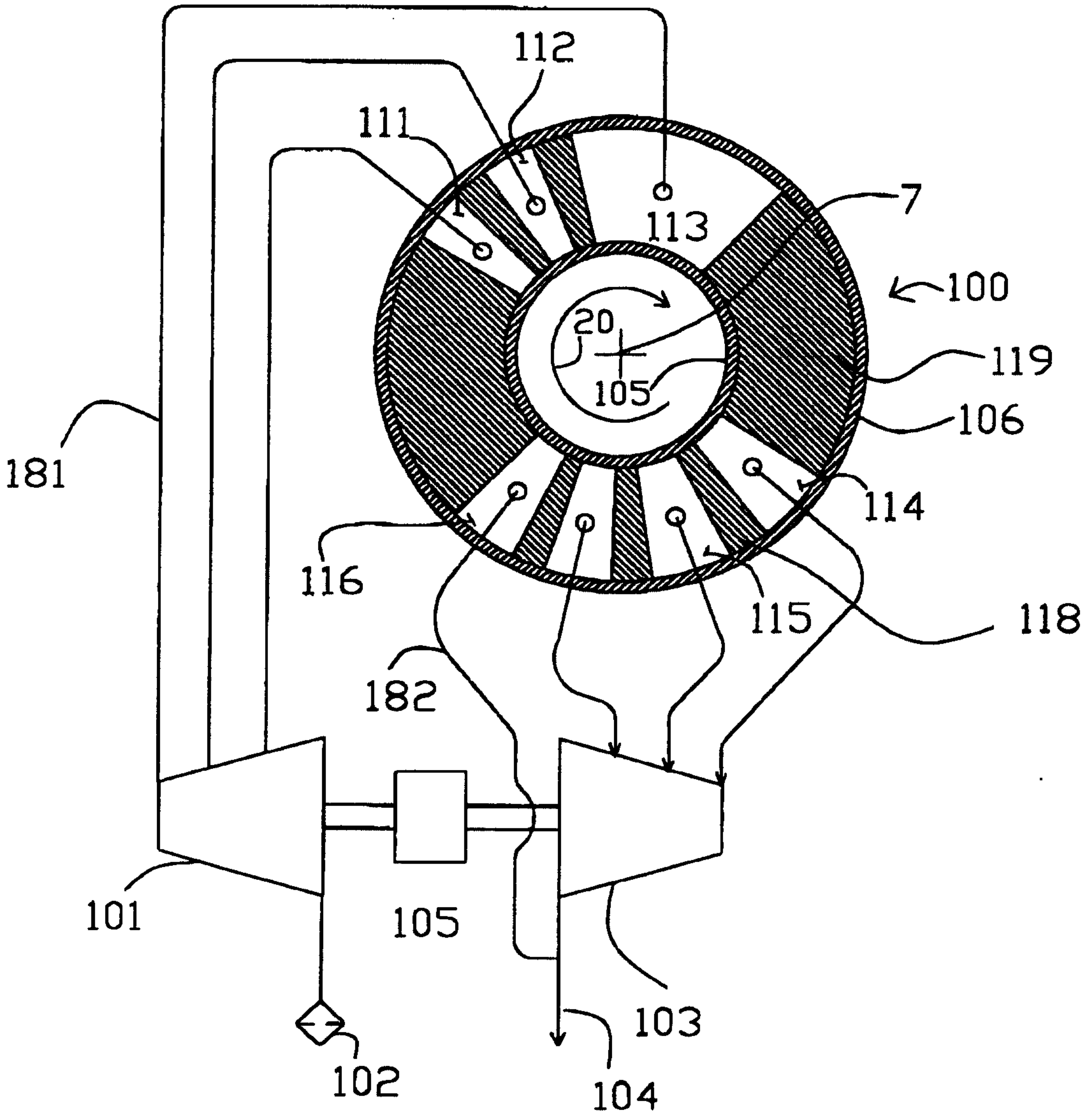
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Fig. 4B

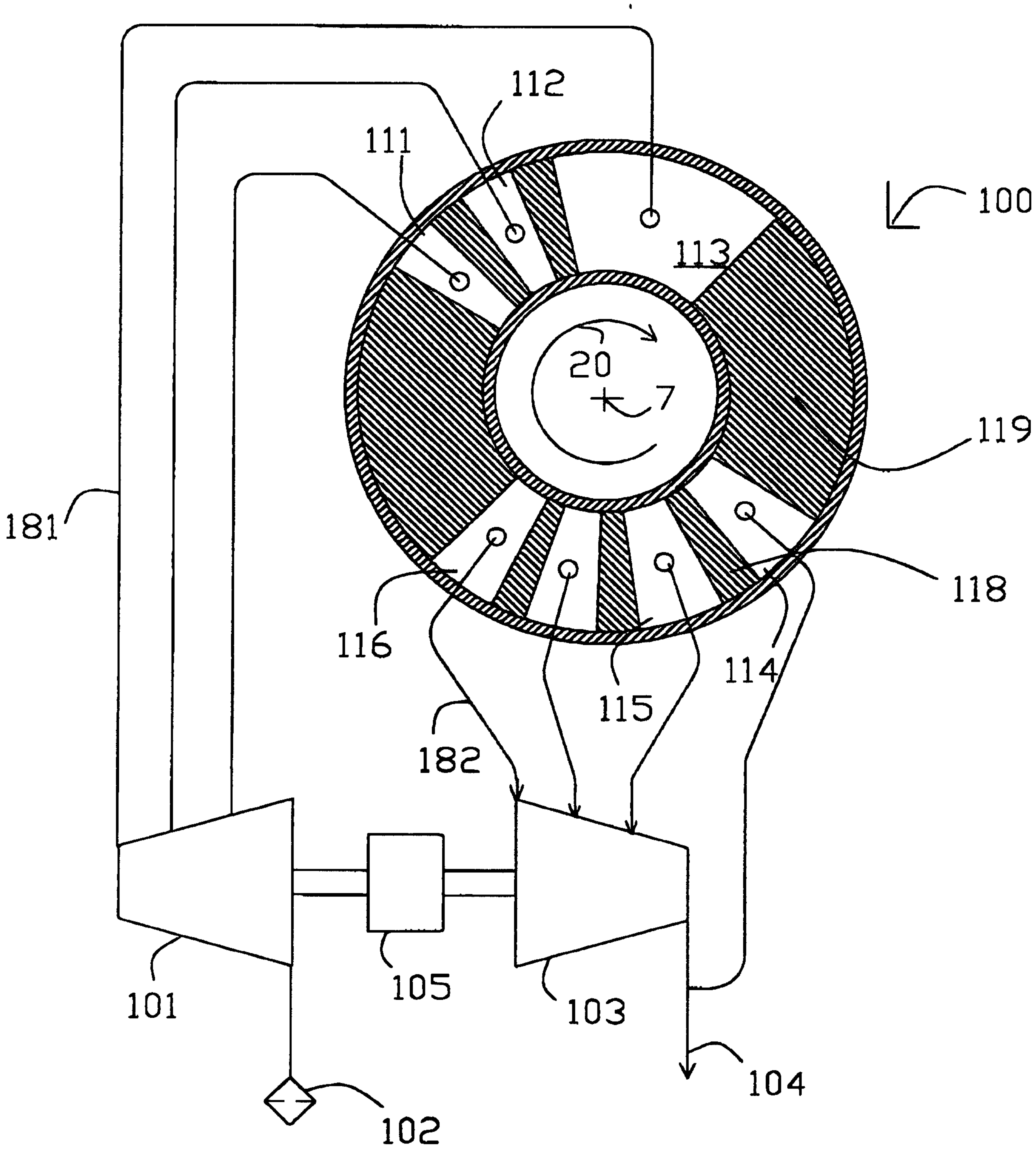
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Fig. 5A

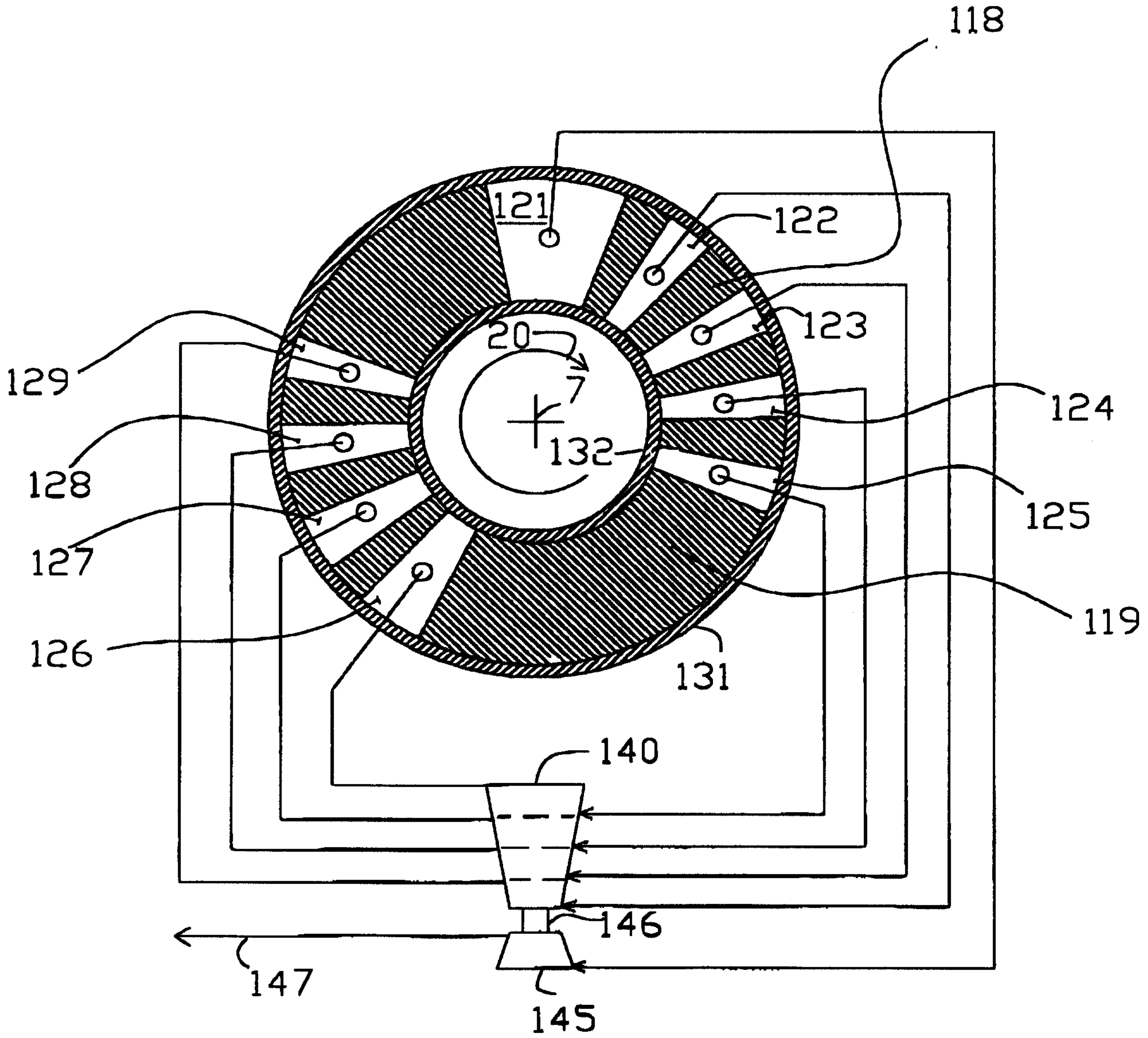
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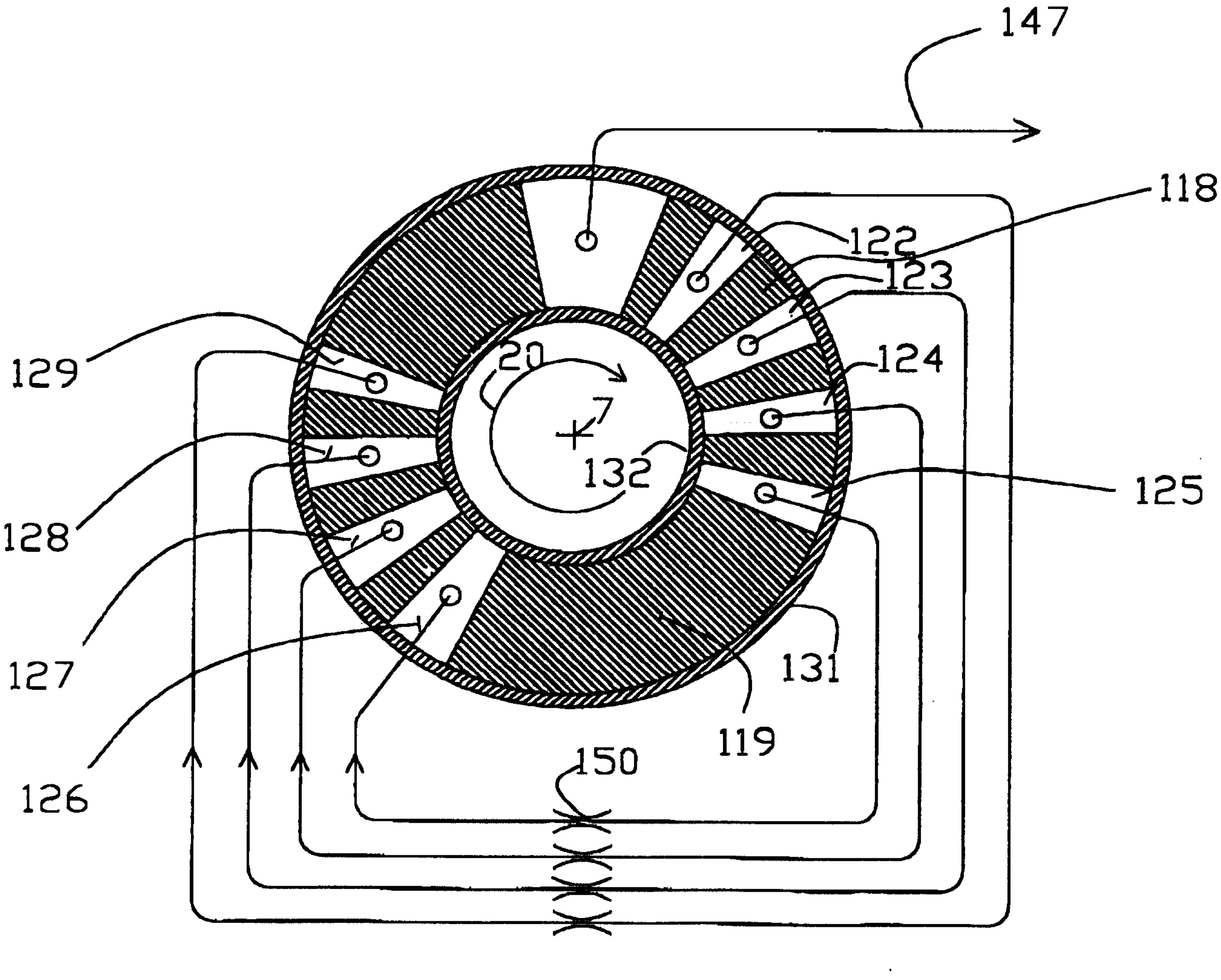
Fig. 5B



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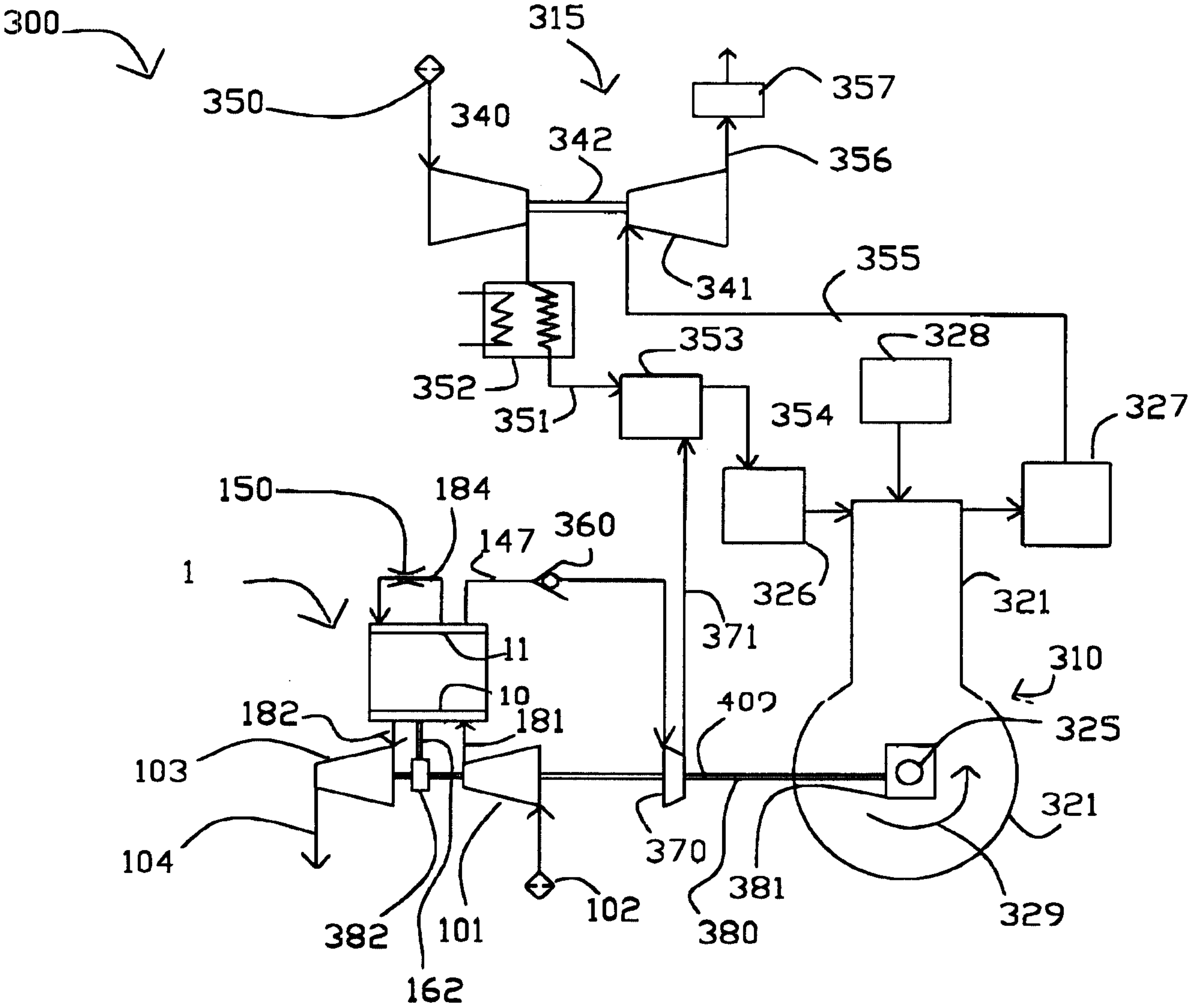
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Fig. 7

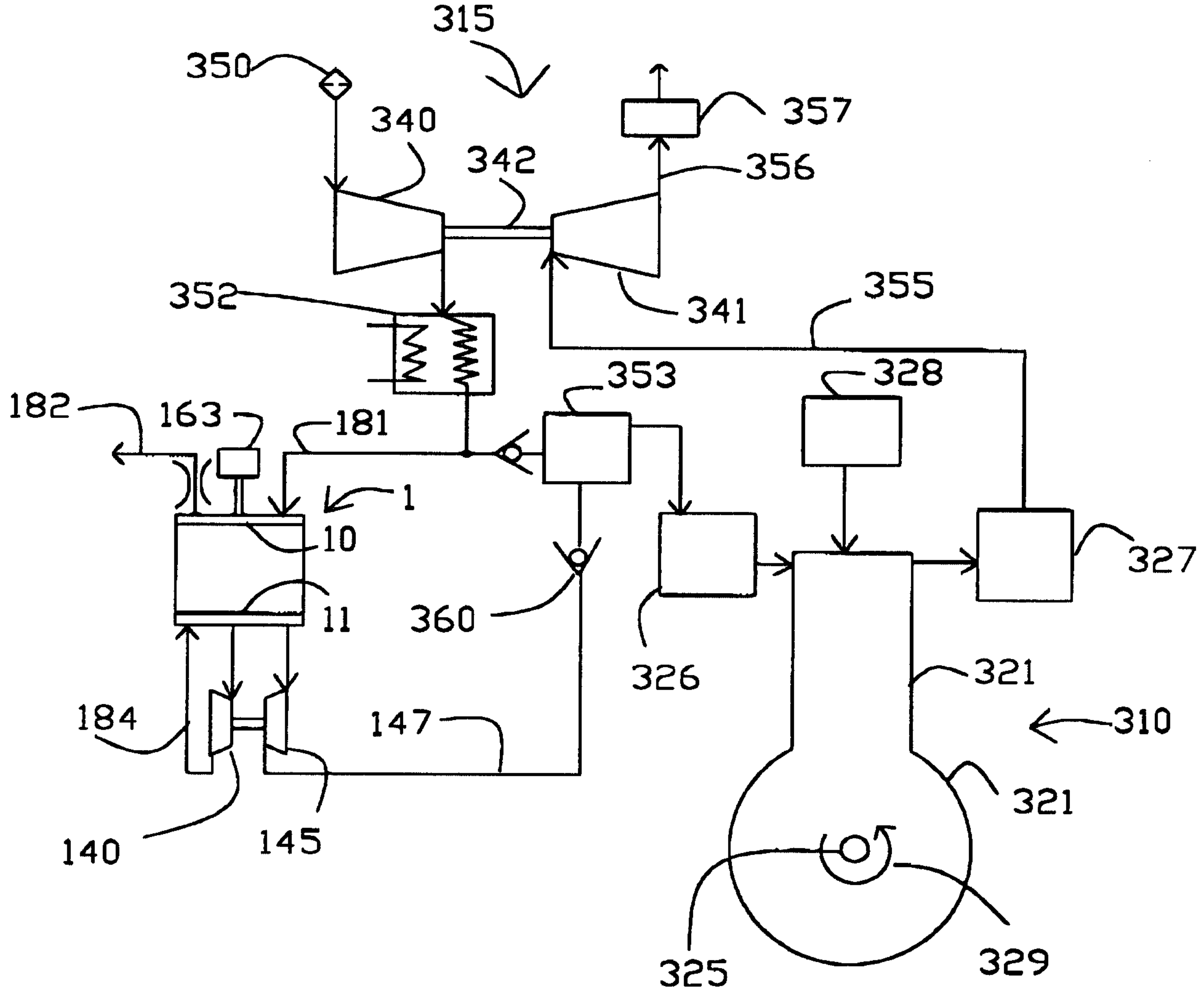
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Fig. 8

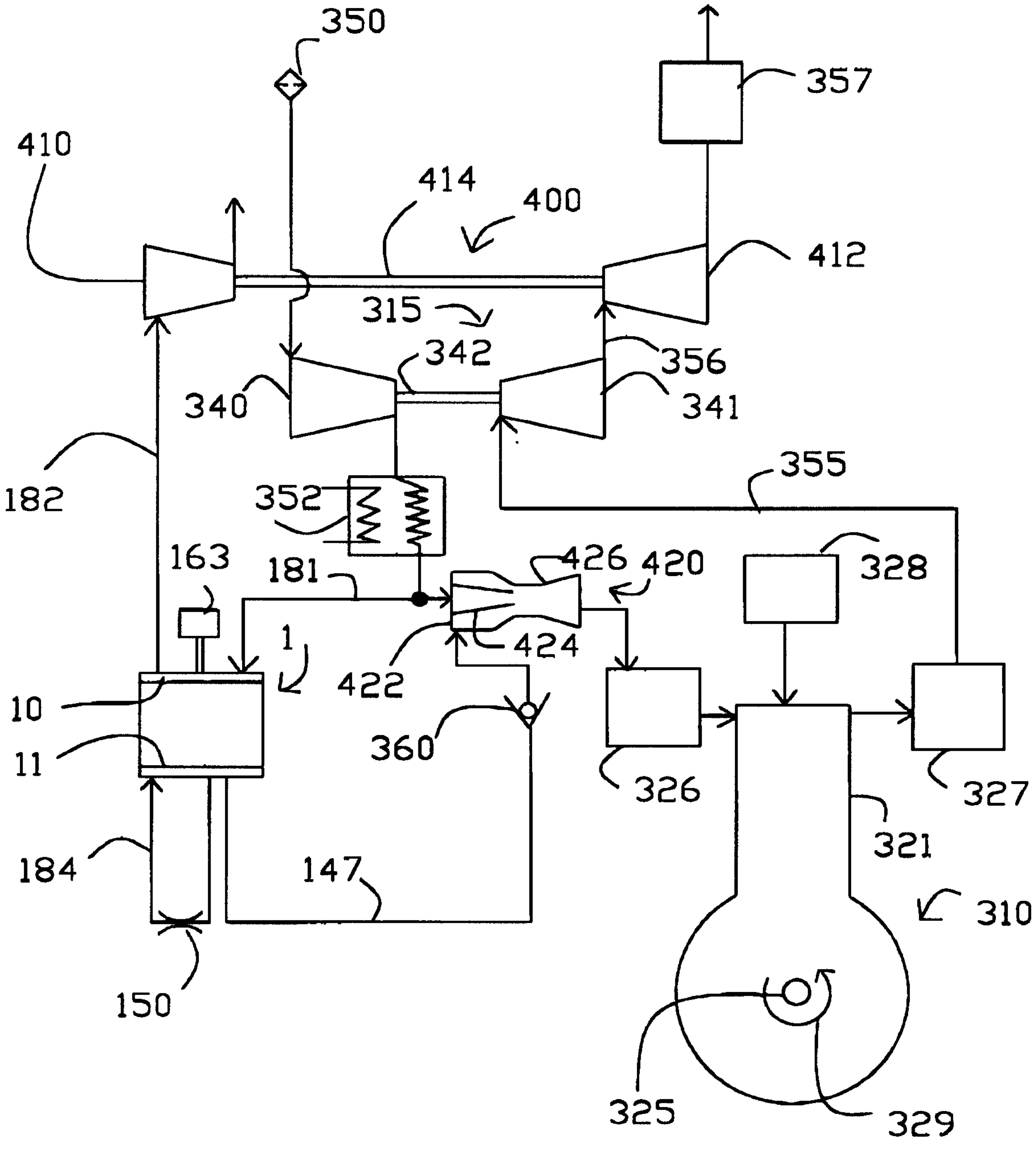
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Fig. 9

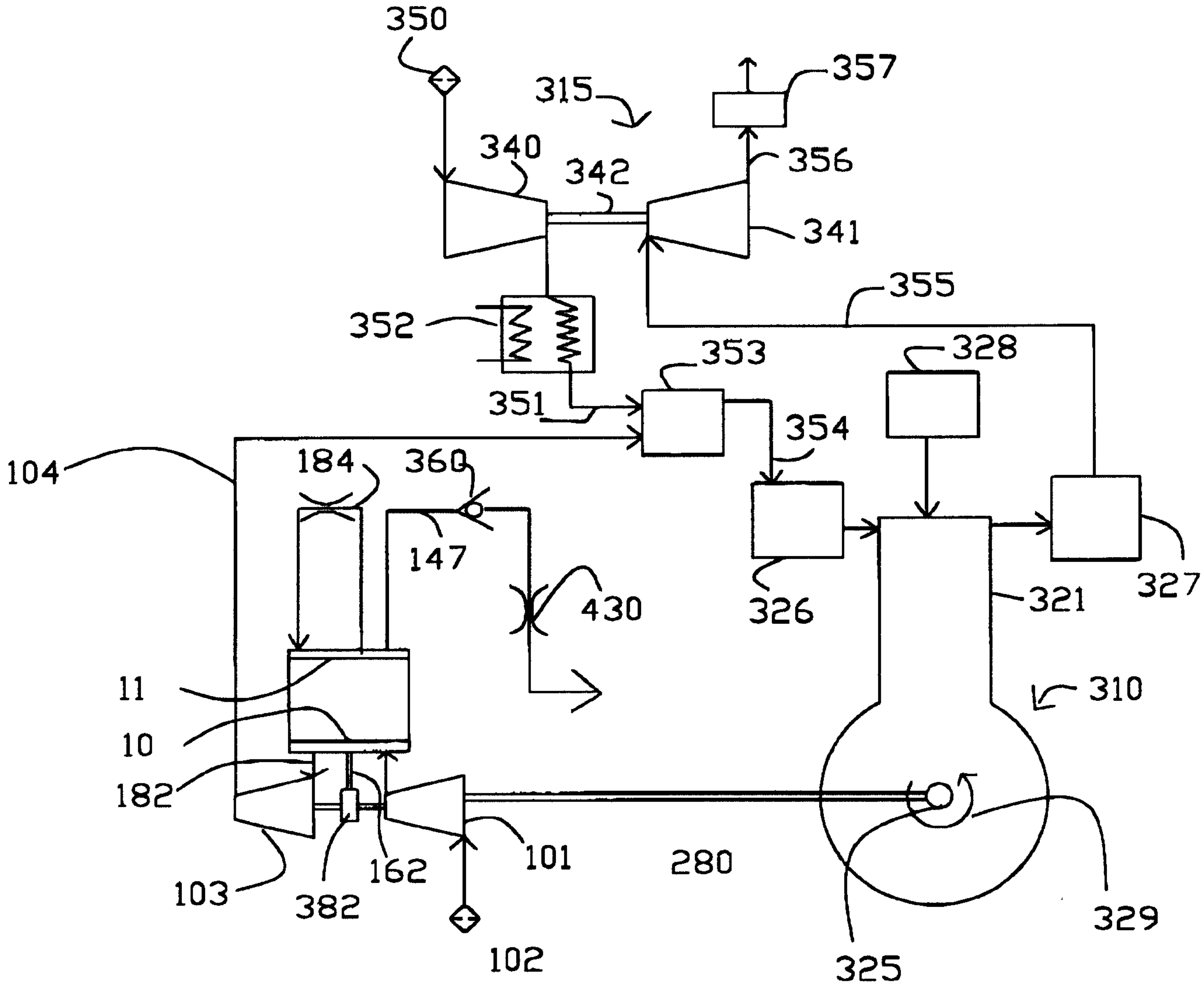
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Fig. 10

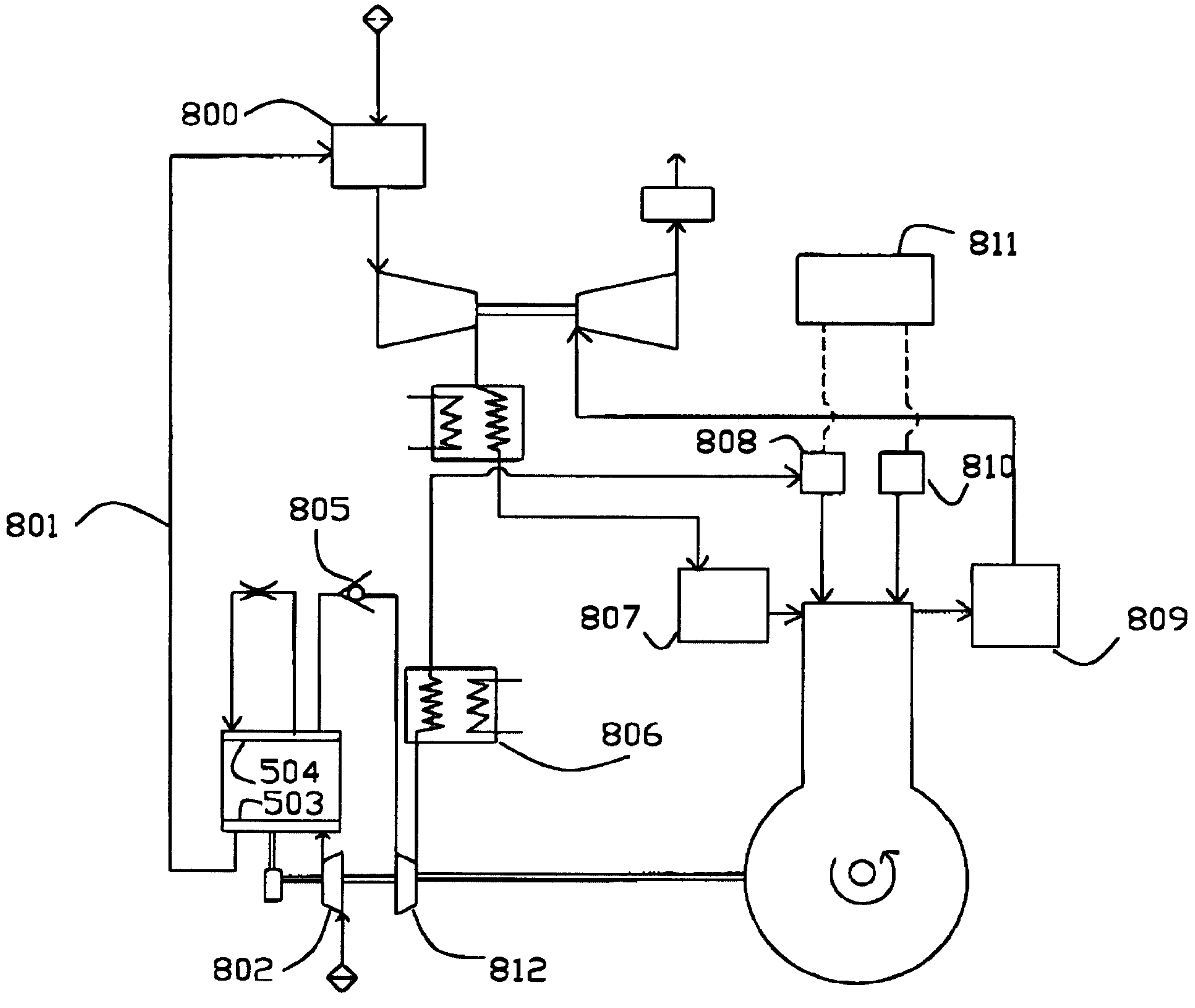

Fig. 11

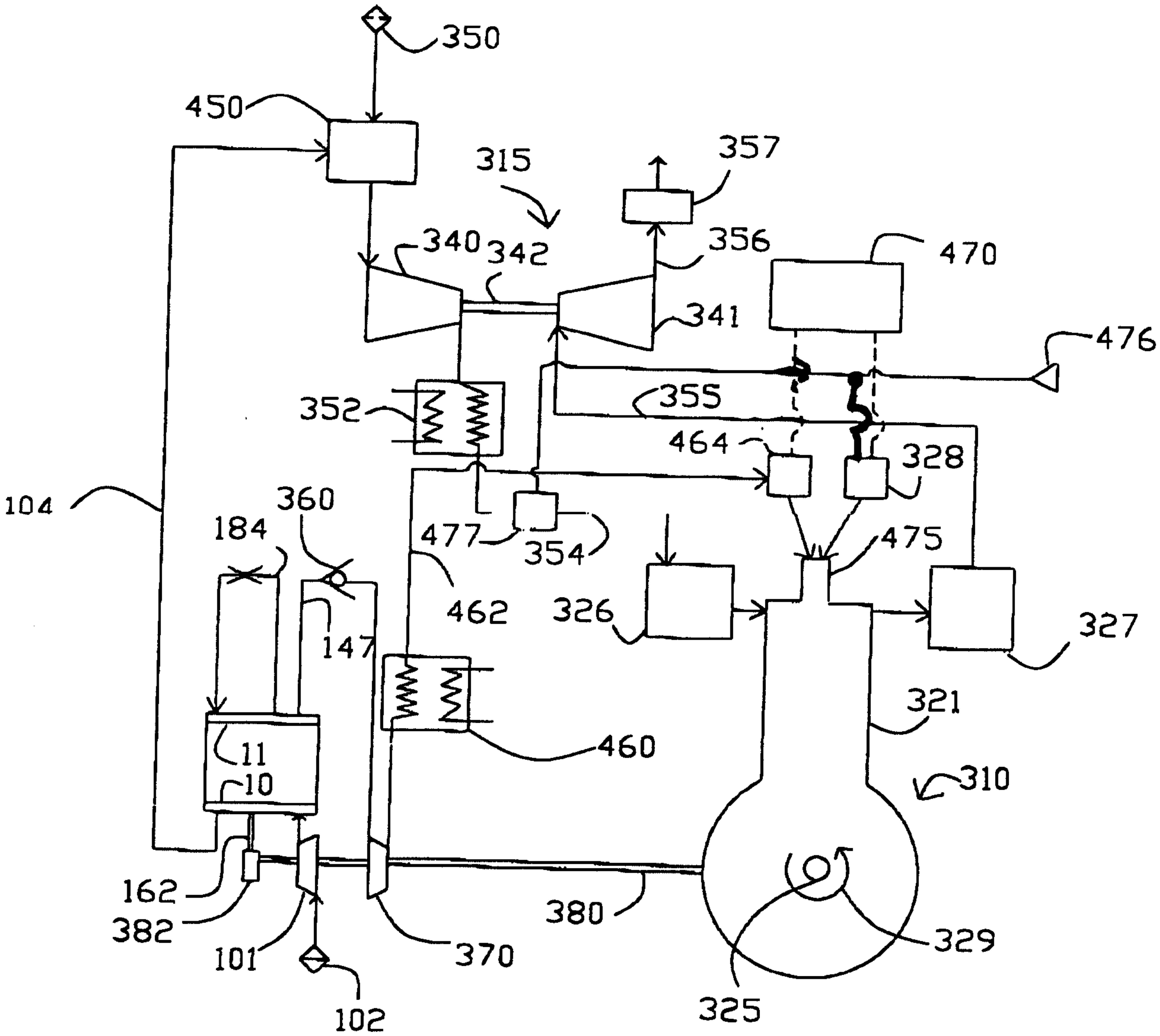
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Fig. 12

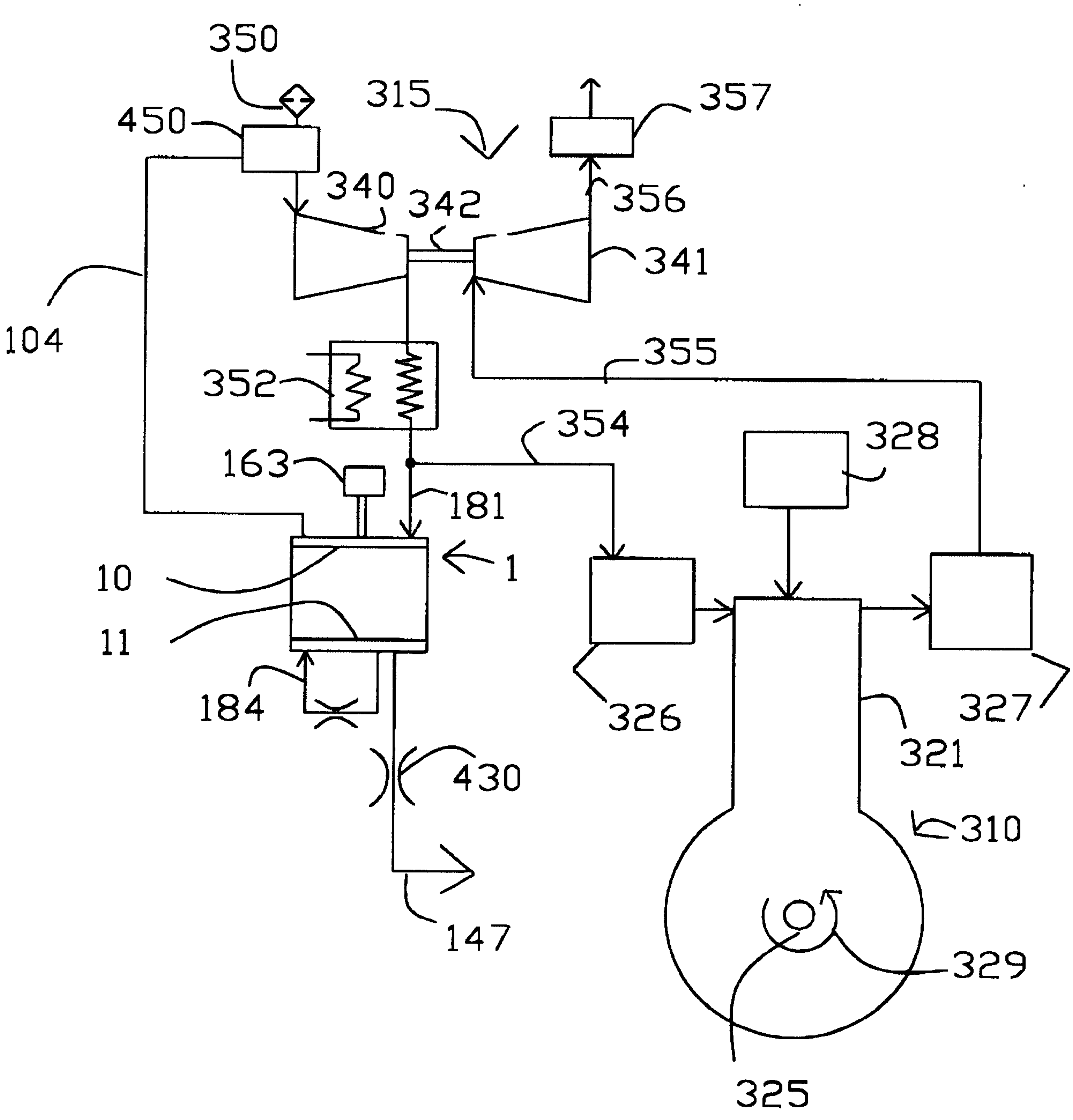
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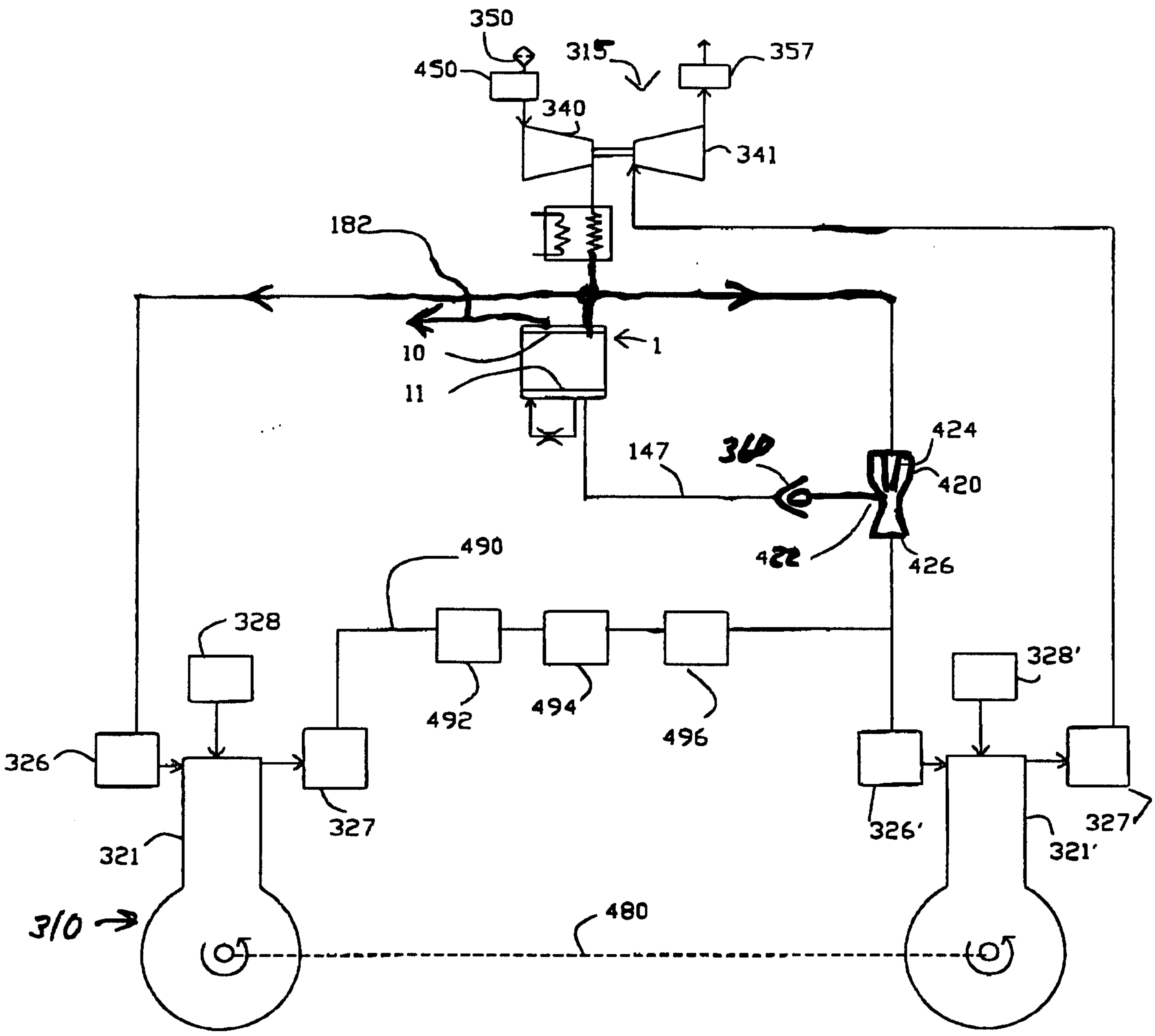
Fig. 13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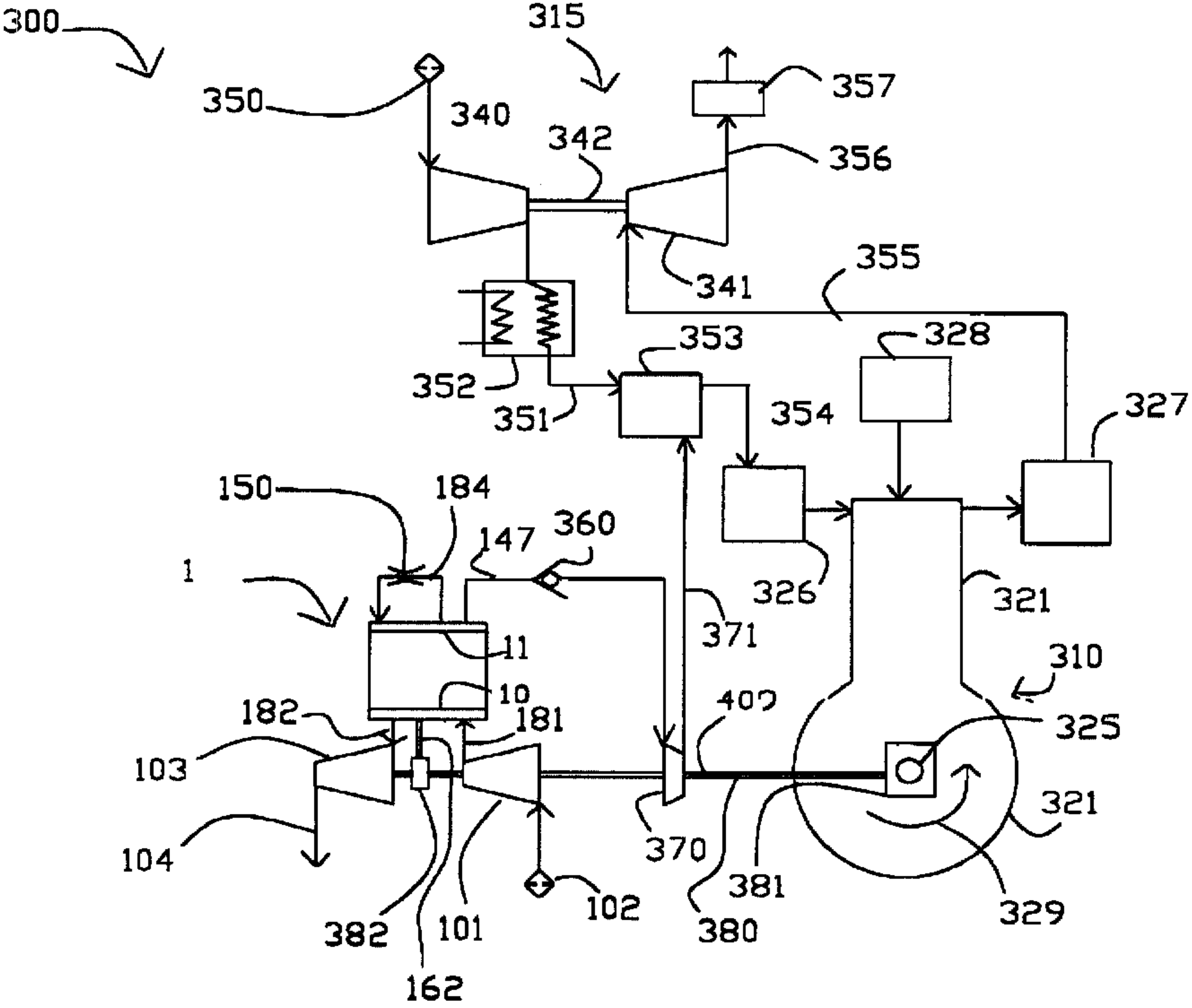
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