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(54) **COMPACT, MODULAR, INTEGRAL PUMP OR TURBINE WITH COAXIAL FLUID FLOW**

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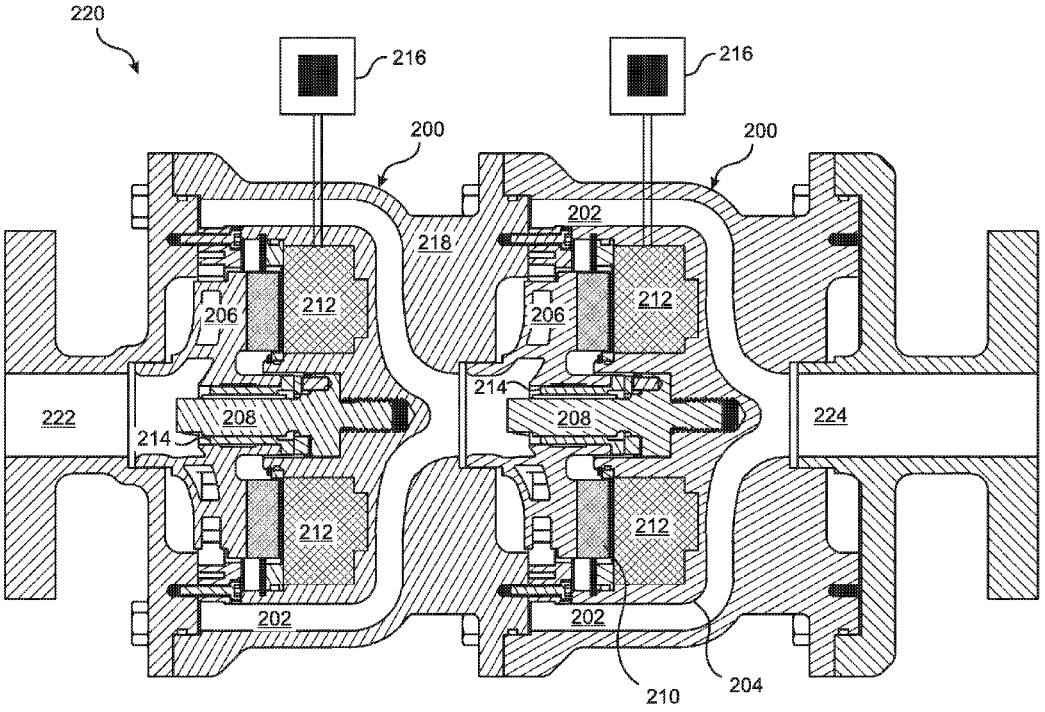
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(57) **ABSTRACT**

A coaxial pump or turbine module directs working fluid past a rotor and through a flow path symmetrically distributed within an annulus formed between an outer module housing and an inner motor or generator coil housing. The inner housing can be cooled by working fluid in the flow path, or by a cooling fluid flowing between passages of the flow path. The flow path can extend over substantially a full length and rear surface of the inner housing. The rotor can be fixed to a rotating shaft, or rotate about a fixed shaft, which can be threaded into the motor and/or module housing. A plurality of the modules can be combined into a multi-stage apparatus, with rotor speeds independently controlled by corresponding variable frequency drives. The motor or generator can include radial or axial permanent magnets and/or induction coils. Embodiments include guide vanes and/or diffusers.



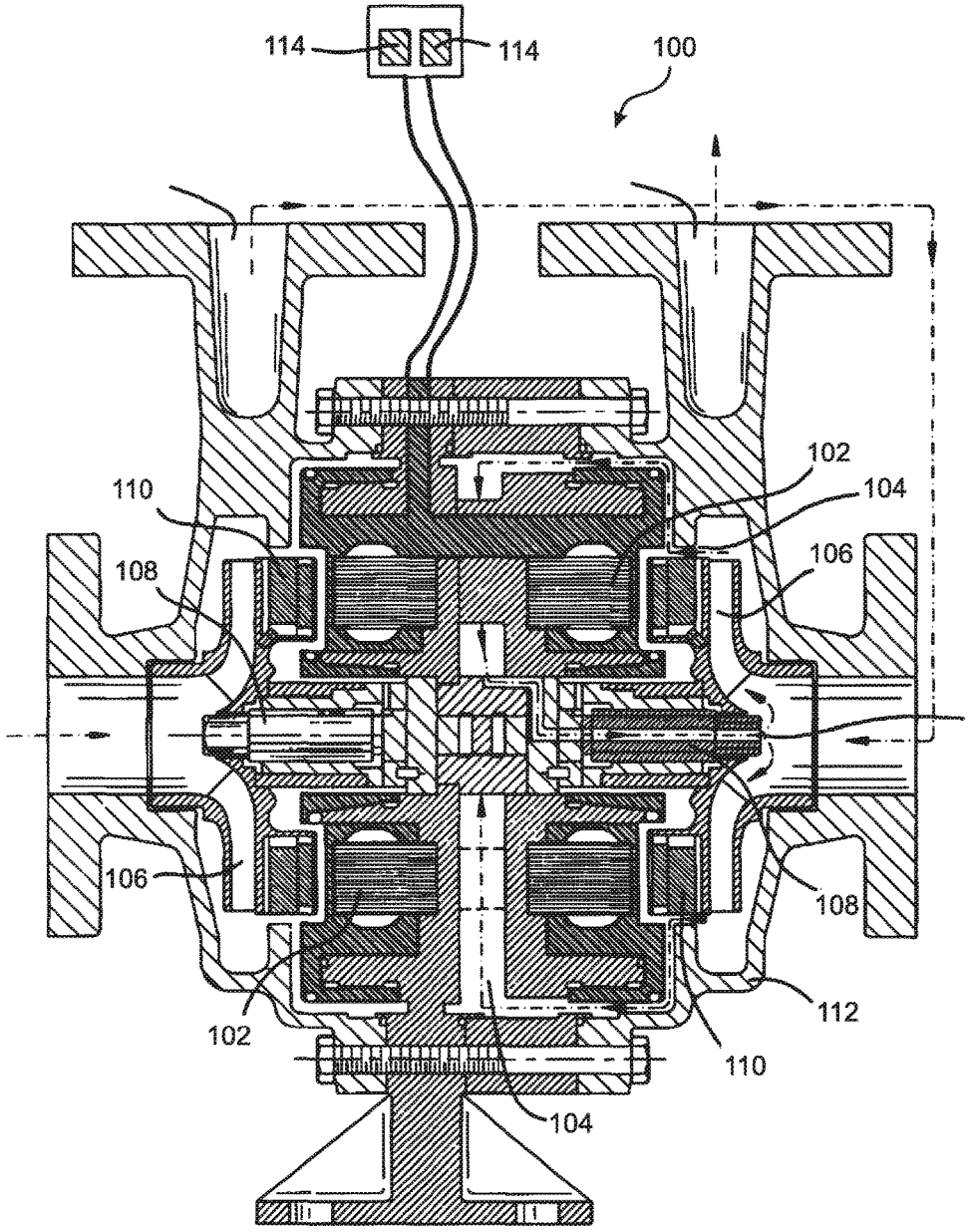


Fig. 1
Prior Art

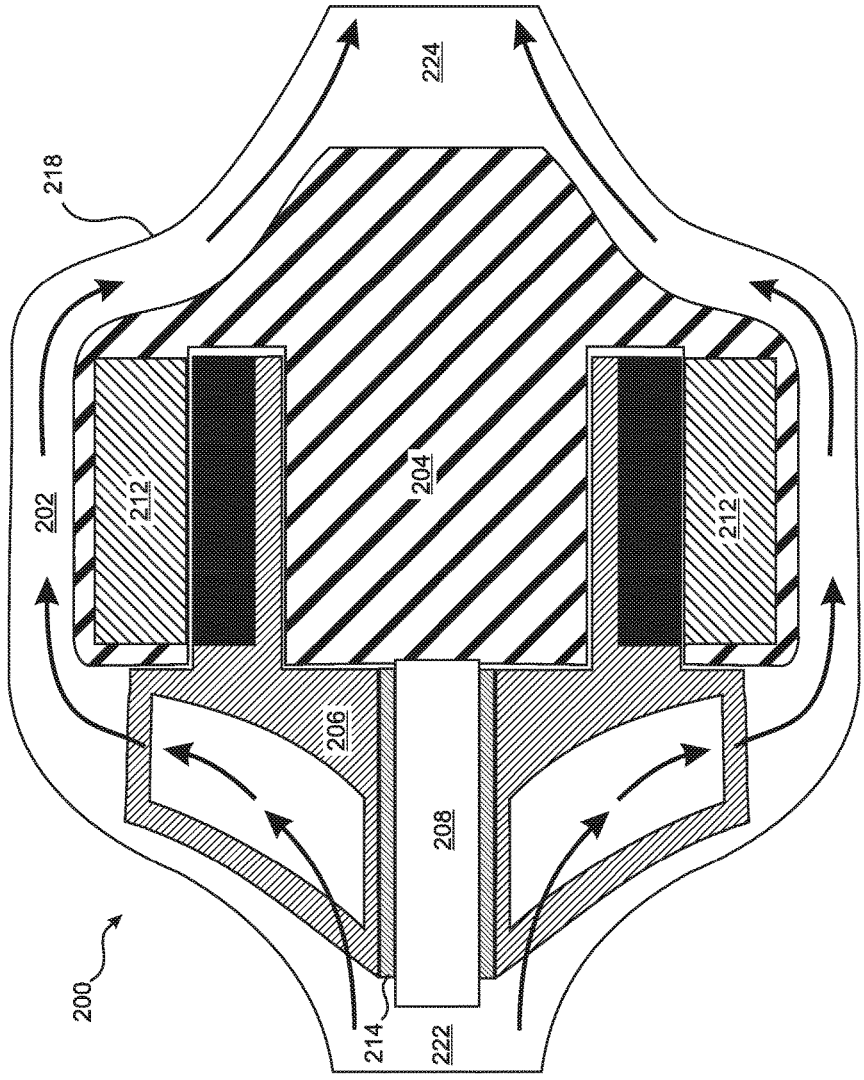


Fig. 2A

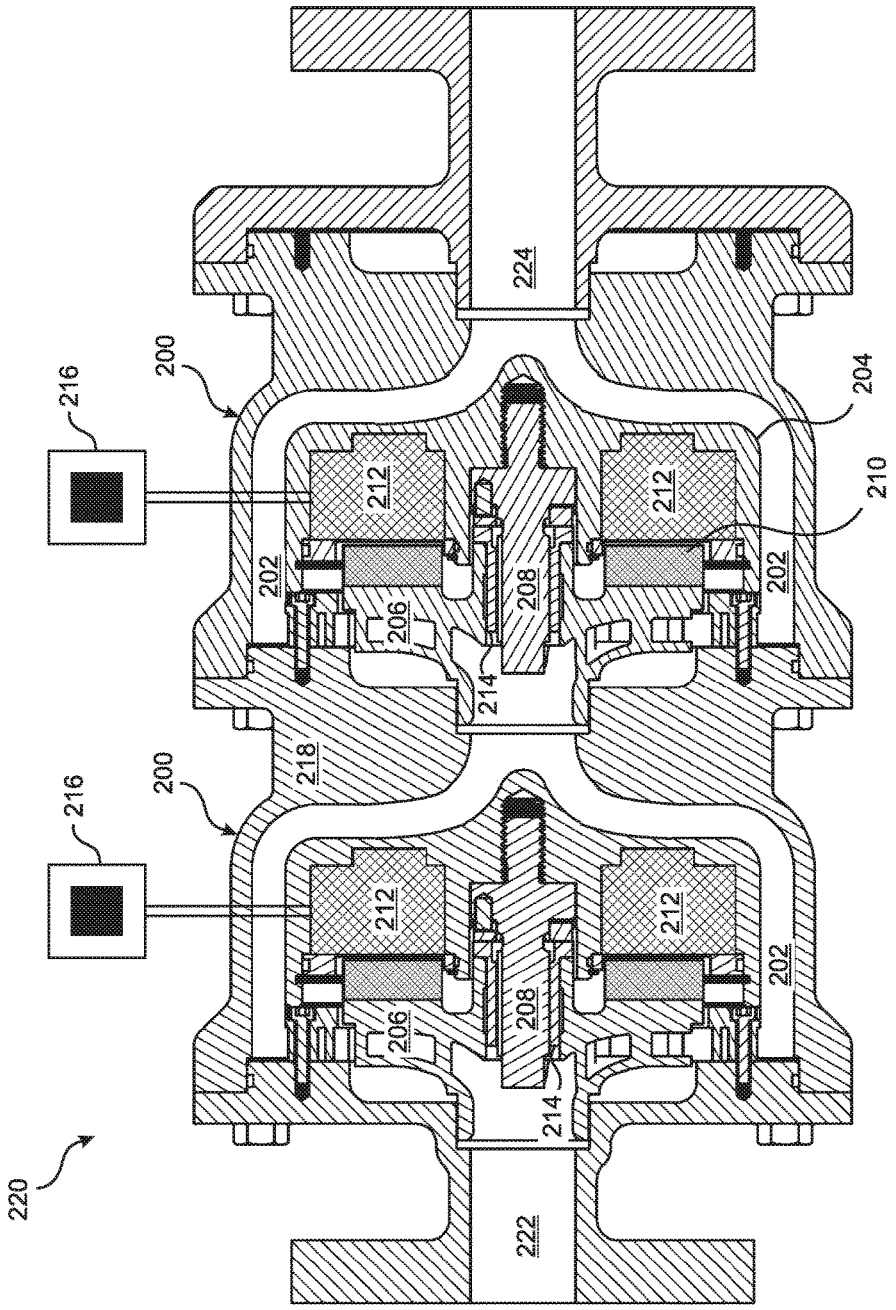


Fig. 2B

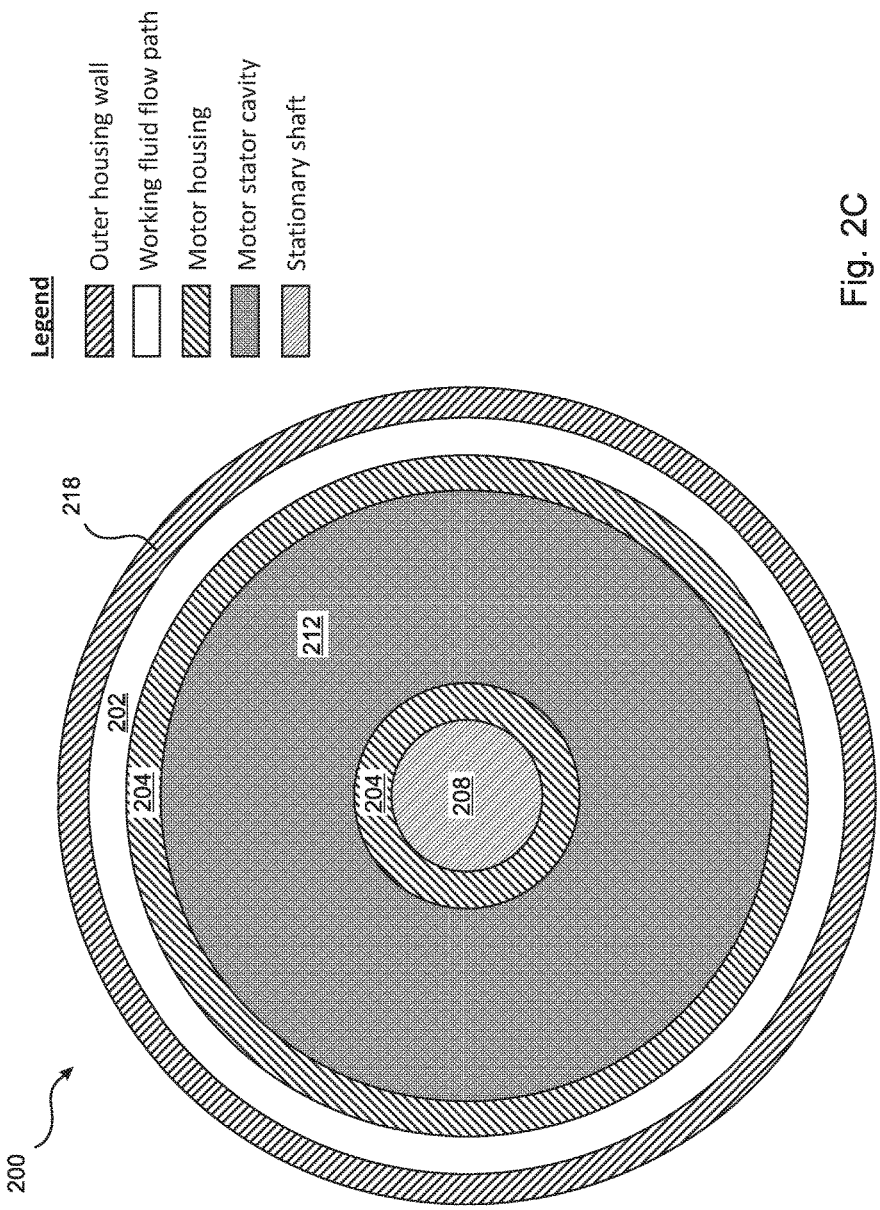

Legend
Outer housing wall
Working fluid flow path
Motor housing
Motor stator cavity
Stationary shaft
200
218
202
204
212
204
208

Fig. 2C

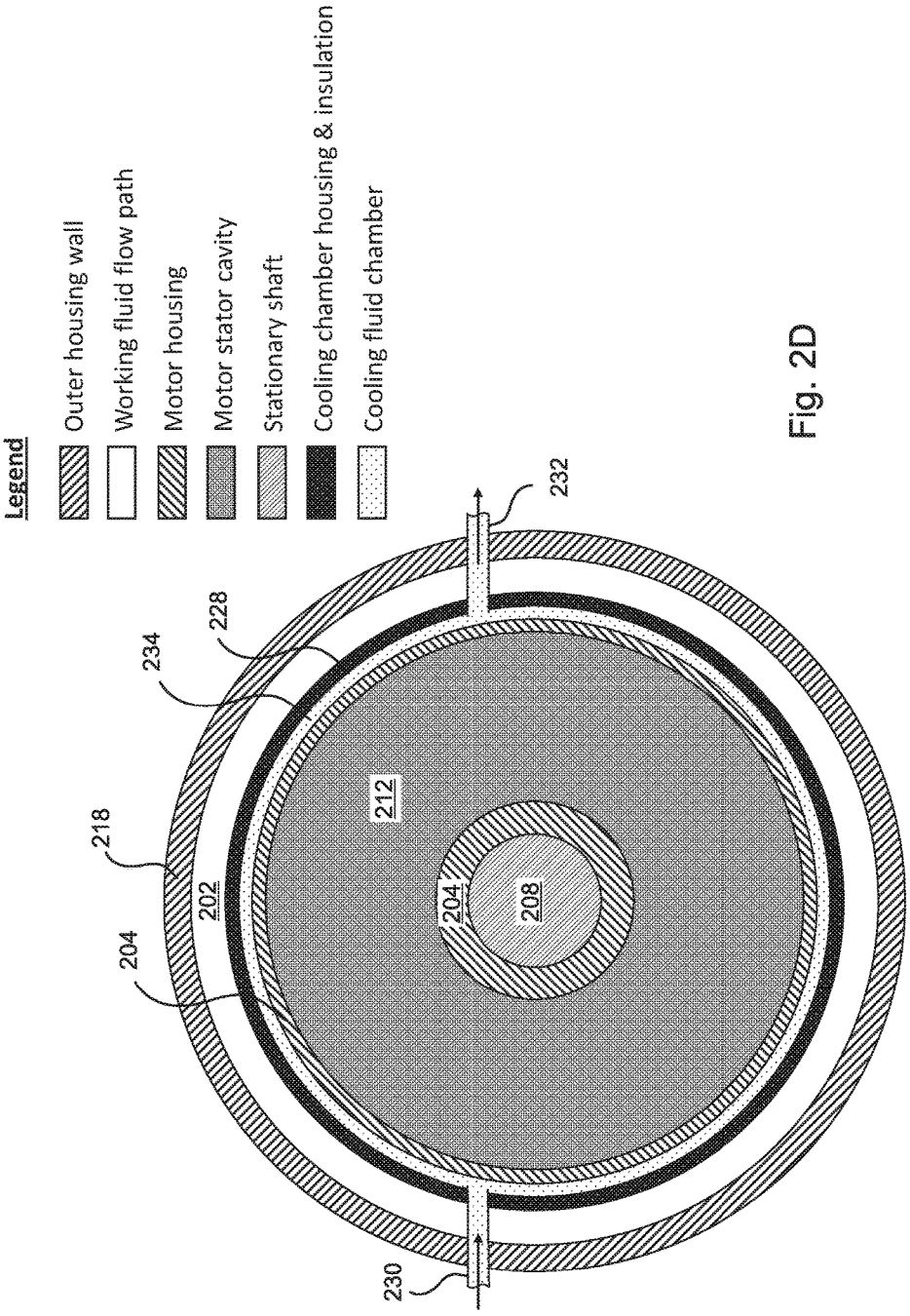

Legend
Outer housing wall
Working fluid flow path
Motor housing
Motor stator cavity
Stationary shaft
Cooling chamber housing & insulation
Cooling fluid chamber
232
228
234
218
202
204
212
204
208
230

Fig. 2D

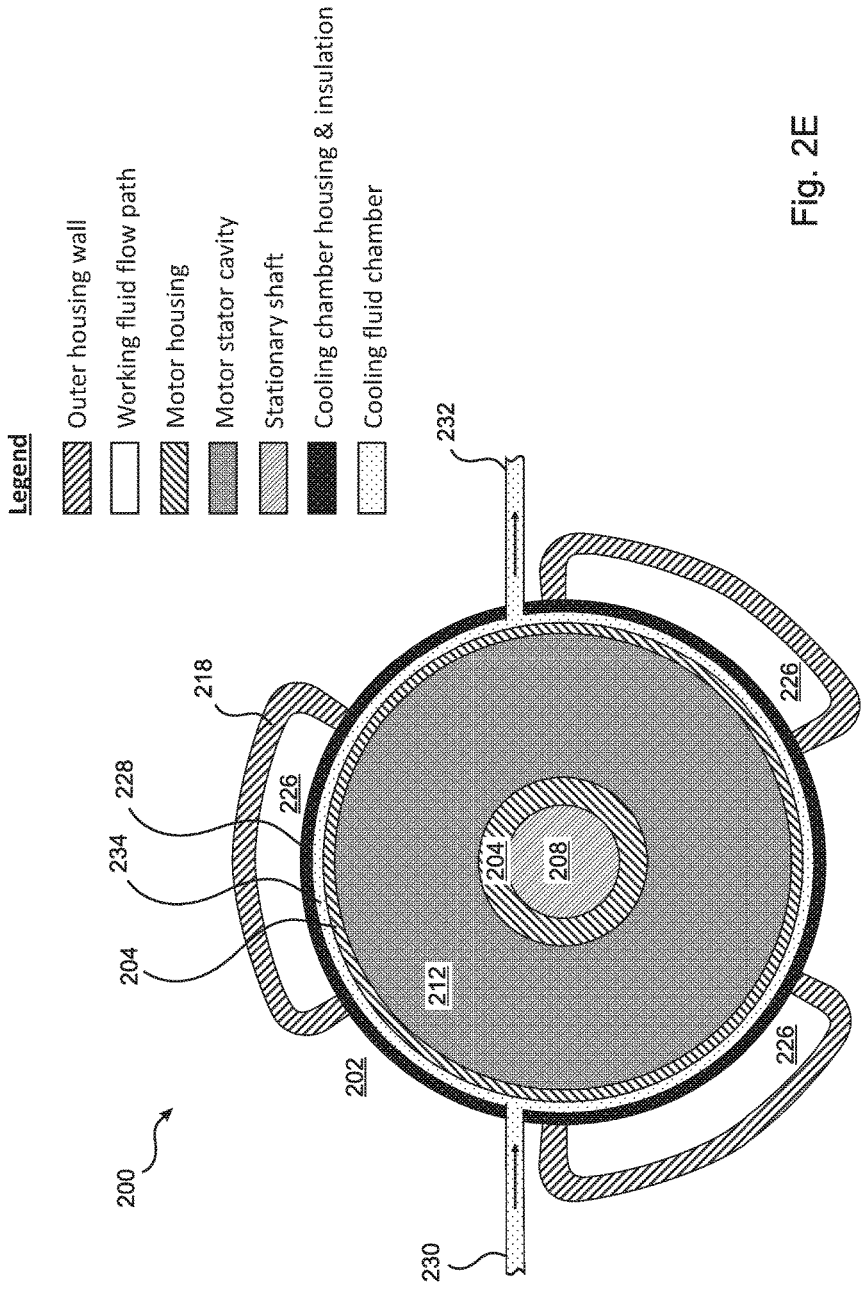

Legend
Outer housing wall
Working fluid flow path
Motor housing
Motor stator cavity
Stationary shaft
Cooling chamber housing & insulation
Cooling fluid chamber
200
202
204
208
212
218
226
228
230
232
234

Fig. 2E

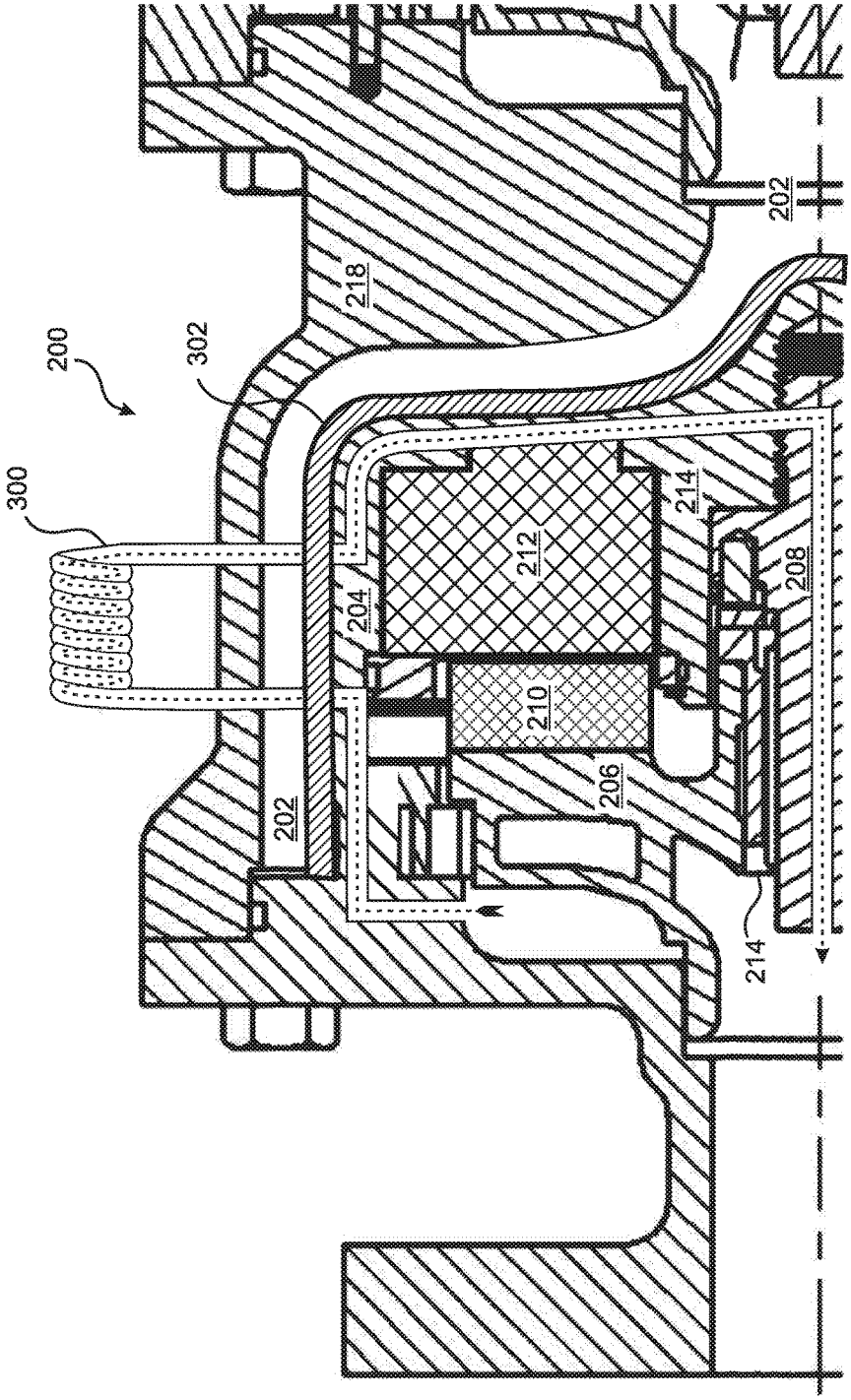


Fig. 3

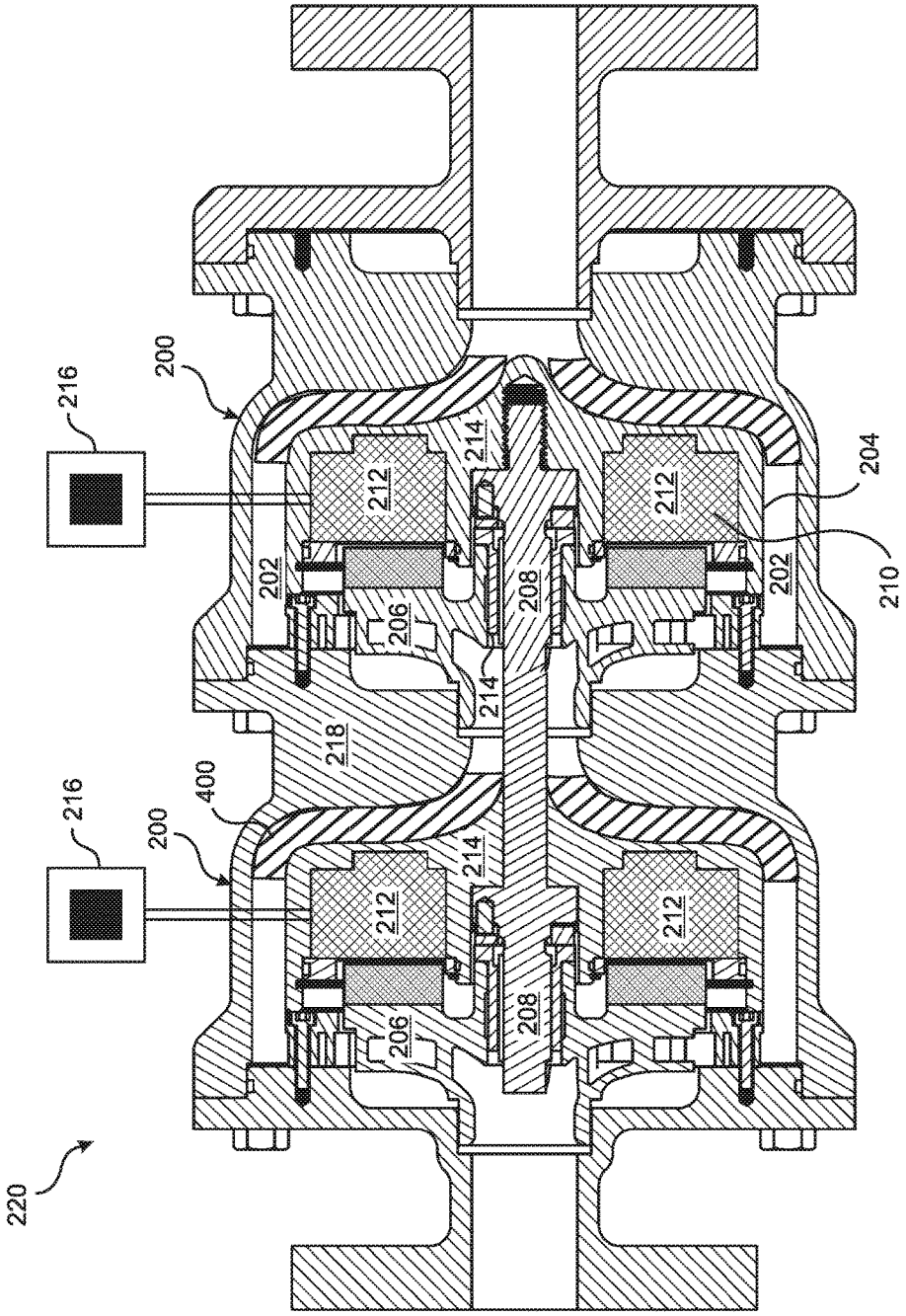


Fig. 4

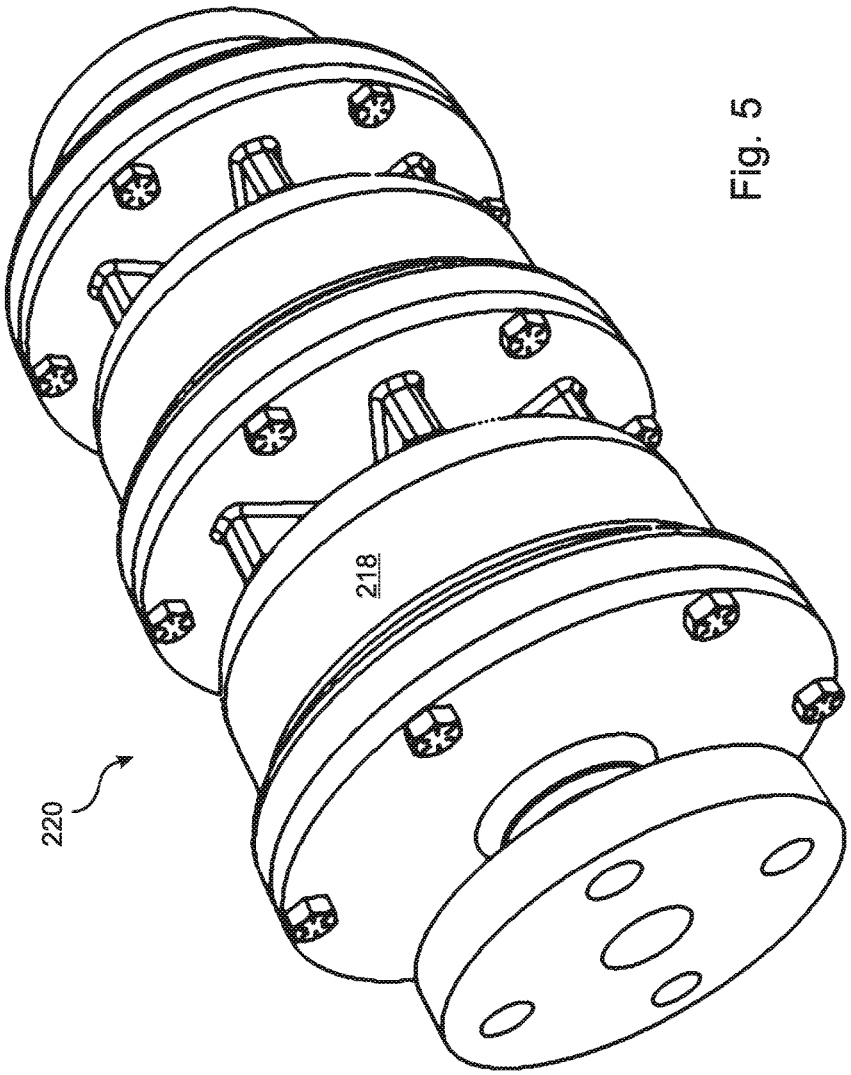


Fig. 5

COMPACT, MODULAR, INTEGRAL PUMP OR TURBINE WITH COAXIAL FLUID FLOW

RELATED APPLICATIONS

[0001] This application is a continuation in part of U.S. application Ser. No. 15/793,457, filed Oct. 25, 2017, which is herein incorporated by reference in its entirety for all purposes.

FIELD OF THE INVENTION

[0002] The invention relates to pumps and turbines, and more particularly, to integral sealless pumps and turbines.

BACKGROUND OF THE INVENTION

[0003] Rotodynamic pumps and turbines are often highly similar in their physical designs, such that the difference between a pump and a turbine can sometimes be mainly a question of use rather than structure. Accordingly, features of the present invention and of the prior art that are discussed herein with reference to a turbine or to a pump should be understood to refer equally to both, except where the context requires otherwise.

[0004] In a conventional rotodynamic pump design, fluid flow and pressure are generated by a rotor, also referred to as an "impeller," that is rotating inside a stationary pump casing. The torque required to drive the rotor is provided by an external motor and transmitted through a rotating shaft to the rotor that rotates within a pump housing. Similarly, in the case of a conventional turbine design, fluid flow and pressure are applied to a rotor, which in the case of a turbine is also referred to as a "runner," causing the rotor to rotate inside of a stationary turbine casing, and the rotation and torque generated by the rotor are transmitted through a rotating shaft to an external generator.

[0005] One of the difficulties of these approaches is that they require the use of dynamic seals to maintain the pressure boundaries at the location where the rotating shaft penetrates the stationary pump or turbine casing. These seals are a source of leakage and other failure modes. In addition, rigid baseplates are required to allow the pump and the motor or turbine and generator to be mounted and aligned with each other so as to avoid vibration issues. Even with rigid baseplates, nozzle loads on the pump or turbine can cause alignment problems between the motor or generator and the mechanical seals.

[0006] These difficulties are avoided by designs that do not include shaft seals. Magnetic coupling drives, for example, do not require dynamic seals on the pump or turbine shaft, because the motor or generator is coupled magnetically through the pump housing to an internal shaft that is supported by product-lubricated bearings located within the housing. However, these designs still require careful alignment of the motor or generator with the rotor housing so as to couple the motor or generator with the rotor shaft as efficiently as possible. Also, the components used for magnetic coupling add complexity and cost to the design.

[0007] Another approach that avoids dynamic shaft seals altogether is to include the motor or generator within the rotor housing, so that shaft seals are not required. Some of these so-called "sealless motor" or "sealless generator" approaches use a radial motor or generator design, whereby magnets are attached at or near the outer radius of the rotor, which is sealed within a thin-walled "can," and an electromagnetic stator located outside of the sealed can surrounds the rotor. However, radial designs necessarily require a significant increase in the diameter of the rotor housing. Another approach is to implement an axial motor or generator design, whereby a disk or "pancake" permanent magnet, brushless DC motor or generator is included within the rotor housing to provide high power density and create the most compact and lightweight single stage pump or turbine units possible.

[0008] However, it can be difficult to cool the motor or generator coils of a sealless motor pump or sealless generator turbine. Typically, special flow paths must be provided within the housing to shunt some of the working fluid through grooves in submerged bearings and/or through another appropriate path to extract heat arising from the coils of the motor or generator. The shunted working fluid is heated by convection from the stator wall and carries the heat away from the stator to be expelled along with the unshunted working fluid.

[0009] Unfortunately, as the shunted fluid passes through passages adjacent to the stator wall, through a hollow rotating shaft, through the shaft bearings, and/or through other appropriate channels, a phase change may occur due to the combination of fluid heating and/or a pressure drop due to the transition from discharge to suction pressure. The resulting exposure to fluid in the vapor phase can result in motor/generator overheating and/or bearing failure. Furthermore, the requirement of diverting a certain fraction of the pump output or turbine input into a cooling flow necessarily reduces the efficiency of the pump or turbine.

[0010] Another problem that is faced by designers of pumps and turbines is how to scale up the capacity of an existing pump or turbine design to meet the requirements of a new application, which generally requires redesigning the physical shape and size of the rotor, operating the rotor at a higher speed, and/or adding additional rotors.

[0011] The total head generated by a pump is a function of the rotor diameter and its rotation speed, while the flow delivery for a given rotor diameter and speed is determined by the rotor width. For a given rotor design, the maximum rotor speed is limited by the amount of torque that the motor can develop. The speed of rotation is also limited by both the frequency limitations of the inverter used to drive the motor and the NPSH (Net Positive Suction Head) available at the inlet of the rotor.

[0012] Similarly, in the case of a sealless generator turbine, the generator places a "load" on the rotor according the electromagnetic coupling between the rotating magnets and the generator coils, under the control of an inverter or other control electronics associated with the generator, such that the maximum output of the generator depends on the maximum torque that can be delivered by the rotor, which for a given fluid flow depends on the rotor diameter and width.

[0013] One approach to increasing output of a pump or turbine is therefore to increase the size of the rotor and the capacity of the motor or generator. However, the additional size and bulk that result from this approach can be problematic.

[0014] One way to reduce the size and bulk of the rotor casing and other components of a pump or turbine, when higher fluid pressures or generator outputs are required, is to use small diameter rotors operating at high speeds. However, this approach does not work for sealless motor and generator

designs, because the rotor is also a component of the motor or generator. In particular, in axial sealless designs smaller diameter rotors provide smaller available disk areas for mounting the permanent-magnets or inductive magnets, thereby limiting the torque that can be developed by the motor, or the electrical power that can be produced by the generator. Another limitation is the relative unavailability of sealless motor designs (magnetic rotors and stators) that can deliver a range of pressures and flow rates, and sealless generator designs that operate efficiently over a range of pressures and flow rates.

[0015] Accordingly, for a sealless pump or turbine, the pump head or turbine output provided by a rotor can only be increased by enlarging the diameter of the rotor. However, this approach increases the bulk of the apparatus, because it requires use of a larger and thicker rotor casing and other structural components to contain the larger components and higher fluid pressures.

[0016] Increasing output by expanding the number of rotors can also be problematic. In a multi-stage pump or turbine, a single, large motor provides torque to a plurality of rotors through a common shaft, or a single, large generator receives torque from a plurality of rotors through a common shaft.

[0017] This approach typically requires a large and bulky motor or generator, and further requires that the shaft must be enlarged in diameter and increased in length as the number of rotor stages is increased, so as to accommodate the combined torque and of all of the rotors. Whether configured in a horizontal or a vertical arrangement, these long shafts with multiple rotor stages require larger bearings and increase the likelihood of bearing failures. In addition, the long shafts of multi-stage pumps can lead to various rotordynamic issues related to shaft deflections and critical speeds. Because of these issues, and for other reasons, each multi-stage pump design is applicable only to a specified number of stages, and cannot be easily scaled to accommodate requirements for different numbers of stages. Instead, scaling of an existing design typically requires a new pump design.

[0018] Furthermore, the elongated shaft, multi-stage approach requires that all of the rotors rotate at the same speed, which can limit the efficiency of the design. In addition, a failure of any one stage in a multi-stage pump will cause an immediate and total failure of the entire pump or turbine.

[0019] Of course, one alternative to designing and implementing a multi-stage pump or turbine is simply to interconnect a plurality of single-stage pumps or turbines in series and/or parallel. In the case of pumps, the output of each pump in series becomes the input of the next pump, which further increases the pressure, while the outputs of pumps configured in parallel are combined to increase output flow. In the case of turbines, the fluid flows through the rotors, either in series or in parallel, and the electrical outputs of the turbine generators are combined in series and/or in parallel to create a higher total output voltage and/or current.

[0020] However, this approach of combining a plurality of pumps or turbines into a multi-stage apparatus requires the use of bulky and complex fluid interconnections or manifolds, so that excessive space is consumed. In addition, the reliability of the apparatus is reduced, because the number of hoses and/or other fluid connections, and therefore the opportunities for leaks and/or other failure modes, increases as the number of pumps or turbines is increased.

[0021] It has been suggested that a sealless disk motor pump might include more than one motor within a common housing. However, the fluid interconnections and motor/generator cooling requirements of a sealless disk motor design tend to limit this approach to only two stages at most.

[0022] For example, with reference to FIG. **1**, one approach includes two centrifugal pump stages within a single sealless motor design **100**, whereby each stage is driven by its own motor **102**, and whereby the two stages are positioned back-to-back, such that the two motors **102** are included within a common central space within the casing **112**, so that they can be cooled by a common process flow path **104**. In the example shown in FIG. **1**, the two rotors **106** face in opposite directions, and each includes permanent magnets **110** attached to a rear side thereof.

[0023] In some versions of this approach, the motors **102** are controlled by separate variable frequency drives ("VFD's") **114** and each of the rotors **106** rotates about a separate, fixed shaft **108**, while in other versions the motors share a common controller and/or shaft. By placing the two motors **102** within the same volume, the cooling path **104** in this approach is only slightly more complex than the cooling path in a single stage integral motor design, and the loss of efficiency due to diverting flow into the cooling path is minimized. However, this approach is, by its nature, limited to only two stages, and there is no obvious approach for expanding the design beyond the two-stage limit.

[0024] What is needed, therefore, is an integral, "sealless" pump or sealless turbine design that is compact and modular, such that more than two of the pump or turbine modules, preferably up to an arbitrarily large number, can be combined in series without bulky fluid interconnections therebetween. It is further preferable in embodiments that little or no process fluid be diverted away from the primary flow path for cooing the motor or generator within each module, that the rotors in the modules rotate separately, and/or that the motors/generators in the modules be separately controllable.

SUMMARY OF THE INVENTION

[0025] The present invention is a "sealless" motor pump or sealless generator turbine that is configured as a highly compact module having a "concentric" flow design. The disclosed modular design enables more than two of the pump or turbine modules, preferably up to an arbitrarily large number, to be combined in series without bulky fluid interconnections therebetween, and with the rotor in each module rotating separately on its own shaft or other supports. In embodiments, little or no process fluid is diverted away from the primary flow path for cooing the motor or generator within each module. In various embodiments, the rotors in the motors or generators in the modules are separately controllable.

[0026] According to the present invention, the coil housing of the motor or generator is concentrically surrounded by the housing of the module, creating an annular space therebetween surrounding the motor or generator coils and centered on a primary axis of the motor or generator. Working fluid enters the module axially through a proximal inlet that is located substantially along the primary axis, and is discharged axially from the module through a distal outlet that is also located substantially along the primary axis. Within the module, the working fluid flows symmetrically

past the motor or generator coils through either a plurality of substantially identical flow passages arranged symmetrically about the circumference of the motor or generator coils, or through a single, annular flow passage that surrounds the motor or generator coils. This symmetric distribution of the flow passage(s) in the region surrounding the motor or generator coils provides a compact design wherein the module housing is only moderately larger in diameter than the motor or generator housing.

[0027] In various embodiments suitable for use with relatively cool working fluids, the flow passages or single annular flow passage is/are in direct thermal contact with the housing of the motor or generator coils, thereby cooling the motor or generator coils. In some of these embodiments, more than 80% of the working fluid is brought into thermal contact with the motor or generator coil housing, and at least 20% of the motor or generator coil housing is in thermal contact with the working fluid. In various embodiments, more than 90% of the working fluid is brought into thermal contact with the motor or generator coil housing, and at least 50% of the motor or generator coil housing surface is in thermal contact with the working fluid.

[0028] In multi-passage embodiments suitable for use with hot working fluids, thermal insulation is provided between each of the plurality of substantially identical flow passages and the housing of the motor or generator coils. In some of these embodiments, a cooling fluid is circulated around the motor or generator coil housing in an annular space, such that the cooling fluid is in direct contact with the housing of the motor or generator coils, thereby cooling the motor or generator coils and protecting them from any residual heating by the hot working fluid.

[0029] In other embodiments where hot working fluid flows through a single, annular flow passage, thermal insulation is provided between the annular flow passage and the housing of the motor or generator coils, and in some of these embodiments, a separate cooling fluid is circulated through a cooling annulus or cooling passages provided beneath the thermal insulation.

[0030] In embodiments, the concentric design of the present invention is implemented as a highly compact module that can be used alone or in series with a plurality of identical modules to form a multi-stage pump or turbine in which each stage includes both a rotor and an associated motor or generator. This modular design allows combination of the modules into an arbitrary number of stages without adding additional complexity or complications to the design, operation, and maintenance of the apparatus. In particular, because the rotor in each module is supported by a dedicated shaft or other supports, high stage counts do not raise any issues regarding shaft size, shaft deflection, rotordynamics, bearing loads, motor alignment, or alignment between stages.

[0031] In some embodiments, the rotor of each module is fixed to a rotating shaft. In other embodiments, the shaft of each module is fixed, and the rotor rotates about the shaft, e.g. on bearings. For example, the shaft for each module can be inserted through the rotor hub and threaded into the module housing, which facilitates easy assembly and maintenance without special tools.

[0032] Certain embodiments include modules having an inverted rotor/stator configuration, whereby the rotor and the stator can both rotate independently from each other in opposite directions. Some embodiments include stators and/or diffusers that rotate individually. In some of these embodiments, the diffusers are implemented in a manner similar to the disclosure of patent application U.S. Ser. No. 15/101,460, which is included herein by reference in its entirety for all purposes.

[0033] In still other embodiments, the disclosed module does not include a shaft. Instead, a wear ring clearance on the front of the rotor acts as the primary radial and axial bearing. Torque is thereby transmitted directly from or to the electromagnet stator coils of the motor to the rotor, or electromagnetic energy is transferred directly from the rotor to the generator, without the use of a rotating shaft.

[0034] In some embodiments, the disclosed pump or turbine module includes a radial motor or generator design, whereby a plurality of permanent magnets are attached at or near the periphery of the rotor, and the rotor is surrounded by an electromagnet stator. In other embodiments, the disclosed module includes an axial, "disk" or "pancake" motor or generator, whereby a plurality of permanent magnets are attached to a rear side of the rotor, and are caused to pass close to electromagnetic coils of an axially adjacent stator as the rotor is rotated. Some embodiments that include permanent magnet motors or generators further include variable speed drives that enable the synchronous operating speeds of the modules to rise above 3600 rpm.

[0035] Other embodiments include induction motors or generators that utilize non-permanent magnets, such as "squirrel cage" rotor coils in which currents are induced by the stator electromagnets during pump or turbine operation.

[0036] In embodiments, the motor or generator coils are sealed from the working fluid using static sealing methods, which eliminates any need for dynamic mechanical seals, and avoids the problems of alignment, leakage, and/or maintenance that would otherwise arise therefrom.

[0037] Various embodiments having centrifugal designs include radial flow rotors. Some of these embodiments include rotors with specific speeds below about 2,000 US units. Other embodiments include stages with radial flux motor or generator designs and higher specific speed mixed flow rotor designs.

[0038] In embodiments, the rotors are axially and radially located by product-lubricated bearings provided in each modular stage, which allows the bearings in each stage to be designed to handle the loads from that stage only. This approach completely eliminates the risk of overloading bearings due to combined stage loading in a multistage arrangement, and provides a design that is more compact because there is no need to use oversized bearings. Using the working fluid as a lubricant for the bearings in embodiments also eliminates the need for an external oil lubrication system and greatly simplifies the overall pump design. In embodiments, one-way thrust bearings are used in place of separate axial and radial bearings.

[0039] In various embodiments, the motors or generators in a multi-stage apparatus are separately controllable. Embodiments include a plurality of variable frequency drives (VFD's), and in some of these embodiments the motor or generator in each stage is independently controlled by a dedicated VFD. One of the key benefits in some of these embodiments is that the first stage can run at lower speeds than the rest of the apparatus, so as to accommodate low net positive suction head ("NPSH") and off-peak conditions. In

some applications, varying the speed of only the final stage provides a useful approach precisely controlling the output pressure and/or flow.

[0040] Providing individual VFD drives for each stage can also serve as a fail-safe redundancy, whereby if one stage fails, the rest will continue to operate and the apparatus will continue to function. The continued function after failure of a pump or turbine stage may be with reduced head and flow, or the speed of the remaining stages can be increased to compensate for the lost head and flow of the failed stage. This approach creates a failure scenario wherein the pump or turbine continues to operate, possibly at reduced head and flow, until an operator, after becoming aware of the stage failure, has time to safely shut down the system. In contrast, the failure of one stage in a traditional pump or turbine would result in failure of the entire apparatus, with a complete loss of performance and a sudden, uncontrolled shutdown of the system. Using a sensorless motor along with an appropriate VFD also reduces the instrumentation required on each stage in various embodiments.

[0041] One general aspect of the present invention is a sealless pump or turbine module having an integral motor or generator, the module comprising an inlet located at a proximal end of the module, the inlet being on a central axis of the module, an outlet located at a distal end of the module, the outlet being on a central axis of the module, an outer housing surrounding the module, a rotor suspended within the outer housing, and a motor within the outer housing configured to drive a rotation of the rotor, or a generator within the outer housing configured to be driven by the rotation of the rotor. The motor or generator comprises a stator within an inner housing, the stator comprising an electromagnet directed toward the rotor and a plurality of magnetic devices cooperative with the rotor and configured to pass in proximity to the electromagnet as the rotor rotates. The pump or turbine module further includes a flow path symmetrically distributed about the inner housing. The pump or turbine module is configured to direct a flow of working fluid from the inlet through the flow path to the outlet such that the working fluid is symmetrically distributed about the inner housing as it flows past the stator within the flow path.

[0042] In some embodiments, the flow path is an annular flow path surrounding the inner housing. In other embodiments, the flow path comprises a plurality of flow passages arranged symmetrically about the inner housing.

[0043] In any of the above embodiments, the rotor can be suspended by a rotatable shaft, and the rotor is fixed to the shaft. Or the rotor can be suspended by a fixed shaft, and configured to rotate about the shaft. In some of these embodiments, the rotor is supported on the fixed shaft by a pair of bearings, one of which maintains an axial position of the rotor while the other of which provides radial support of the rotor. In other of these embodiments, the rotor is supported axially and radially on the fixed shaft by a single, one-way thrust bearing. In any of these embodiments, the rotor can be supported on the fixed shaft by at least one bearing that is lubricated by the process fluid. In any of these embodiments, the fixed shaft can be fixed to at least one of the inner housing and the module housing, which can be by threaded attachment.

[0044] In any of the above embodiments, the magnetic devices can be permanent magnets or squirrel cage coils.

[0045] In any of the above embodiments, the magnetic devices can be fixed to the rotor, or they can be fixed to a disk that is coaxial with the rotor and proximal to the rotor.

[0046] In any of the above embodiments, the flow path can extend over at least 50% of a surface of the inner housing, and at least 90% of the working fluid that flows through the module from the inlet to the outlet is caused to flow through in direct thermal contact with the inner housing.

[0047] In any of the above embodiments, the module can be configured to require all of the working fluid flowing from the inlet to the outlet to flow through the flow path.

[0048] In any of the above embodiments, the module can further comprise thermal insulation interposed between the flow path and the inner housing, and a cooling fluid path formed between the thermal insulation and the inner housing, the cooling fluid path being in thermal communication with the inner housing and configured to enable an exchange of heat between the inner housing and a cooling fluid flowing through the cooling fluid path.

[0049] In any of the above embodiments, the module can further comprise stationary guide vanes within the flow path through which electrical wiring is routed without exposing the electrical wiring to the working fluid.

[0050] In any of the above embodiments, the stator can be configured to rotate independently of the rotor and in a direction that is opposite to a rotation of direction of the rotor.

[0051] In any of the above embodiments, the module can further comprise a diffuser that is cooperative with the rotor but is driven by a separate diffuser motor and is thereby able to rotate independently of the rotor.

[0052] In any of the above embodiments, the electromagnet of the stator can be directed toward a radial periphery of the rotor, and the magnetic devices can be fixed near the radial periphery of the rotor, or the stator can be directed toward a side of the rotor, and the magnetic devices can be fixed to the side of the rotor or to a disk that is coaxial with and proximal to the side of the rotor.

[0053] A second general aspect of the present invention is a multi-stage apparatus comprising a plurality of interconnected modules, each of said modules comprising an inlet located at a proximal end of the module, the inlet being on a central axis of the module, an outlet located at a distal end of the module, the outlet being on a central axis of the module, an outer housing surrounding the module, a rotor suspended within the outer housing, and a motor within the outer housing configured to drive a rotation of the rotor, or a generator within the outer housing configured to be driven by the rotation of the rotor. The motor or generator comprises a stator within an inner housing, the stator comprising an electromagnet directed toward the rotor, and a plurality of magnetic devices cooperative with the rotor and configured to pass in proximity to the electromagnet as the rotor rotates. The module further comprises a flow path symmetrically distributed about the inner housing. Each of the modules is configured to direct a flow of working fluid from the inlet through the flow path to the outlet such that the working fluid is symmetrically distributed about the inner housing as it flows past the stator within the flow path.

[0054] In embodiments, at least two of the motors or generators of the modules can be independently controlled so as to cause the corresponding rotors to rotate at different

rates. In some of these embodiments, the two, independently controlled motors or generators are controlled by separate variable frequency drives.

[0055] In any of these embodiments, the modules can be configured such that the apparatus as a whole is able to continue functioning as a pump or as a turbine despite failure of at least one of the modules included in the apparatus.

[0056] And any of these embodiments can further include control electronics that provide shared support to at least two of the modules.

[0057] The features and advantages described herein are not all-inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification, and claims. Moreover, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes, and not to limit the scope of the inventive subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0058] FIG. **1** is a cross-sectional illustration drawn to scale of a prior art two-stage integral motor pump cooled by a dedicated cooling flow;

[0059] FIG. **2**A is a cross-sectional, simplified illustration of a single-stage module of the present invention having a radial motor design;

[0060] FIG. **2**B is a cross-sectional illustration drawn to scale of a two-stage embodiment of the present invention having an axial motor design;

[0061] FIG. **2**C is a simplified cross-sectional view of an embodiment that includes an annular flow path through the annular space;

[0062] FIG. **2**D is a cross-sectional view similar to FIG. **2**C, but including an additional concentric layer of thermal insulation and a concentric cooling annular passage;

[0063] FIG. **2**E is a simplified cross-sectional view of an embodiment that includes a plurality of flow paths that are equally distributed about the coil housing of the motor or generator and insulated therefrom;

[0064] FIG. **3** is a cross-sectional illustration drawn to scale of an embodiment similar to FIG. **2**, but including a separate cooling flow path (cooling path not drawn to scale);

[0065] FIG. **4** is a cross-sectional illustration drawn to scale of an embodiment similar to FIG. **2**, but including guide vanes in the process flow path; and

[0066] FIG. **5** is a perspective view drawn to scale of the outer housing of the pump of FIG. **2**.

DETAILED DESCRIPTION

[0067] The present invention is a "sealless" motor pump or sealless generator turbine that is configured as a module having a "concentric" flow design. As an example, a pump embodiment **200** of the present invention is illustrated in FIG. **2**A. It can be seen in the figures that the housing **204** of the motor coils is surrounded by the housing **218** of the module, forming an annular space **202** therebetween. According to the present invention, the working fluid is distributed symmetrically about the annular space **202**, either among a plurality of substantially identical flow passages or through a single annular flow passage. In the embodiment of FIG. **4**A, the annular space **202** serves as an annular flow passage **202** through which the working fluid flows from the inlet **222** to the outlet **224**.

[0068] In the embodiment of FIG. **2**A, the annular flow passage **202** is in direct thermal contact with the housing **204** of the motor coils **212**. This configuration is suitable for applications where the working fluid is relatively cool. In the embodiment, the working fluid is directed by the rotor **206** to pass through the annular flow passage **202** over and around the motor coil housing **204** of the module, so that the motor coils **212** are directly cooled by the discharge of the rotor **206**, and do not require a separate, dedicated cooling fluid.

[0069] In embodiments, the concentric design of the present invention is implemented as a separate, highly compact module that can be used alone, as shown in FIG. **2**A, or combined with a plurality of identical modules to form a multi-stage pump or turbine, as shown in FIG. **2**B. This modular approach enables extension of the design to an arbitrary number of stages without adding additional complexity or complications to the design, operation, and maintenance of the apparatus. In particular, high stage counts do not raise any issues regarding shaft size, shaft deflection, rotordynamics, bearing loads, motor alignment, or alignment between stages.

[0070] More specifically, FIG. **2**B illustrates a two-stage pump embodiment **220** wherein a central axis of the motor **212** in each stage **200** is substantially collinear with the stationary shaft **208** about which the rotor **206** is rotated, such that the process fluid from the rotor **206** flows axially over the motor housing **204** through the annular flow passage **202** formed between the motor housing **204** and the pump coil housing **218** in each stage **200**. While only two stages **200** are shown in FIG. **2**B for convenience of illustration, it will be understood that embodiments are extendable to an arbitrary number of pump stages **200**.

[0071] In some multi-stage embodiments, the rotor **206** in each stage **200** is independently driven, such that the rotor speed of each stage **200** can be separately controlled. For example, a separate variable frequency drive ("VFD") **216** can be dedicated to the control of each stage **200** of the pump.

[0072] In the embodiment of FIG. **2**B, in each stage **200** of the pump **220** a plurality of permanent magnets **210** are attached to a rear side of the rotor **206**, and are caused to pass close to electromagnetic coils **212** of an adjacent stator **212** as the rotor **206** is rotated. Rotors **206** in other embodiments include induction motors that utilize non-permanent magnets **210** such as "squirrel cage" rotor coils in which currents are induced by the stator electromagnets **212** during pump or turbine operation. Torque is thereby transmitted directly from the electromagnet motor coils **212** to the rotor **206**, or electromagnetic energy is transferred from the rotor to the generator coils, without the use of a rotating shaft. In embodiments, the motor coils **212** are sealed from the working fluid using static sealing methods (not shown), which eliminates any need for dynamic mechanical seals, and avoids the problems of alignment, leakage, and/or maintenance that would otherwise arise therefrom.

[0073] Axial and radial locating of the rotor **206** in each stage is provided in the embodiment of FIG. **2**B by product-lubricated bearings. By using individual bearings **214** for each rotor stage **200**, the bearings **214** in each stage **200** can be designed to handle the loads from that stage only, and the risk of overloading bearings from combined stage loading in a multistage arrangement **220** is completely eliminated. Using the working fluid as a lubricant for the bearings **214**

in embodiments eliminates the need for an external oil lubrication system and greatly simplifies the overall pump design and maintenance.

[0074] In some embodiments, such as FIG. **2**A, the rotor in each stage is fixed to a rotating shaft. In other embodiments, such as FIG. **2**B, the shaft **208** in each stage is inserted through the hub of the rotor **206** and fixed to the motor or generator coil housing **204**, and the rotor **206** rotates about the shaft **208**, e.g. on bearings. This approach facilitates easy assembly and maintenance without special tools. In similar embodiments, the shaft **208** is threaded or otherwise supported by the pump or pump or turbine module housing **218**, or by any combination of the pump or pump module housing **218** and the motor housing **204**. In still other embodiments, there is no shaft, and instead a wear ring clearance on the front of the rotor **206** acts as the primary radial and axial bearing.

[0075] Certain embodiments include stages **200** having an inverted rotor/stator configuration, whereby the rotor **206** and the stator **212** can both rotate independently from each other in opposite directions. Some embodiments include a plurality of rotors **206** fixed to a common fixed or rotating shaft **208**, combined with stators and/or diffusers that rotate individually. In some of these embodiments, the diffusers are implemented in a manner similar to the disclosure of patent application U.S. Ser. No. 15/101,460, which is included herein by reference in its entirety for all purposes.

[0076] In still other embodiments, there is no shaft, and instead a wear ring clearance on the front of each rotor **206** acts as the primary radial and axial bearing. Torque is thereby transmitted directly from or to the electromagnet stator coils **212** of the motor to the rotor, or electromagnetic energy is transferred from the rotor **206** to the coils **212** of the generator, without the use of a rotating shaft.

[0077] FIG. **2**C is a simplified cross-sectional illustration of an embodiment having an annular flow passage, similar to FIG. **2**A, where the cross section is taken through the pump motor coils **212** perpendicular to the primary axis of the motor.

[0078] The embodiment of FIGS. **2**A and **2**B, and **2**C are suitable for use with relatively cool working fluids, whereby the annular flow passage **202** brings the working fluid into direct thermal contact with the motor or generator coil housing **212**, thereby cooling the motor or generator coils. In FIGS. **2**A, **2**B, and **2**C, more than 80% of the working fluid is brought into thermal contact with the motor or generator coil housing **212**, and at least 20% of the motor or generator coil housing **212** is in thermal contact with the annular flow path **202**. In various embodiments, more than 90% of the working fluid is brought into thermal contact with the motor or generator coil housing **212**, and at least 50% of the motor or generator coil housing surface **212** is in thermal contact with the annular flow path **202**.

[0079] With reference to FIG. **2**D, in some embodiments where a high temperature working fluid is anticipated, the design of FIG. **2**C is modified by including an additional concentric layer of thermal insulation **228** between the annular flow passages **202** and the housing **204** of the motor or generator coils **212**. A concentric cooling annular passage **234** is thereby created between the insulation **228** and the coil housing **204**, through which a cooling fluid, such as water or a cooling oil, can be circulated from an inlet **230** to an outlet **232**.

[0080] With reference to FIG. **2**E, in other embodiments the working fluid is distributed among a plurality of substantially identical flow passages **226** arranged symmetrically within the annular space **202** about the circumference of the motor or generator coils **212**. In the embodiment of FIG. **2**E, the flow passages **226** are formed by the motor housing walls **218**. The embodiment of FIG. **2**E further includes a concentric annular layer of insulation **228** and concentric cooling annular passage **234**, similar to FIG. **2**D.

[0081] With reference to FIG. **3**, in embodiments a small amount of the working fluid is diverted through a separate cooling path **300**, where it is cooled and then circulated through the concentric annular cooling passage **234** in thermal contact with the motor housing **204** to cool the motor coils **212**. In similar embodiments, a separate cooling fluid, such as water or a cooling oil, is circulated through the cooling path **300** without diverting any of the working fluid.

[0082] Fluid cooling of the motor or generator coils **212** in various embodiments allows the system to operate with high temperature working fluids, and also enables the system to provide higher performance limits and greater power density in the overall pump or turbine even if the working fluid is not elevated in temperature.

[0083] With reference to FIG. **4**, embodiments include guide vanes **400**, either in the annular space **202** if the flow passage is annular, or elsewhere in the flow path. In the illustrated embodiment, the guide vanes **400** control the flow of the process fluid in a section of the concentric flow path at the end of the motor or generator coils **212**, where the flow path turns radially inward toward the central axis of the module. The guide vanes **400** break the flow path into a plurality of separate but symmetric paths until the flow reaches the central axis and flows axially out through the outlet **224** and into the next stage **200**. In embodiments, the guide vanes **400** direct the process fluid within the flow path into close proximity with the motor or generator housing **218**.

[0084] The guide vanes **400** can also provide a casing wall that can be used to route power cables from the sealed motor or generator **212**, through the fluid passages **202**, and out of the pump casing **218** to the variable frequency control **216**. In embodiments, the guide vanes **400** also act as fins to provide additional convective surface area to cool the motor or generator coils **212**, and/or to provide space for integral cooling passages **300** connected to an external cooling fluid source.

[0085] In the embodiments of FIGS. **2**B-**4**, the illustrated apparatus **220** includes a plurality of completely modular pump stages **200**. While only two stages **200** are shown in these figures, it can be easily seen that any number of the stages **200** can be combined in series without adding additional complexity or complication to the design, operation, and maintenance of the pump **200**. In particular, high stage counts according to the disclosed design do not raise any issues regarding shaft size, shaft deflection, rotor dynamics, bearing loads, motor alignment, or alignment between stages **200**.

[0086] Some of these embodiments include at least some drive electronics that are shared between more than one stage. For example, in some embodiments AC power is converted to DC power by a common set of large electronic, which is then distributed to the individual pump or turbine stages as needed.

[0087] With reference again to FIGS. **2**B and **4**, embodiments include a plurality of variable frequency drives ("VFD's") **216**, and in some of these embodiments the motor or generator coils **212** in each stage **200** of the pump or turbine are independently controlled by a dedicated VFD **216** or other controller. One of the key benefits in some of these embodiments is that the first stage can run at lower speeds than the rest of the pump, so as to accommodate low net positive suction head ("NPSH") and off-peak conditions. In some applications, varying the speed of only the final stage provides a useful approach for precisely controlling the output pressure and/or flow.

[0088] Providing an individual VFD drive **216** for each stage **200** can also serve as a fail-safe redundancy, whereby if one stage fails, the rest will continue to operate and the pump will continue to function. The continued function after failure of a pump stage may be with reduced head and flow, or the speed of the remaining stages can be increased to compensate for the lost head and flow of the failed stage. This approach creates a failure scenario wherein the pump continues to operate, possibly at reduced head and flow, until an operator, after becoming aware of the stage failure, has time to safely shut down the system. In contrast, the failure of one stage in a traditional pump or turbine typically results in failure of the entire pump or turbine, with a complete loss of performance and a sudden, uncontrolled shutdown of the system.

[0089] In the embodiment of FIG. **2**A, the motor is a radial motor that includes permanent magnets mounted about the periphery of the rotor, while the embodiments of FIGS. **2**B-**4** include motors in each pump stage **200** that are disk or "pancake" style motors that include permanent magnets **210** mounted on the rear surfaces of the rotors **206**. Induction motors are used in other embodiments. Some embodiments include variable speed drives that enable the synchronous operating speeds of the pump stages **200** to rise above 3600 rpm.

[0090] In the embodiment of FIGS. **2**A-**4** the pump stages **200** are centrifugal designs having radial flow rotors **206**. Some of these embodiments include rotors with specific speeds below about 2,000 US units. Other embodiments include pump stages **200** with radial flux rotor designs.

[0091] In the embodiment of FIGS. **2**B-**4**, combined radial and one-way thrust bearings **214** are used in place of separate axial and radial bearings. The illustrated embodiments include stationary shafts **208** inserted through the hubs of the rotors **206** and threaded into the pump stage housing **218**, which facilitate easy assembly and maintenance without special tools. Using a sensor-less motor along with appropriate VFD drives **216** also reduces any requirement for instrumentation on each stage **200** in the illustrated embodiments.

[0092] FIG. **5** is a perspective view of the exterior of a pump similar to the pump of FIG. **2**B.

[0093] Certain embodiments include stages **200** having an inverted rotor/stator configuration, whereby the rotor and the stator can both rotate independently from each other in opposite directions. And some embodiments include stators and/or diffusers that rotate individually, for example with separate motors driving the rotors and diffusers. In some of these embodiments, the diffusers are implemented in a manner similar to the disclosure of patent application U.S. Ser. No. 15/101,460.

[0094] As is well known in the art, rotodynamic pumps and turbines are often highly similar in their physical designs, such that the difference between a pump and a turbine can sometimes be mainly a question of use rather than structure. Accordingly, while FIGS. **2**A-**5** illustrate embodiments that are pumps, the features of the present invention that are discussed herein with reference to a turbine or to a pump should be understood to refer equally to both, except where the context requires otherwise.

[0095] The foregoing description of the embodiments of the invention has been presented for the purposes of illustration and description. Each and every page of this submission, and all contents thereon, however characterized, identified, or numbered, is considered a substantive part of this application for all purposes, irrespective of form or placement within the application. This specification is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of this disclosure.

[0096] Although the present application is shown in a limited number of forms, the scope of the invention is not limited to just these forms, but is amenable to various changes and modifications without departing from the spirit thereof. The disclosure presented herein does not explicitly disclose all possible combinations of features that fall within the scope of the invention. The features disclosed herein for the various embodiments can generally be interchanged and combined into any combinations that are not self-contradictory without departing from the scope of the invention. In particular, the limitations presented in dependent claims below can be combined with their corresponding independent claims in any number and in any order without departing from the scope of this disclosure, unless the dependent claims are logically incompatible with each other.

I claim:

1. A sealless pump or turbine module having an integral motor or generator, the module comprising:
- an inlet located at a proximal end of the module, the inlet being on a central axis of the module;
- an outlet located at a distal end of the module, the outlet being on a central axis of the module;
- an outer housing surrounding the module;
- a rotor suspended within the outer housing;
- a motor within the outer housing configured to drive a rotation of the rotor, or a generator within the outer housing configured to be driven by the rotation of the rotor, the motor or generator comprising:
- a stator within an inner housing, the stator comprising an electromagnet directed toward the rotor; and
- a plurality of magnetic devices cooperative with the rotor and configured to pass in proximity to the electromagnet as the rotor rotates; and
- a flow path symmetrically distributed about the inner housing;
- the module being configured to direct a flow of working fluid from the inlet through the flow path to the outlet such that the working fluid is symmetrically distributed about the inner housing as it flows past the stator within the flow path.

2. The module of claim **1**, wherein the flow path is an annular flow path surrounding the inner housing.

3. The module of claim **1**, wherein the flow path comprises a plurality of flow passages arranged symmetrically about the inner housing.

4. The module of claim **1**, wherein the rotor is suspended by a rotatable shaft, and the rotor is fixed to the shaft.

5. The module of claim **1**, wherein the rotor is suspended by a fixed shaft, and the rotor is configured to rotate about the shaft.

6. The module of claim **5**, wherein the rotor is supported on the fixed shaft by a pair of bearings, one of which maintains an axial position of the rotor while the other of which provides radial support of the rotor.

7. The module of claim **5**, wherein the rotor is supported axially and radially on the fixed shaft by a single, one-way thrust bearing.

8. The module of claim **5**, wherein the rotor is supported on the fixed shaft by at least one bearing that is lubricated by the process fluid.

9. The module of claim **5**, wherein the fixed shaft is fixed to at least one of the inner housing and the module housing.

10. The module of claim **5**, wherein the fixed shaft is fixed to at least one of the inner housing and the module housing by threaded attachment.

11. The module of claim **1**, wherein the magnetic devices are permanent magnets.

12. The module of claim **1**, wherein the magnetic devices are squirrel cage coils.

13. The module of claim **1**, wherein the magnetic devices are fixed to the rotor.

14. The module of claim **1**, wherein the magnetic devices are fixed to a disk that is coaxial with the rotor and proximal to the rotor.

15. The module of claim **1**, wherein the flow path extends over at least 50% of a surface of the inner housing, and at least 90% of the working fluid that flows through the module from the inlet to the outlet is caused to flow through in direct thermal contact with the inner housing.

16. The module of claim **1**, wherein the module is configured to require all of the working fluid flowing from the inlet to the outlet to flow through the flow path.

17. The module of claim **1**, further comprising:

thermal insulation interposed between the flow path and the inner housing; and

a cooling fluid path formed between the thermal insulation and the inner housing, the cooling fluid path being in thermal communication with the inner housing and configured to enable an exchange of heat between the inner housing and a cooling fluid flowing through the cooling fluid path.

18. The module of claim **1**, further comprising stationary guide vanes within the flow path through which electrical wiring is routed without exposing the electrical wiring to the working fluid.

19. The module of claim **1**, wherein the stator is configured to rotate independently of the rotor and in a direction that is opposite to a rotation of direction of the rotor.

20. The module of claim **1**, further comprising a diffuser that is cooperative with the rotor but is driven by a separate diffuser motor and is thereby able to rotate independently of the rotor.

21. The module of claim **1**, wherein the electromagnet of the stator is directed toward a radial periphery of the rotor, and the magnetic devices are fixed near the radial periphery of the rotor.

22. The module of claim **1**, wherein the electromagnet of the stator is directed toward a side of the rotor, and the magnetic devices are fixed to the side of the rotor or to a disk that is coaxial with and proximal to the side of the rotor.

23. A multi-stage apparatus comprising a plurality of interconnected modules, each of said modules comprising:

an inlet located at a proximal end of the module, the inlet being on a central axis of the module;

an outlet located at a distal end of the module, the outlet being on a central axis of the module;

an outer housing surrounding the module;

a rotor suspended within the outer housing;

a motor within the outer housing configured to drive a rotation of the rotor, or a generator within the outer housing configured to be driven by the rotation of the rotor, the motor or generator comprising:

a stator within an inner housing, the stator comprising an electromagnet directed toward the rotor; and

a plurality of magnetic devices cooperative with the rotor and configured to pass in proximity to the electromagnet as the rotor rotates; and

a flow path symmetrically distributed about the inner housing;

each of said modules being configured to direct a flow of working fluid from the inlet through the flow path to the outlet such that the working fluid is symmetrically distributed about the inner housing as it flows past the stator within the flow path.

24. The apparatus of claim **23**, wherein at least two of the motors or generators of the modules can be independently controlled so as to cause the corresponding rotors to rotate at different rates.

25. The apparatus of claim **24**, wherein the two, independently controlled motors or generators are controlled by separate variable frequency drives.

26. The apparatus of claim **23**, wherein the modules are configured such that the apparatus as a whole is able to continue functioning as a pump or as a turbine despite failure of at least one of the modules included in the apparatus.

27. The apparatus of claim **23**, further comprising control electronics that provide shared support to at least two of the modules.

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