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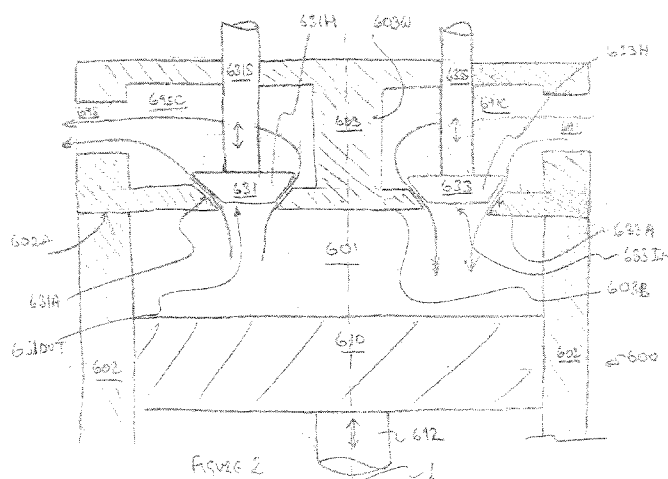
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(57) Abstract: Embodiments of the invention provide dry gaseous fluid pump apparatus comprising: a fluid inlet and a fluid outlet; at least one pump body having an internal wall defining an internal pump chamber thereof; a compression member provided within the pump chamber; and valve means being operable selectively to allow fluid to be drawn from the fluid inlet and into the pump chamber when at least a portion of the compression member is translated in a first direction and to be exhausted from the pump chamber through the fluid outlet when said at least a portion of the compression member is translated in a second direction opposite the first, the valve means being arranged to be actuated by actuator means under the control of control means to perform at least one selected from amongst the functions of allowing fluid to be drawn from the fluid inlet into the pump chamber and allowing fluid to be exhausted from the pump chamber through the fluid outlet, the apparatus comprising a linear drive assembly operable to drive the at least a portion of the compression member to and fro within the pump chamber.

FLUID PUMP AND METHOD OF PUMPING A FLUID

FIELD OF THE INVENTION

The present invention relates to apparatus for pumping fluids. Embodiments of the invention are directed in particular to apparatus for pumping gases without exposing the gases to lubricating oils.

BACKGROUND OF THE INVENTION

Pumping of fluids such as gases, vapours, liquids, slurries and the like is a requirement in a wide range of industrial, domestic and laboratory environments. The fluid may be or comprise a gas, a vapour or a liquid. To accomplish pumping it is known to provide a fluid pump employing a piston arranged to reciprocate back and forth within a pump chamber, typically a cylinder.

As the piston moves in one direction fluid is drawn into the pump chamber through an inlet valve. As the piston moves in the opposite direction fluid is forced out of the chamber through an outlet valve. Lubricant is typically provided between the piston and a wall of the pump chamber. The lubricant may have one or more of a number of effects. For example, lubricant typically reduces friction between the piston and pump chamber wall, thereby reducing wear and an amount of heating of the piston and chamber wall. Reducing wear has the advantage that a mechanical life of the pump is extended. The lubricant may also act as a sealing agent.

In certain applications it is undesirable to use lubricant. In some cases this is because the lubricant may cause contamination of the fluid being pumped and/or react with the fluid being pumped. In the case of vacuum pumps, the use of lubricant may be undesirable due to a risk that lubricant or volatile molecules emanating from the lubricant may be introduced into the apparatus from which fluid is being pumped. This can occur for example due to reverse flow of vapour from the pump chamber through the inlet valve, a phenomenon known as backstreaming. In some applications including pumps and compressors in the medical or food industries, contamination of fluid being pumped by the apparatus with lubricant or vapours associated with lubricant can be harmful to humans or animals by inhalation or ingestion.

It is therefore known to provide lubricant-free pumps, such as dry pumps, for pumping fluids.

FIG. 1 shows a known fluid pump 1 (which may also be referred to as a compressor) that is particularly suited to use as a vacuum pump under lubricant-free conditions (i.e. as a 'dry' pump). The pump has a cylinder 2 within which a piston 10 is arranged to be slidable.

The piston 10 is coupled to a coupling rod 12 which is in turn coupled to a crankshaft 11. As the crankshaft 11 rotates the coupling rod 12 causes the piston 10 to move in a reciprocal manner to and fro within the cylinder 2.

The cylinder 2 has a front end 2A (sometimes referred to as a top end or head end) at which an outlet valve 30A is provided. The outlet valve 30A comprises a valve disc 31 and a valve seat 2S, the valve seat 2S being provided by the front end 2A of the cylinder 2.

The valve disc 31 is displaceable between a seated condition in which the valve disc 31 abuts the valve seat 2S forming a gas tight seal therewith, and an open condition in which gas is allowed to pass between the valve seat 2S and the disc 31 and out from the cylinder 2. Thus the outlet valve 30A may assume a closed condition or an open condition.

The cylinder 2 may be referred to more generally as a 'pump body'. An internal volume of the cylinder 2 into which fluid is drawn may be referred to as a 'pump chamber'.

As the piston 10 executes reciprocal movement within the cylinder 2, the piston 10 alternately moves from a top dead centre (TDC) position in which a front surface 10S of the piston 10 is at its most forward position (at or near the front end 2A of the cylinder 2) and a bottom dead centre (BDC) position in which the front surface 10S is at its most rearward position, away from the front end 2A and towards a rear end 2B of the cylinder 2.

With the piston 10 at the BDC position, inlet apertures 94 formed in a wall of the cylinder 2 are exposed to an internal volume of the cylinder between the piston 10 and the valve disc 31 allowing gas that is to be pumped to flow into the cylinder 2 through the inlet apertures 94.

As the crankshaft 11 continues to rotate, the piston 10 moves back towards the TDC position, this movement being referred to as an exhaust stroke of the piston. During the exhaust stroke gas in the cylinder 2 is compressed. If the gas reaches a sufficient pressure before the piston 10 reaches the TDC position, the valve disc 31 is displaced from its seated

condition allowing compressed gas in the cylinder 2 to be exhausted from the cylinder 2 around a periphery of the valve disc 31.

If the gas does not reach a sufficient pressure before the piston 10 reaches the TDC position, the piston 10 is arranged to abut the valve disc 31 and to force the valve disc 31 away from its seated position thereby to open the outlet valve 30A and exhaust the compressed gas.

It is to be understood that the provision of an outlet valve 30A in the form of a valve disc 31 having a diameter substantially equal to or greater than a diameter of the cylinder 2 has the advantage that a pump having an increased compression ratio may be obtained compared with other known pumps. This is due at least in part to the provision of an outlet valve having a head having a diameter similar to that of the cylinder 2.

Furthermore, with such a design the piston 10 is able to abut the valve disc 31 and to force open the valve disc 31 to exhaust the gas even when the gas pressure alone is insufficient to open the outlet valve 30A. This has the advantage that lower ultimate pressures may be obtained in a recipient being pumped by the pump.

EP0922166 describes a piston-driven vacuum pump having similar features to that described above.

STATEMENT OF THE INVENTION

Embodiments of the invention may be understood with reference to the appended claims.

In one aspect of the invention for which protection is sought there is provided dry gaseous fluid pump apparatus comprising: a fluid inlet and a fluid outlet; at least one pump body having an internal wall defining an internal pump chamber thereof; a compression member provided within the pump chamber; and valve means being operable selectively to allow fluid to be drawn from the fluid inlet and into the pump chamber when at least a portion of the compression member is translated in a first direction and to be exhausted from the pump chamber through the fluid outlet when said at least a portion of the compression member is translated in a second direction opposite the first, the valve means being arranged to be actuated by actuator means under the control of control means to perform at least one selected from amongst the functions of allowing fluid to be drawn from the fluid inlet into the pump chamber and allowing fluid to be exhausted from the pump chamber through the fluid

outlet, the apparatus comprising a linear drive assembly operable to drive the at least a portion of the compression member to and fro within the pump chamber.

In other words, because the apparatus is a dry gas pump apparatus, embodiments of the invention are arranged to be operable without exposing gas that is being pumped by the apparatus to gaseous or liquid lubricant. Some embodiments of the invention are arranged to operate without exposing fluid being pumped to substantially solid lubricant. Some embodiments of the invention may be referred to as 'oilless' or 'lubricant free' pumping devices or compressors. This feature may be particularly important in medical, foodstuffs and other applications where a gas pumped by the apparatus may be inhaled or otherwise consumed by a human or animal.

Embodiments of the invention have the advantage over known fluid pump apparatus that because actuator means under the control of a control means is provided, the valve means may be opened and closed by the actuator means independently of a pressure difference across the valve means.

In contrast, valve means not having actuator means that is operable under the control of control means must rely on a difference in pressure across the valve means to open the valve means. In typical known systems, a closure member of the valve is biased to a closed position by a spring member. If an opening force on the closure member is sufficient to overcome the bias of the spring, the closure member moves away from the closed position and the valve assumes an open condition.

The use of such valves in known pump apparatus has the disadvantage that the compression member (which is in the form of a piston slidable in a cylinder in known apparatus) must move a sufficient distance within the pump chamber to create a pressure difference across the valve sufficient to force the valve to open. In some applications such as vacuum pump applications the pressure required to open the inlet and outlet valves may require a not inconsiderable force to be applied to the piston. This results in a requirement to provide a piston drive of not inconsiderable size and weight, such drives typically having a relatively large power requirement.

Embodiments of the present invention allow a number of improvements over known pump apparatus to be made. For example in some embodiments the pump is smaller, lighter and of lower power consumption than known pump apparatus.

This is at least in part because when the compression member completes an exhaust stroke over which fluid is expelled from the pump chamber and then begins an intake stroke to draw fluid into the pump chamber, the valve means may be actuated to allow fluid to be drawn through the fluid inlet before a pressure difference across the valve means between the fluid inlet and the pump chamber increases substantially. Thus actuation of the valve means may be performed substantially independently of a pressure difference across the valve means. It is to be understood that the valve means may be actuated to allow fluid to be drawn into the pump chamber even when there is substantially no pressure difference between the fluid inlet and the pump chamber.

It is to be understood that the term compression member includes a member the whole of which is translated within the pump chamber such as a piston. The term also includes a member of which only a portion is translated within the pump chamber. Such a member may for example be a member that is caused to deform, deflect or otherwise change shape or form in order to compress fluid within the pump chamber. Thus a membrane or like component that is fixed to a portion of the apparatus such as a rim of the pump chamber and caused to deform thereby to vary the size of the pump chamber is included by the term compression member.

It is to be understood that the pump chamber may define a volume of circular cross-section (i.e. a cylindrical cross-section) or any other cross-section. For example, the pump chamber may have a substantially square cross-section, a substantially rectangular cross-section or a substantially elliptical cross-section. Other shapes are also useful. The pump body and/or pump chamber may be substantially cylindrical in some arrangements.

It is to be understood that as the at least a portion of the compression member moves away from its forward-most position, being also a position of smallest pump chamber volume (which may be referred to as a 'top dead centre' (TDC) position) at the start of a suction cycle, fluid may be drawn into the pump chamber through the valve assembly by controlling the actuator means to open the valve means. This has the feature that a 'head vacuum' that is otherwise created as the compression member so moves may be relieved. It is to be understood that the force required to move the compression member may be not inconsiderable when high differential pressures exist across the compression member.

By way of example, in the case of some known vacuum pumps, when the piston member moves away from the TDC position a pressure in the pump chamber may be reduced by up to at least 1 bar below a pressure outside the pump chamber. For a piston 55mm in

diameter, an instantaneous torque of around 7-8Nm may be required in order to move the piston from the TDC position towards a bottom dead centre (BDC) position.

Such a torque is unachievable by certain drive means that it is desirable to use with fluid pumps. Accordingly, embodiments of the invention have the advantage that linear drive means of reduced power (and therefore size) compared with rotary drive means may be employed. Embodiments of the invention are suitable for use with magnetic linear drive assemblies, piezo linear drive means or any other suitable linear drive means.

Valve means that may be opened to allow fluid to flow into the pump chamber may also be referred to as 'torque relief' valve means since in some embodiments it enables a reduction in an amount of torque that is required to be developed by the actuator means, such as a motor driving the compression member to and fro within the pump chamber.

For example, in the case that a rotary electric motor is used to drive the compression member, the torque that must be developed by the motor to drive the compression member may be reduced.

In the case of the example cited above with a piston having a diameter of 55mm, the inlet valve may have a diameter of around 10-15mm in order to reduce the torque to a sufficiently low value in some embodiments.

In conventional pumping apparatus, a rotary-linear drive means and not a linear drive assembly is employed to drive a piston reciprocating within a cylinder. Typically, the rotary-linear drive means employs a crank shaft or similar that is coupled to the piston by means of a connecting rod. Circular motion of the crank shaft is converted to linear motion of the piston by the connecting rod as described above with respect to FIG. 1.

This arrangement suffers the disadvantage that periodic lateral forces are introduced between the piston and the cylinder as the crank shaft rotates and the piston reciprocates.

These lateral forces enhance a rate of wear of the piston and cylinder. The rate of wear is particularly acute in embodiments where lubrication between the piston and cylinder is not or cannot be employed.

The use of a linear drive means, being a drive means in which substantially linear motion is generated directly by the drive means (rather than indirectly through rotation of a crank

shaft) has the advantage that a rate of wear of the compression member (such as a piston) and the sidewall of the pump chamber may be reduced.

It is to be understood that bearings supporting the crank shaft of a rotary-linear drive experience considerable loads and severe changes in load direction as the piston reciprocates in the cylinder. This can cause a charge of grease with which the bearings are packed to be urged out from the region in which the bearings are provided.

In conventional lubricant-free apparatus where lubricant is not present between the piston and cylinder, grease is still required for the crankshaft bearings and loss of grease from these bearings manner can considerably reduce an expected length of a service life of the apparatus. This is a particular problem for lubricant-free pumps because of the absence of alternative sources of lubricant for the bearings, such as oil migrating from an oil sump of the apparatus.

It is to be understood that in known pumps such as that of FIG. 1 a magnitude of the cosine forces exerted on the sidewall of the cylinder may be reduced if a length of the coupling rod is increased. However, increasing the length of the coupling rod results in an increase in a size (and weight) of the apparatus.

The valve means of the apparatus may comprise an inlet valve through which fluid may be drawn into the pump chamber from the fluid inlet and an outlet valve through which fluid may be expelled from the pump chamber to the fluid outlet, each valve having a closure member operable to open or close the valve thereby to allow or prevent flow of fluid therethrough.

Advantageously at least one of the inlet and outlet valves are actuated by the actuator means.

Further advantageously both the inlet valve and the outlet valve are actuated by the actuator means.

Advantageously the inlet and outlet valves are provided with respective different closure elements.

Optionally the inlet and outlet valves share a common closure element, the closure element being operable by the actuator means to move between a first position in which the inlet

valve is open and the outlet valve is closed and a second position in which the inlet valve is closed and the outlet valve is open.

The inlet and outlet valves may be provided by a shuttle valve assembly. In some embodiments the common closure element may be considered to correspond to the shuttle of a conventional shuttle valve.

The valve means may further comprise an auxiliary valve, the auxiliary valve being provided in a flow-path of fluid between the inlet and outlet valves and the pump chamber such that fluid flowing into or out from the pump chamber flows through the auxiliary valve, the auxiliary valve being operable by the actuator means to prevent a flow of fluid into or out from the pump chamber.

Thus it is to be understood that the auxiliary valve may be operable to place the inlet and outlet valves in fluid isolation from the pump chamber or in fluid communication with the pump chamber.

This feature has the advantage that an amount of dead space or dead volume within the pump chamber associated with the valve means may be further reduced.

It is to be understood that by dead space is meant a volume between the valve assembly and compression member that is not swept by the compression member as the compression member moves to and fro within the pump chamber.

A reduced size of dead space enhances a pumping efficiency of the pump apparatus. It also reduce a length of time a fluid spends within the pump chamber. This can be advantageous in a number of applications. For example, in the case of intermittent flow through the apparatus of a corrosive fluid, a reduced 'dwell time' of the fluid within the pump chamber can reduce an amount of corrosion of the apparatus caused by the corrosive fluid.

In some applications, it may be required to pump a fluid having a finite lifetime and/or a fluid having a finite lifetime in a particular state. An example of such a fluid may be a hyperpolarised gas such as hyperpolarised helium-3 or any other suitable hyperpolarised gas.

A hyperpolarised gas typically loses its magnetic polarisation over time. A reduction in the amount of time the gas is present within the apparatus may therefore be desirable in some

applications, e.g. where hyperpolarised gas is being pumped into a chamber for the performance of an experiment or being pumped to a human or animal for inhalation.

The actuator means may comprise at least one drive unit.

The actuator means may comprise a first drive unit operable to open and close the inlet valve and a second drive unit operable to open and close the outlet valve.

In some arrangements a plurality of inlet and/or outlet valves may be provided. Where a plurality of inlet or outlet valves are provided the plurality of valves may be actuated by a single actuator.

It is to be understood that in some arrangements where a plurality of inlet valves and/or a plurality of outlet valves are provided, a corresponding plurality of drive units may be provided, one for each one of the plurality of inlet and/or outlet valves.

In some arrangements the inlet and outlet valves may be actuated by a single drive unit.

The actuator means may comprise a drive unit operable to open and close the auxiliary valve.

The drive unit may comprise a piezo-electric drive.

It is to be understood that by the term piezo-electric drive or 'piezo-drive' is meant a drive unit comprising a piezoelectric material, the drive unit being operable to cause actuation of a valve by application of a suitable electric field to the piezo-electric material. The piezo-drive may be operable according to a slip-stick method of operation or any other suitable method. Slip-stick methods are described for example in US2010314970. For example, the piezo-drive may be operable according to a travelling wave mode such as that described in US5596241, a standing wave as described in US5453653 and US2003052573 or any other suitable method.

The content of US2010314970, US5596241, US5453653 and US2003052573 is hereby incorporated by reference.

Alternatively or in addition the drive unit may comprise an electromagnetic drive.

By providing a valve assembly according to embodiments of the present invention the size of a linear drive means capable of driving the compression member may be reduced to a size compatible with a number of important applications. Thus, the possibility of employing linear drive means in a greater range of applications is facilitated by embodiments of the present invention.

Examples of the type of drive means that may be suitable for use in some embodiments of the invention include QDrive STAR (TM) motors produced by CFIC Inc of Troy, New York, USA. The motors employ an electromagnetic actuator to drive a drive member in the form of a rod member in an axial direction parallel to a longitudinal axis of the rod member.

Suitable drive means for certain embodiments may be arranged to have a drive member of relatively short stroke, such as a stroke of up to around 10mm, or in the range from around 10 to around 20mm.

In some embodiments of the invention it is desirable to provide the pumping apparatus, including the drive means, within a fluid-tight casing.

Because an entire pump apparatus may be provided in a fluid-tight casing, including the drive means, a requirement to provide seals between the casing and moving components passing through the casing (such as a coupling rod) may be avoided. In known pump apparatus where the drive means is too large to be provided within the stationary pump casing and has instead to be provided external to the casing, a coupling rod may be required to pass through the casing.

By avoiding the requirement to provide the drive means external to the casing, leakage of fluid (such as air) into the pump apparatus from an external environment by means of the seals may be eliminated. Similarly, leakage of pumped fluid out from the pump apparatus to the external environment by means of the seals may also be eliminated.

In some embodiments in which a magnetic linear drive is employed having an electromagnet and associated permanent magnet, a coupling rod of the compression member may be supported in a magnetic field of the electromagnet by flexure supports. The electromagnet may be provided close to or in thermal contact with an outer wall of the pump apparatus in order to allow efficient conduction of heat away from the electromagnet in use.

It is to be further understood that it is desirable to maintain a relatively small clearance between the compression member and a sidewall of the pump chamber in order to allow for expansion of the compression member and pump chamber in use. The actual value of the clearance will in practice depend upon a size of the components, the materials from which they are to be made, and anticipated working temperatures of the components. It is to be understood that it is desirable to make the clearance as small as possible to reduce leakage of fluid there past.

The drive unit may comprise an electric motor. The drive unit may comprise a linear electric motor.

A digital encoder or other device may be employed for determining the position of the compression member. Such a device may be particularly useful in embodiments where the drive unit comprises an electric motor.

The valve means may be provided in a head portion of the apparatus facing the compression member.

Advantageously the apparatus may comprise sensor means for sensing a position of the compression member. The control means may be arranged to control the actuator means responsive to the position of the compression member.

Optionally the sensor means comprises at least one selected from amongst an optical sensor, a magnetic sensor, an acoustic sensor or transducer and an electromagnetic radiation sensor.

Advantageously the apparatus is arranged to sense a position of the compression member by detection of a signal generated by a transmitter and received by a receiver following scattering or reflection of the signal by the compression member, the signal being one selected from amongst an optical signal, an acoustic signal and an electromagnetic signal.

The apparatus may be arranged to sense the position of the compression member by reference to an amount of a Doppler shift between the transmitted and received signals.

The sensor means may be provided in a substantially fixed location. In some embodiments the sensor means may be provided in the pump body. The sensor means may be provided in a head portion of the apparatus. Other locations are also useful including a portion of the

apparatus opposite the head portion. The sensor means may be arranged to transmit a signal through the pump chamber towards a face of the compression member that is exposed to the pump chamber volume and to detect a signal scattered or reflected therefrom. Alternatively the sensor means may be arranged to transmit a signal towards a portion of the compression member that is not exposed to the pump chamber volume and to detect a signal scattered or reflected therefrom. In some arrangements this may be a portion of the compression member that is on an opposite side of the compression member to that which is exposed to the pump chamber. This may be a side facing the linear drive means although other arrangements are also useful.

In some embodiments the apparatus may be arranged to determine the position of the compression member by sensing the position of a coupling rod by means of which the drive means drives the compression member. In the case that the drive means comprises a piezo-drive, the apparatus may be arranged to determine the position of the coupling rod by means of a signal provided by the drive means. In some embodiments the apparatus may be arranged to determine how far the drive means has driven the coupling rod from a reference position in order to determine the position of the compression member.

In the case of a piezo-driven actuator operating in a stepwise manner, such as in a slip/stick stepwise manner, the apparatus may be arranged to determine how many slip/stick steps the drive means has performed in a given direction and to determine the position of the compression member accordingly. In some embodiments the apparatus may be arranged to determine how many steps the drive means has moved the coupling rod or compression member since the coupling rod or compression member was at a reference position. Other arrangements are also useful.

The apparatus may be arranged to take into account thermal expansion of one or more components thereof in determining a position of the compression member. It is to be understood that in some embodiments the purpose of determining the position of the compression member is at least in part to enable a position of the compression member at which the compression member changes direction of movement to be controlled more precisely. As discussed in further detail below, this feature enables a substantial increase in compression ratio to be obtained. It is to be understood that the apparatus may be arranged to control the drive means such that a distance of closest approach of the compression member to a limit of travel of the compression member during an exhaust stroke thereof is sufficiently small to achieve a required compression ratio. The limit of travel may for

example be set so as to prevent impact of the compression member with an internal surface of the pump body, such as a head thereof, an inlet or outlet valve, or any other portion.

The apparatus may comprise sensor means for sensing a pressure of fluid in the pump chamber, the control means being arranged to control the actuator means for actuating the valve means responsive to the pressure of fluid in the pump chamber.

Alternatively or in addition the control means may be arranged to control the drive means responsive to the pressure of fluid in the pump chamber. Thus the control means may be arranged to control movement of the compression member responsive to the pressure of fluid in the pump chamber as determined by sensor means. For example, the control means may be arranged to control a length of a stroke of the compression member, a position at which the compression member changes direction of travel or any other suitable parameter responsive to the pressure of fluid in the pump chamber.

Advantageously at least a portion of the compression member is arranged to reciprocate between a first position proximate the valve means and a second position distal the valve means.

Further advantageously the control means is operable to control the valve means to allow a flow of fluid into the pump chamber from the fluid inlet when the at least a portion of the compression member moves from the first position towards the second position thereby to reduce a magnitude of a force required to so move the compression member.

Optionally the control means is operable to control the valve means to allow a flow of fluid into the pump chamber from the fluid inlet when the at least a portion of the compression member is substantially at the first position thereby to reduce a magnitude of a force required to so move the compression member.

It is to be understood that the valve means may be controlled to allow fluid into the pump chamber from the fluid inlet at any suitable position of the at least a portion of the compression member at or between the first and second positions.

Advantageously the valve means may be controlled to allow fluid to flow into the pump chamber when the at least a portion of the compression member moves from the first position to the second position before said at least a portion reaches the second position thereby to relieve the vacuum otherwise created as the compression member so moves.

It is to be understood that because the inlet valve is controlled by the actuator means, the inlet valve may be opened when the at least a portion of the compression member is substantially at the first position, in some embodiments. In embodiments having an outlet valve that is also closed by actuator means, the apparatus may be configured to close the outlet valve and subsequently to open the inlet valve. The apparatus may be configured to close the outlet valve and subsequently to open the inlet valve when the compression member is substantially at the first position.

As described above, in known arrangements the inlet valve cannot be opened until the at least a portion of the compression member has moved a sufficient distance from the first position to allow a pressure difference across the inlet valve to exceed the force required to open the inlet valve. This force may be provided by a spring element or like arrangement. In some known arrangements a valve such as a 'flapper valve' arrangement may be employed.

The control means may be arranged to open the outlet valve as the at least a portion of the compression member moves from the second position to the first position and to close the outlet valve when the at least a portion of the compression member is substantially at the first position thereby to increase the amount of fluid exhausted through the outlet valve.

Thus, the outlet valve can remain open even when the pressure of fluid within the pump chamber is substantially the same as that on the fluid outlet side of the outlet valve, as the at least a portion of the compression member moves towards the first position to compress the fluid and exhaust the fluid from the pump chamber through the outlet valve. Thus the outlet valve can remain open for a longer period compared with valves not actuated by an actuator under the control of a controller.

This is because there is no requirement for a pressure difference to exist across the outlet valve in order to open the outlet valve, or maintain the outlet valve in an open condition.

The apparatus may be coupled to first and second respective different volumes and arranged to pump gas from the first volume to the second volume.

The first volume may for example be a chamber or any other suitable volume. For example, a chamber or other volume of a gas storage vessel.

The second volume may be atmosphere or a volume vented directly to atmosphere, a chamber or any other suitable volume. For example, a chamber or other volume of a different gas storage vessel.

The linear drive assembly may comprise a coupling rod coupled to the compression member, the drive assembly being arranged to drive the coupling rod to and fro in a substantially straight line along a direction substantially coincident with a longitudinal axis of the coupling rod.

Advantageously the drive assembly comprises a piezoelectric drive portion.

As in the case of the electromagnetic drive described above, the piezo-drive may also be arranged to propel the coupling rod in an axial direction to and fro thereby to cause the compression member to execute reciprocal motion within the pump chamber.

Use of a linear drive in the form of a piezo-drive has the advantage over an electromagnetic linear drive that a piezo-drive may be configured not to generate an electromagnetic field during operation. This has the advantage that a magnitude of a magnetic field to which a gas being pumped is exposed may be reduced. This is particularly advantageous when it is required to pump certain gases such as hyperpolarised gases since the magnetic field can result in loss of magnetic polarisation of the gas.

Furthermore, in some arrangements a piezo-drive (or plurality of piezo-drives if required) may be arranged to generate a lower amount of heat compared with an electromagnetic drive.

It is to be understood that the amount of heat generated by the linear drive (and in particular a piezo-drive) may be arranged to be sufficiently low to allow the drive to be sealed in a vacuum-tight package and operated within a volume of the pump in which the pressure is below atmospheric pressure.

Such operation is not possible with some known drives due to a reduction in the extent to which heat generated by the drive can be dissipated. This may be due at least in part to the fact that the gaseous atmosphere in which the drive is operated is below atmospheric pressure, resulting in reduced cooling by thermal conduction through the gas. Furthermore, the volume in which the drive is accommodated may be relatively small in order to provide a

compact fluid pump apparatus further reducing an extent to which heat can be conducted or otherwise transferred away from the drive.

This can cause the drive to operate at a higher temperature than is desirable and ultimately to fail prematurely.

Use of a piezo-drive has the further advantage that an amount of outgassing of the piezo-drive is less than that of other known linear drives. This is at least in part because piezo-drives may be fabricated substantially entirely from inorganic crystalline material. Thus, organic materials that have a tendency to outgas such as polymeric materials are not required to be used.

Furthermore, piezo-drives may be operated without a requirement for lubrication of the interface between the coupling rod and a remainder of the drive. Thus problems associated with vaporisation of such lubricant may be eliminated.

Furthermore, since the piezo-drive requires only an electrical power supply for its operation, it can be powered by means of an electrical feed-through from the ambient environment in which the pump apparatus is situated into the vacuum-tight environment within the pump apparatus. That is, no mechanical feed-throughs are required in some embodiments.

Mechanical feed-throughs typically require seals to be provided allowing relative motion between the seal and the feed-through which are prone to wear particularly when lubricant cannot be employed. Other mechanical feed-throughs such as bellows-type arrangements and the like typically experience wear and/or fatigue at a relatively rapid rate and are therefore undesirable for use in pumping applications where repeated reciprocal mechanical motion to drive the piston is required.

It is to be further understood that piezo-drives are capable of providing substantially pure linear translational motion such that substantially no cosine or like lateral forces are exerted by the compression member on the internal wall of the pump chamber as it is caused to reciprocate to and fro within the pump chamber. This has the advantage that an amount of wear of the pump chamber due to reciprocal translation of the compression member may be reduced.

It is to be understood that these lateral forces may be described as radial forces, for example in the case where the internal volume of the pump chamber swept by the compression member is of cylindrical cross-section.

As noted above, since lubricant cannot be employed within the pump chamber between the compression member and internal wall of the pump chamber it is important to reduce such radial forces as much as possible.

A further advantage of employing a linear drive is that a stroke and/or a rate of travel of the compression member may be more easily controlled. In contrast, when a crank is used to drive the coupling rod the crank is typically arranged to rotate continuously and at a constant speed. The stroke of the compression member is therefore of a substantially fixed, constant length and the speed of the compression member varies in a periodic manner.

In the case of a linear drive, the direction of travel of the coupling rod is changed by halting the coupling rod and reversing the direction of travel. In contrast, in the case of a rotary-linear drive the rotating crank rotates at a substantially constant speed and may be required to have a not inconsiderable inertia in order to provide for smooth operation.

The ability to vary the length of the stroke of the reciprocating compression member has the advantage that the stroke may be changed responsive to one or more parameters such as a pressure of gas to be pumped at the inlet of the pump apparatus and/or a pressure of gas at the outlet.

In some arrangements the stroke may be arranged to increase with increasing pressure at the inlet.

In some arrangements the stroke may be arranged to decrease with increasing pressure at the inlet.

In some arrangements the speed of the compression member over a given stroke may be changed responsive to a pressure of fluid at the inlet or outlet. In some arrangements the speed may be increased with increasing pressure at the inlet. In some arrangements the speed may be decreased with increasing pressure at the inlet.

Other arrangements are also useful

The drive assembly may comprise an electromagnetic drive portion.

The linear drive assembly may be provided in fluid communication with the compression member.

This feature has the advantage that a mechanical feed-through between volumes at different respective pressures may not be required. This is because the compression member and linear drive means are in fluid communication with one another. Thus in the case that the apparatus is operated as a vacuum pump, the portion of the compression member in fluid communication with the linear drive assembly will share a common vacuum with the linear drive assembly.

By eliminating the requirement to provide a mechanical feed-through, a risk that fluid pumped by the apparatus leaks out from the apparatus may be reduced. Furthermore, a risk of leakage of fluid into the apparatus thereby mixing with fluid pumped by the apparatus may be reduced.

Still furthermore, a risk of contamination of fluid pumped by the apparatus with lubricant associated with a mechanical feed-through may be eliminated.

It is to be understood that a mechanical feed-through may comprise the coupling rod, the coupling rod passing through a housing of the apparatus, seal means being typically required between the coupling rod and housing. The housing may be provided by the pump body in some arrangements.

The linear drive assembly may be provided in a vacuum-tight package and thereby sealed from an environment external to the apparatus.

In some embodiments the apparatus may have an inlet valve actuated by actuator means under the control of control means whilst the outlet valve is actuated by pressure difference across the outlet valve. Alternatively the apparatus may have an outlet valve actuated by actuator means under the control of control means whilst the inlet valve is actuated by pressure difference across the inlet valve.

In some embodiments the outlet valve may be provided by a plate member arranged to cover one end of the pump chamber such that the compression member may contact the plate member and displace the plate member to an open condition. An inlet valve may be

mounted to the plate member thereby to allow gas to be drawn into the pump chamber, the inlet valve being actuated by actuator means under the control of control means. The control means may be arranged to open the inlet valve when it is determined that the compression member is no longer in contact with the plate member following contact between the compression member and plate member at or close to TDC. It is to be understood that in some embodiments the control means may be arranged to open the inlet valve when it is determined that the compression member is a prescribed distance from the plate member during the exhaust stroke regardless of whether the compression member has contacted the plate member.

The apparatus may be arranged wherein the closure member of the inlet valve is operable to open in a direction away from the pump chamber.

This feature has the advantage that intrusion of the valve into the pump chamber thereby increasing a dead space of the pump chamber may be prevented. It is to be understood that if the closure member of the inlet valve were to open inwardly into the pump chamber a volume of the pump chamber when the compression member reaches a limit of its distance of travel in the second direction would be increased, thereby increasing a dead space of the apparatus and reducing a compression ratio of the apparatus.

In a further aspect of the invention for which protection is sought there is provided a pumping assembly comprising at least first and second fluid pump apparatus according to the preceding aspect.

Advantageously a fluid outlet of the first pump apparatus may be in fluid communication with a fluid inlet of the second pump apparatus wherein the first and second pump apparatus are coupled in series.

Optionally respective compression members of the first and second pump apparatus are arranged to reciprocate along a common axis.

Alternatively respective compression members of the first and second pump apparatus may be arranged to reciprocate along respective parallel axes.

In a still further alternative respective compression members of the first and second pump apparatus may be arranged to reciprocate along non-parallel axes.

Optionally respective compression members of the first and second pump apparatus are arranged to reciprocate along substantially orthogonal axes.

Respective compression members of the assembly may be arranged to reciprocate either in phase or in anti-phase with respect to one another.

In a further aspect of the invention for which protection is sought there is provided a method of dry pumping a gaseous fluid by means of dry pumping apparatus comprising: drawing fluid through a fluid inlet into a pump chamber via valve means when at least a portion of a compression member is translated in a first direction and exhausting fluid from the pump chamber through a fluid outlet via valve means when said at least a portion of the compression member is translated in a second direction opposite the first, the method comprising actuating the valve means by actuator means under the control of control means to perform at least one selected from amongst the functions of allowing fluid to be drawn from the fluid inlet via the valve means into the pump chamber and allowing fluid to be exhausted from the pump chamber via the valve means through the fluid outlet, the method further comprising driving the at least a portion of the compression member to and fro within the pump chamber by means of a linear drive assembly.

In another aspect of the invention for which protection is sought there is provided dry gaseous fluid pump apparatus comprising: a fluid inlet and a fluid outlet; at least one pump body having an internal wall defining an internal pump chamber thereof; a compression member provided within the pump chamber; and valve means being operable selectively to allow fluid to be drawn from the fluid inlet and into the pump chamber when at least a portion of the compression member is translated in a first direction and to be exhausted from the pump chamber through the fluid outlet when said at least a portion of the compression member is translated in a second direction opposite the first, the valve means comprising an inlet valve having at least one closure member arranged to be actuated by actuator means under the control of control means, the valve means being operable to perform at least one selected from amongst the functions of allowing fluid to be drawn from the fluid inlet into the pump chamber through the inlet valve and allowing fluid to be exhausted from the pump chamber through the fluid outlet, wherein the at least one closure member is operable to open in a direction away from the pump chamber.

Advantageously the apparatus may comprise a linear drive assembly operable to drive the at least a portion of the compression member to and fro within the pump chamber.

In one aspect of the invention for which protection is sought there is provided fluid pump apparatus comprising: a fluid inlet and a fluid outlet; at least one pump chamber having an internal wall defining an internal volume thereof; a compression member provided within the internal volume of the pump chamber; and valve means arranged to be actuated by actuator means under the control of control means, the valve means being operable selectively to allow fluid either to be drawn from the fluid inlet and into the pump chamber by translating at least a portion of the compression member in a first direction or to be exhausted from the pump chamber through the fluid outlet by translating said at least a portion of the compression member in a second direction opposite the first.

DESCRIPTION OF THE DRAWINGS

Embodiments of the invention may be understood with reference to the following drawings:

FIGURE 1 shows a cross-section of a prior art pump with a piston of the pump at a position approximately midway between BDC and TDC positions;

FIGURE 2 is a cross-sectional view of a portion of a pump according to an embodiment of the invention having inlet and outlet valves that may be actuated by means of respective actuators;

FIGURE 3 shows the pump of FIG. 2 including a linear drive for driving a piston of the pump;

FIGURE 4 is a cross-sectional view of a pump according to a further embodiment of the invention having inlet and outlet valves and further including an auxiliary valve in a flow-path of gas between a pump chamber and the inlet and outlet valves;

FIGURE 5 is a cross-sectional view of a pump similar to that of the embodiment of FIG. 4 in which the inlet and outlet valves are provided in the form of a shuttle valve assembly;

FIGURE 6 shows a floating coupling between a piston and a coupling rod of a pump according to an embodiment of the invention; and

FIGURE 7 shows pump apparatus according to a further embodiment of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

FIG. 2 shows a portion of a pump apparatus or pump 600 according to an embodiment of the present invention.

The pump 600 has a cylinder 602 defining a pump chamber 601 within which a piston 610 is reciprocally slidable. A coupling rod 612 is coupled to the piston 610 and arranged to be translated to and fro along a longitudinal axis L of the cylinder 602 by a piezo-actuated linear drive 662 provided within a piston drive module 660 (FIG. 3).

In an alternative embodiment a different type of linear drive may be employed. In some embodiments the linear drive means is or comprises a magnetic drive means. In some embodiments the magnetic drive means has an electromagnet (which may be or include a solenoid coil) through which an alternating current is arranged to be fed. The alternating current generates an alternating magnetic field by means of which the coupling rod 612 is driven back and forth.

A front end 602A of the cylinder 602 has a head block 603 coupled thereto around a periphery of the cylinder 602 to seal the cylinder 602 from an external environment.

The head block 603 has an inlet valve 633 and an outlet valve 631 mounted therein. The valves 633, 631 each have a valve stem 633S, 631S coupled to a valve head 633H, 631H. Piezo-actuated linear drives 633D, 631D are provided within a valve drive module 680 (FIG. 3) and arranged to translate the respective stems 633S, 631S of the valves 633, 631 along a direction parallel to the longitudinal axis L of the cylinder 602. This allows the valves 633, 631 to be moved between open and closed conditions.

The head block 603 has an inlet aperture 691 in fluid communication with the inlet valve 633 and arranged to receive a flow of fluid to be pumped by the pump 600. Fluid flowing through the head block inlet aperture 691 enters an inlet cavity 691C within the head block 603. When the inlet valve 633 is in the open condition (shown in FIG. 2) fluid may be drawn into the pump chamber 601 through an inlet valve aperture 633IN.

The head block 603 also has an outlet aperture 695 in fluid communication with the outlet valve 631. When the outlet valve 631 is in the open condition (shown in FIG. 2) fluid is able to flow out of the pump chamber 601 through an outlet valve aperture 631OUT into an outlet

cavity 695C within the head block 603. The fluid is then able to exit the head block 603 through the head block outlet aperture 695.

The inlet and outlet cavities 691C, 695C are provided in fluid isolation from one another by means of an internal wall 603W of the head 603.

The inlet valve linear drive 633D is operable to urge the head portion 633H of the inlet valve 633 against an inlet valve seat 633A formed in a basal portion 603B of the head block 603 facing the cylinder 602. With the head portion 633H in this position the inlet valve 633 is in a closed condition, whereby the inlet valve aperture 633IN is closed. In the embodiment shown the head portion 633H is in the form of a disc having a diameter that tapers between opposed major surfaces thereof. The inlet valve seat 633A is of a corresponding complementary shape to the head portion 633H allowing a snug fit between the head portion 633H and seat 633A when in the closed condition.

As described above, the outlet valve 631 has a corresponding head portion 631H coupled to the stem 631S. The head portion 631H is operable to be urged against an outlet valve seat 631A formed in the basal portion 603B of the head block adjacent the inlet valve seat 633A allowing the valve 633 to assume a closed condition, closing the outlet valve aperture 631OUT.

It is to be understood that because the inlet and outlet valves 633, 631 are each operable to assume open or closed conditions by means of respective piezo-actuated linear drives 633D, 631D the valves 633, 631 may be opened and closed independently of a difference in pressure of fluid across the respective valves 633, 631.

This feature has the advantage that the valves may be opened and closed at different times and for longer or shorter periods of time than might otherwise be possible in order to improve performance of the pump 600.

Thus it is to be understood that when the piston 610 is at or near its position of closest approach to the head block 603 (a position that will be referred to as 'top dead centre' or TDC, although this expression is to be understood as not limiting an orientation of the pump in use), the outlet valve 631 may be closed. The precise position of the piston 610 at which the outlet valve 631 is closed may be controlled in order to optimise the amount of gas expelled before the inlet valve 633 is opened.

It is to be understood that the inlet valve 633 may be opened at any suitable moment in time independently of the position of the outlet valve 631 and piston 610. Thus it is to be understood that the inlet valve 633 may be opened relatively soon after (or at substantially the same time as) the outlet valve 631 is closed. Other arrangements are also useful.

Opening of the inlet valve 633 when or soon after TDC has been reached has the advantage that the piston 610 is not required to pull against a closed pump chamber 601 before gas to be pumped is allowed to flow into the pump chamber 601. It is to be understood that an amount of force required to pull the piston 610 from the TDC position is higher when the inlet valve 633 is closed compared to when the inlet valve 633 is open. Since the force required to be developed by the piezo-actuated linear drive 662 may be reduced in this way a linear drive 662 having a reduced drive force capability may be employed compared with known arrangements.

Furthermore, because the inlet and outlet valves 633, 631 are actuated by respective piezo-actuated linear drives 633D, 631D the force with which each valve head 633H, 631H is urged against the corresponding valve seat 633A, 631A may also be controlled independently of the pressure difference across the respective valves 633, 631.

It is to be understood that in known pumps the inlet and outlet valves are urged to the closed condition by means of a spring element and/or by a difference in pressure across the valve.

Embodiments of the present invention are advantageous over arrangements in which spring elements are employed because spring elements can deteriorate in their effectiveness over time and suffer wear due to lack of lubrication. Furthermore, in order to open the valve a pressure difference across the valve must be sufficient to overcome the closure force of the spring. In contrast, embodiments of the present invention allow the inlet and outlet valves 633, 631 to be opened independently of the pressure difference and without a requirement for spring elements.

Spring elements also suffer the disadvantage that heat is generated due to flexure of the spring elements and sliding contact between the spring elements and other surfaces with which they are in contact.

It is to be understood that in the embodiment of FIG. 2, because the inlet valve 633 is actuated by an actuator 633D it is capable of opening by movement of the valve head 633H against the direction of flow of fluid into the cylinder 602 when it is required to allow fluid to

pass into the cylinder 602. This is in contrast to conventional sprung valves in which displacement of the valve head 633H occurs in the direction of fluid flow due to a difference in pressure between fluid on opposite sides of the head 633H. Thus the inlet valve head 633H does not intrude into the cylinder 602 thereby increasing a dead space between the piston 610 and head 603 when the piston 610 is at TDC.

Embodiments of the present invention involve only sliding contact between the valve stems 633S, 631S and respective actuators 633D, 631D or between the coupling rod 612 and actuator 662. Therefore an amount of heat required to be dissipated by the pump 600 is significantly reduced, particularly the amount within the head block 603.

A further advantage of employing piezo-actuators to open and close the valves 633, 631 is that the valves 633, 631 may be arranged to have high opening and closing forces even when no power is applied to the respective actuator 633D, 631D.

Thus, the valve head 633H, 631H may be moved to abut the valve seat 633A, 631A and to be urged against the valve seat 633A, 631A with a relatively high force. If power to the actuator 684, 682 is then terminated the valve head 633H, 631H will remain urged against the seat 633A, 631A. This allows a high integrity seal to be formed between the head 633H, 631H and seat 633A, 631A to prevent leakage therepast.

Conversely, the valve head 633H, 631H may be translated away from the seat 633A, 631A with a relatively high force if required.

Furthermore, it is to be understood that inlet and outlet valves actuated by means of piezo-actuators may be fabricated from non-magnetic materials and materials that do not outgas (or which outgas by a relatively insignificant amount). The use of non-magnetic materials can be particularly useful in certain applications, for example applications in which polarised gases are pumped such as spin-polarised gases. Likewise a low-outgassing property enables applications in high vacuum applications and applications where contamination of a gas being pumped is highly undesirable.

Embodiments of the invention employing piezo-actuated linear drives have the advantage that relatively high opening and closing rates may be obtained allowing high opening and closing repetition rates.

In some arrangements a controller arranged to control opening and closing of the inlet and outlet valves 633, 631 is provided with a signal responsive to a position of the piston 610. The signal may be derived from a drive signal for the piezo-drive 662 driving the piston 610 or from a measurement of a position of the piston 610, for example by means of a sensor such as an optical sensor. One or more pressure sensors may be provided in addition or instead for generating signals responsive to which the controller may control operation of the valves 633, 631. For example, one or more sensors may be arranged to sense pressure within the pump chamber 601, and/or in or near one or both of the inlet and outlet chambers 691C, 695C.

In some arrangements an electromagnetic, acoustic or other signal is employed to determine a position of the piston 610, for example by means of a Doppler shift between a transmitted signal and a received signal. The measurement may be made at a location external to the environment of the pump chamber 601 or within the same atmosphere as the pump chamber 601.

Other arrangements are also useful.

It is to be understood that in the embodiment of FIG. 2 and FIG. 3 the head block 603 and piezo-actuated linear drives 633D, 631D for the inlet and outlet valves 633, 631 respectively may be provided in a vacuum-tight package which will be referred to as a valve drive module 680 (FIG. 3). An electrical feed-through element 688 is provided to allow electrical power to be provided to the actuators 633D, 631D within the sealed valve drive module 680.

By vacuum-tight package is meant that the package is capable of preventing air from leaking from an outside of the package to an interior of the package where the actuators are located. In some arrangements the vacuum-tight package is a helium gas leakproof package, i.e. helium gas present on an external surface of the package is not able to leak into the package.

Similarly, the piezo-actuated linear drive 662 for driving the piston 610 is also provided within a vacuum-tight package of a piston drive module 660. An electric feed-through 668 is provided allowing electrical power to be provided to the drive 662.

In some arrangements the piezo-actuated linear drives 633D, 631D, 662 are provided in a common vacuum-tight package.

In some arrangements a common controller controls operation of each of the piezo-actuated linear drives 633D, 631D, 662. Thus opening and closing of the valves 633, 631 may be readily coordinated with the reciprocal translation of the piston 610.

As noted above the position of the piston 610 at a given moment in time may be determined by means of an optical or other sensor. The position of the piston 610 may be determined by reference to the piston 610 itself or to the coupling rod 612 which forms part of the piezo-actuated linear drive 668 in the arrangement shown.

Other arrangements are also useful.

FIG. 4 shows a pump 700 according to an alternative embodiment of the invention. Again, like features of the embodiment of FIG. 4 to those of the embodiment of FIG. 2 are shown with like reference signs prefixed numeral 7 instead of numeral 6.

The pump 700 differs from that of the embodiment of FIG. 2 and FIG. 3 in that a single auxiliary valve 741 is provided in the basal portion 703B of the head block 603 to allow fluid to flow into or out from the cylinder 702.

The auxiliary valve 741 has a head portion 741H arranged to be urged against a single valve seat 741A provided in the basal portion 703B of the head block 703 by an auxiliary valve stem 741S. A piezo-drive 741D is provided to translate the stem 741S to an fro along an axis of the valve 741 to open and close the valve.

Respective inlet and outlet valves 733, 731 are provided in the head block 703 in a flow-path of fluid between the auxiliary valve 741 and the fluid inlet and fluid outlet 791, 795 respectively. The inlet and outlet valves 733, 731 are arranged to be actuated by means of respective linear drives 733D, 731D. In the embodiment of FIG. 4 the linear drives 741D, 733D, 731D are piezo-actuated linear drives.

An auxiliary valve chamber 741C is provided in fluid communication with the inlet and outlet valve heads 733H, 731H and auxiliary valve head 741H. Fluid flowing into or out from the cylinder 702 is arranged to flow through the auxiliary valve chamber 741C.

In use the pump 700 may be operated as follows.

With the piston 710 at its position of closest approach to the head block 703 of the pump 700 the outlet valve 731, auxiliary valve 741 and inlet valve 733 are all closed. The auxiliary valve 741 and inlet valve 733 are then opened and the piston 710 translated away from the head block 703 to draw fluid into the cylinder 702 through the inlet valve 733.

It is to be understood that the order in which the inlet valve 733 and auxiliary valve 741 are opened and the precise moment at which they are closed may be determined so as to optimise a performance of the pump 700. Thus in some arrangements the inlet valve 733 may be opened before the auxiliary valve 741 is opened. In some alternative arrangements the inlet valve 733 may be opened after the auxiliary valve 741 has been opened.

When the piston 710 reaches its furthest distance of travel from the head block 703 the auxiliary valve 741 and inlet valve 733 are both closed. Again, the order in which the auxiliary valve 741 and inlet valve 733 are closed and the precise moment at which they are closed may be determined so as to optimise performance of the pump 700.

The piston 710 then begins to travel back towards the head block 703 compressing fluid present in the cylinder 702. The auxiliary valve 741 and outlet valve 731 are then opened to allow compressed fluid to be exhausted from the cylinder 702. The order in which the auxiliary valve 741 and outlet valve 731 are opened and the precise moment at which the valves 741, 731 are opened may be determined so as to optimise performance of the pump 700.

As the piston 710 approaches the head block 703 or when the piston 710 reaches its position of closest approach to the head block 703 the inlet valve 733 and auxiliary valve 741 are closed. In some arrangements the valves 733, 741 may be closed after the piston 710 reaches its position of closest approach and has remained substantially stationary for a prescribed period to allow time for compressed gas to flow out from the cylinder 702. Other arrangements are also useful.

It is to be understood that the order in which the auxiliary valve 741 and outlet valve 731 are closed and the precise moment at which the valves 741, 731 are opened may be determined so as to optimise performance of the pump 700.

FIG. 5 shows a pump 800 according to a further embodiment of the invention. The embodiment of FIG. 5 is similar to that of FIG. 4 except that the inlet and outlet valves 733, 731 of the embodiment of FIG. 4 are replaced by a shuttle valve assembly 835.

Like features of the embodiment of FIG. 5 to the embodiment of FIG. 4 are shown with like reference signs prefixed numeral 8 instead of numeral 7.

As may be seen in FIG. 5 the shuttle valve assembly 835 has an inlet conduit 835IN leading from the fluid inlet 891 of the pump 800 and an outlet conduit 835OUT leading to a fluid outlet 895 of the pump 800.

The assembly 835 has a single inlet/outlet conduit 835C in fluid communication with the auxiliary valve 841.

A shuttle element 835H is provided within the assembly 835. A shuttle drive 831D in the form a linear piezo-actuator is coupled to the shuttle element 835H by means of a stem 835S. The drive 831D is arranged to drive the stem 835S and thereby shuttle element 835H back and forth within the assembly 835 thereby to open or close the fluid inlet and outlet conduits 835IN, 835OUT respectively.

In a first position A of the shuttle element 835H (shown in solid outline in FIG. 5) the shuttle element 835H closes the inlet conduit 835IN thereby preventing flow of fluid to the auxiliary valve 841 from the fluid inlet 891. In this position of the shuttle element 835H the outlet conduit 835OUT is open allowing fluid to flow from the auxiliary valve 841 to the fluid outlet 895.

In a second position B of the shuttle element 835H (shown in dotted outline in FIG. 5) the shuttle element 835H closes the outlet conduit 835OUT thereby preventing flow of fluid out of the pump 800. In this position of the shuttle element 835H the inlet conduit 835IN is open allowing fluid to flow to the auxiliary valve 841 from the fluid inlet 891.

It is to be understood that in use the piston 810 is caused to reciprocate to and fro within the cylinder 802. As it does so the auxiliary valve 841 is opened and closed in concert with movement of the shuttle element 835 to selectively allow fluid to flow into the cylinder 802 from the fluid inlet 891 and to flow out from the cylinder 802 to the fluid outlet 895.

It is to be understood that the precise moment at which the auxiliary valve 841 is opened and closed, and the precise moment at which shuttle element 835H of the shuttle assembly 835 is translated to and fro as the piston 810 is reciprocates within the cylinder 802 may be selected to optimise fluid pump operation in a given set of circumstances.

In some embodiments a pattern or sequence of actuations of the various components may be arranged to adapt to the pressure of fluid at the inlet 891, a pressure difference between the inlet and outlets 891, 895 or any other suitable parameter.

Embodiments of the invention have the advantage that fluid pump apparatus may be provided that is capable of operation in a more efficient manner. This is at least in part because the inlet and outlet valve arrangement is controlled by means of actuators.

Furthermore, the use of ceramic-based actuators such as piezoelectric materials has the advantage that reduced contamination of gases being pumped may be achieved. In some arrangements the use of ceramic-based actuators allows pumping of gases that would otherwise react with materials such as metallic materials from which valves are typically constructed.

Some embodiments of the invention have the further advantage that a head portion and/or a piston drive portion may be provided within the same atmosphere as the cylinder 802. This eliminates the need for mechanical feed-throughs enabling an increase in reliability and decrease in risk of contamination of fluid being pumped by gas leakage into the pump or out-gassing of lubricant or other materials associated with the feed-throughs.

Furthermore, in some embodiments a 'floating piston' arrangement is employed. In such an arrangement, the piston is permitted to have some freedom of movement in a lateral direction relative to the coupling rod. In other words, the piston is permitted to move in a direction towards the sidewall of the pump. This feature has the advantage that a certain amount of misalignment of a direction of drive of the piston by a linear drive means relative to the longitudinal axis of the pump chamber may be compensated for by relative movement between the piston and the coupling rod.

In some embodiments a 'floating piston' arrangement is employed in which relative lateral movement of a piston is allowed with respect to the coupling rod.

FIG. 6 shows an example of such an embodiment. In the arrangement shown a coupling rod 912 is coupled to a piston 910 by means of a resilient float element 911 in the form of a substantially S-shaped element. The float element 911 is arranged to be axially stiff in the sense that the float element 911 has a relatively large resistance to compression along a direction between the piston 910 and the coupling rod 912 (i.e. parallel to cylinder axis L).

However, the float element 911 is arranged to allow lateral movement of the piston relative to the coupling rod 912 (i.e. in a direction normal to cylinder axis L) thereby to prevent a build-up of an excessive lateral force between the piston 910 and cylinder sidewall 902.

This has the advantage that wear of the piston 910 and sidewall 902 may be reduced.

The embodiment of FIG. 6 is also arranged such that rubbing or sliding movement between the piston 910 and float element 911 and rubbing or sliding movement between the float element 911 and coupling rod 912 are substantially prevented. This has the advantage of reducing wear for the reasons discussed above.

FIG. 7 shows a fluid pump 100 according to an alternative embodiment of the invention. Like features of the pump 100 of the embodiment of FIG. 7 to the pump shown in FIG. 1 are labelled with like reference signs incremented by 100.

The pump 100 is provided with a cylinder 102 defining a pump chamber 101 within which a piston 110 is reciprocally slidable. A coupling rod 112 is coupled to the piston 110 and arranged to be translated to and fro along a longitudinal axis L of the cylinder 102 by a piezo-actuated linear drive 162 provided within a piston drive module 160 (FIG. 3).

The cylinder 102 has a front end 102A (sometimes referred to as a top end or head end) at which an outlet valve 130A is provided. The outlet valve 130A is comprised by a valve disc 131 and a valve seat 102S, the valve seat 102S being provided by the front end 102A of the cylinder 102.

The valve disc 131 is displaceable between a seated condition in which the valve disc 131 abuts the valve seat 102S forming a substantially gas tight seal therewith, and an open condition in which gas is allowed to pass between the valve seat 102S and the disc 131 and out from the cylinder 102. Thus the outlet valve 130A may assume a closed condition or an open condition. It is to be understood that in the embodiment of FIG. 7 the outlet valve 130A is caused to move between closed and open conditions responsive to a difference in pressure of gas across the valve disc 131.

Gas passing out from the cylinder 102 through the outlet valve 130A is arranged to pass out from the pump 100 through an outlet aperture 195.

The valve disc 131 has an inlet valve 133 provided therein that is in fluid communication with a fluid inlet 191 of the pump 100 via a flexible inlet conduit 191C. The inlet conduit 191C prevents gas that has been exhausted from the cylinder 102 from mixing with gas that is drawn through the inlet aperture 191. The inlet valve 133 passes through the valve disc 131 and is operable by means of a piezo-actuator between open and closed conditions under the control of a controller 150. An electrical control line is provided connecting the inlet valve 133 to the controller 150.

With the inlet valve 133 in the open condition, gaseous fluid may be drawn into the pump 100 via the inlet aperture 191, along the inlet conduit 191C, through the inlet valve 133 and into the pump chamber 101.

The controller 150 is arranged to coordinate opening and closing of the inlet valve 133 with movement of the piston 110 to and fro within the cylinder 102. In some embodiments the controller 150 issues signals to the inlet valve 133 to control opening and closing thereof, and corresponding signals to the piston drive module 160 to control reciprocal movement of the piston 110.

It is to be understood that in some arrangements the controller 150 is arranged to control the inlet valve 133 to open when the piston 110 is at its furthest limit of travel towards the valve disc 131 (top dead centre or TDC position) and to close when the piston is at its further limit of travel away from the valve disc 131. In some embodiments a sensor 110S is provided by means of which the controller 150 may determine the position of the piston 110 as it approaches the valve disc 131. When a face of the piston 110 reaches a prescribed distance from the valve disc 131 the direction of movement of the piston 110 is reversed and the inlet valve 133 is opened by the controller 150. In the embodiment shown the sensor 110S is embedded in a wall of the cylinder 102 adjacent the position of the valve disc 131. In some embodiments the sensor 110S is provided in or on the valve disc 131. In some embodiments the sensor 110S is provided adjacent the inlet valve 133. In some embodiments the sensor 110S may be integral to the inlet valve 133.

The sensor may be any suitable sensor, including but not limited to an optical sensor, an acoustic sensor and an electromagnetic sensor. The sensor may be provided with a transmitter portion. In the case of an optical sensor the sensor may comprise an optical transmitter, the sensor being operable to detect optical radiation scattered by the piston 110 as it moves to and fro within the cylinder 110.

In some alternative embodiments the sensor may comprise an acoustic transmitter and a corresponding acoustic signal receiver such as an ultrasonic transmitter/receiver module, or an electromagnetic signal transmitter and a corresponding electromagnetic signal receiver, such as a radar transmitter/receiver module. The controller 150 to which the sensor is connected may be operable to determine the position of the piston 110 by measuring a Doppler shift between a transmitted and a received signal such as an acoustic or electromagnetic signal following reflection from the compression member.

It is to be understood that by providing the sensor 110S adjacent to or supported by the valve disc 131 the controller 150 is able more conveniently to ensure that the distance of closest approach of the piston 110 to the valve disc 131 is substantially constant regardless of the temperature of the pump 100 or state of wear of any component thereof. That is, the controller 150 may compensate dynamically for variations in temperature of one or more components and maintain a substantially constant distance of closest approach of the piston 110 to the valve disc 131 throughout a period of operation of the pump 100. In contrast in systems not having dynamic compensation capability, allowance for variations in temperature must be made.

The pump 100 may be arranged such that as the temperature of the pump 100 varies so the distance of closest approach of the piston 110 to the valve disc 131 varies within an allowed range. The pump may be arranged to maintain the allowed range as small as possible.

It is to be understood that for pumps that are required to achieve high compression ratios such as at least 100:1 or 1000:1, a reduction in the distance of closest approach of the piston to the valve disc 131 by a relatively small amount can make a substantial difference to the maximum value of compression ratio achievable. Thus, for a piston having a stroke of 100mm, a reduction in the distance of closest approach of the piston 110 from 1mm to 0.1mm would result in an increase in compression ratio of from 100:1 to 1000:1. Such increases may be invaluable in certain particularly demanding pumping applications.

It is to be understood that thermal expansion effects may result in substantial variations in the minimum distance of closest approach of the cylinder 110 to the valve disc 131. By providing a feedback signal to the controller 150 in respect of piston position, the minimum distance can be reduced and maintained substantially constant throughout a period of operation of the pump 100.

In some embodiments gas pump apparatus having a valve disc 131 covering substantially the whole of the 'top' end of the cylinder 102 such as that shown in FIG. 7 may be arranged to drive the piston 110 so as to contact the valve disc 131 at the end of an exhaust stroke. In some arrangements this can result in an increase in the compression ratio achievable by the apparatus, particularly at relatively low inlet gas pressures. In some embodiments the apparatus may be arranged to open the inlet valve 133 as the piston 110 moves away from TDC at or close to the moment at which the piston 110 is no longer in contact with the valve disc 131. The presence of the sensor 110S may be useful in determining when contact between piston 110 and valve disc 131 has been lost.

It is to be understood that the feature of a linear drive has the advantage that a stroke of the piston 110 may be varied dynamically, as can the position of the piston 110 at which a reversal of the direction of travel of the piston 110 may be effected. Thus a pump 110 having unprecedented flexibility of operation may be provided, allowing fine control of piston operating conditions such that the pump 100 may achieve a high compression ratio independently of the effect of phenomena such as temperature, the pressure of gas being drawn through the pump 100 and component wear.

It is to be understood that the use of a sensor for sensing piston position is useful in embodiments having a movable valve disc 133 covering substantially the whole of the 'top' end of the cylinder 102 as well as in embodiments in which the cylinder 102 has a closed top end with an outlet valve that does not cover the whole of the top end, such as those of FIG. 2 to 5. The presence of the sensor is useful in enabling an increase in compression ratio as described above.

Throughout the description and claims of this specification, the words "comprise" and "contain" and variations of the words, for example "comprising" and "comprises", means "including but not limited to", and is not intended to (and does not) exclude other moieties, additives, components, integers or steps.

Throughout the description and claims of this specification, the singular encompasses the plural unless the context otherwise requires. In particular, where the indefinite article is used, the specification is to be understood as contemplating plurality as well as singularity, unless the context requires otherwise.

Features, integers, characteristics, compounds, chemical moieties or groups described in conjunction with a particular aspect, embodiment or example of the invention are to be

understood to be applicable to any other aspect, embodiment or example described herein unless incompatible therewith.

CLAIMS:

1. Dry gaseous fluid pump apparatus comprising:
a fluid inlet and a fluid outlet;
at least one pump body having an internal wall defining an internal pump chamber thereof;
a compression member provided within the pump chamber; and
valve means being operable selectively to allow fluid to be drawn from the fluid inlet and into the pump chamber when at least a portion of the compression member is translated in a first direction and to be exhausted from the pump chamber through the fluid outlet when said at least a portion of the compression member is translated in a second direction opposite the first, the valve means being arranged to be actuated by actuator means under the control of control means to perform at least one selected from amongst the functions of allowing fluid to be drawn from the fluid inlet into the pump chamber and allowing fluid to be exhausted from the pump chamber through the fluid outlet,
the apparatus comprising a linear drive assembly operable to drive the at least a portion of the compression member to and fro within the pump chamber.
2. Apparatus as claimed in claim 1 comprising an inlet valve through which fluid may be drawn into the pump chamber from the fluid inlet and an outlet valve through which fluid may be expelled from the pump chamber to the fluid outlet, each valve having a closure member operable to open or close the valve thereby to allow or prevent flow of fluid therethrough.
3. Apparatus as claimed in claim 2 wherein at least one of the inlet and outlet valves are actuated by the actuator means.
4. Apparatus as claimed in claim 3 wherein both the inlet valve and the outlet valve are actuated by the actuator means.
5. Apparatus as claimed in claim 4 wherein the inlet and outlet valves are provided with respective different closure elements.
6. Apparatus as claimed in claim 4 wherein the inlet and outlet valves share a common closure element, the closure element being operable by the actuator means to move between a first position in which the inlet valve is open and the outlet valve is closed and a second position in which the inlet valve is closed and the outlet valve is open.

7. Apparatus as claimed in any one of claims 2 to 6 wherein the valve means further comprises an auxiliary valve, the auxiliary valve being provided in a flow-path of fluid between the inlet and outlet valves and the pump chamber such that fluid flowing into or out from the pump chamber flows through the auxiliary valve, the auxiliary valve being operable by the actuator means to prevent a flow of fluid into or out from the pump chamber.
8. Apparatus as claimed in any preceding claim wherein the actuator means comprises at least one drive unit.
9. Apparatus as claimed in claim 8 as depending through claim 5 wherein the actuator means comprises a first drive unit operable to open and close the inlet valve and a second drive unit operable to open and close the outlet valve.
10. Apparatus as claimed in claim 8 or 9 depending through claim 7 wherein the actuator means comprises a drive unit operable to open and close the auxiliary valve.
11. Apparatus as claimed in any one of claims 8 to 10 wherein the drive unit comprises a piezo-electric drive.
12. Apparatus as claimed in any one of claims 8 to 11 wherein the drive unit comprises an electromagnetic drive.
13. Apparatus as claimed in any one of claims 8 to 12 wherein the drive unit comprises an electric motor.
14. Apparatus as claimed in any preceding claim wherein the valve means is provided in a head portion of the apparatus facing the compression member.
15. Apparatus as claimed in any preceding claim comprising sensor means for sensing a position of the compression member, the control means being arranged to control the actuator means responsive to the position of the compression member.
16. Apparatus as claimed in claim 15 wherein the sensor means comprises at least one selected from amongst an optical sensor, a magnetic sensor, an acoustic sensor and an electromagnetic radiation sensor.

17. Apparatus as claimed in claim 15 or claim 16 arranged to sense a position of the compression member by detection of a signal generated by a transmitter of the sensor means and received by a receiver of the sensor means following reflection from the compression member, the signal being one selected from amongst an optical signal, an acoustic signal and an electromagnetic signal.

18. Apparatus as claimed in claim 17 arranged to sense the position of the compression member by reference to an amount of a Doppler shift between the transmitted and received signals.

19. Apparatus as claimed in any preceding claim comprising sensor means for sensing a pressure of fluid in the pump chamber, the control means being arranged to control the actuator means responsive to the pressure of fluid in the pump chamber.

20. Apparatus as claimed in any preceding claim wherein the at least a portion of the compression member is arranged to reciprocate between a first position proximate the valve means and a second position distal the valve means.

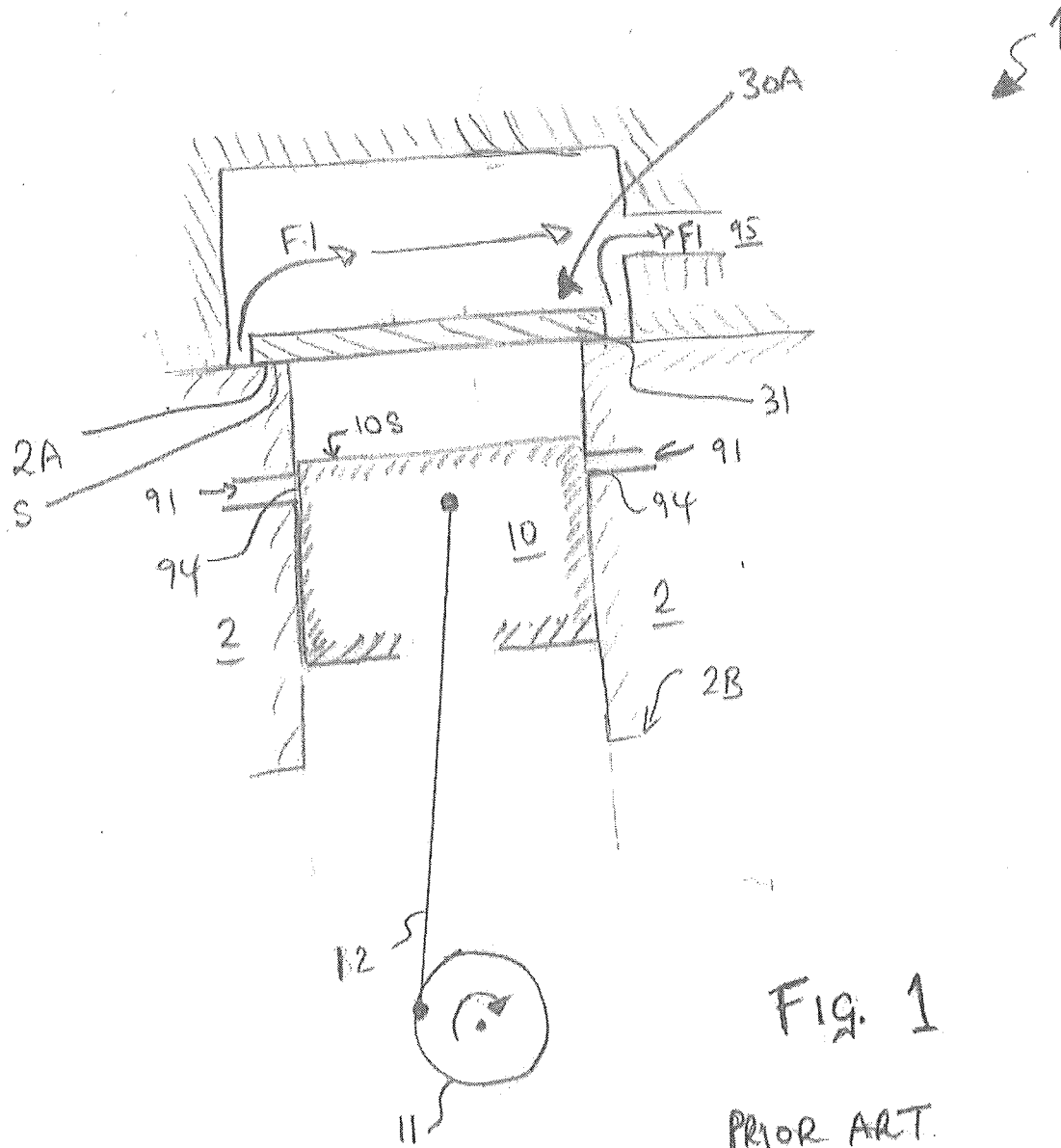
21. Apparatus as claimed in claim 20 wherein the control means is operable to control the valve means to allow a flow of fluid into the pump chamber from the fluid inlet when the at least a portion of the compression member moves from the first position towards the second position thereby to reduce a magnitude of a force required to so move the compression member.

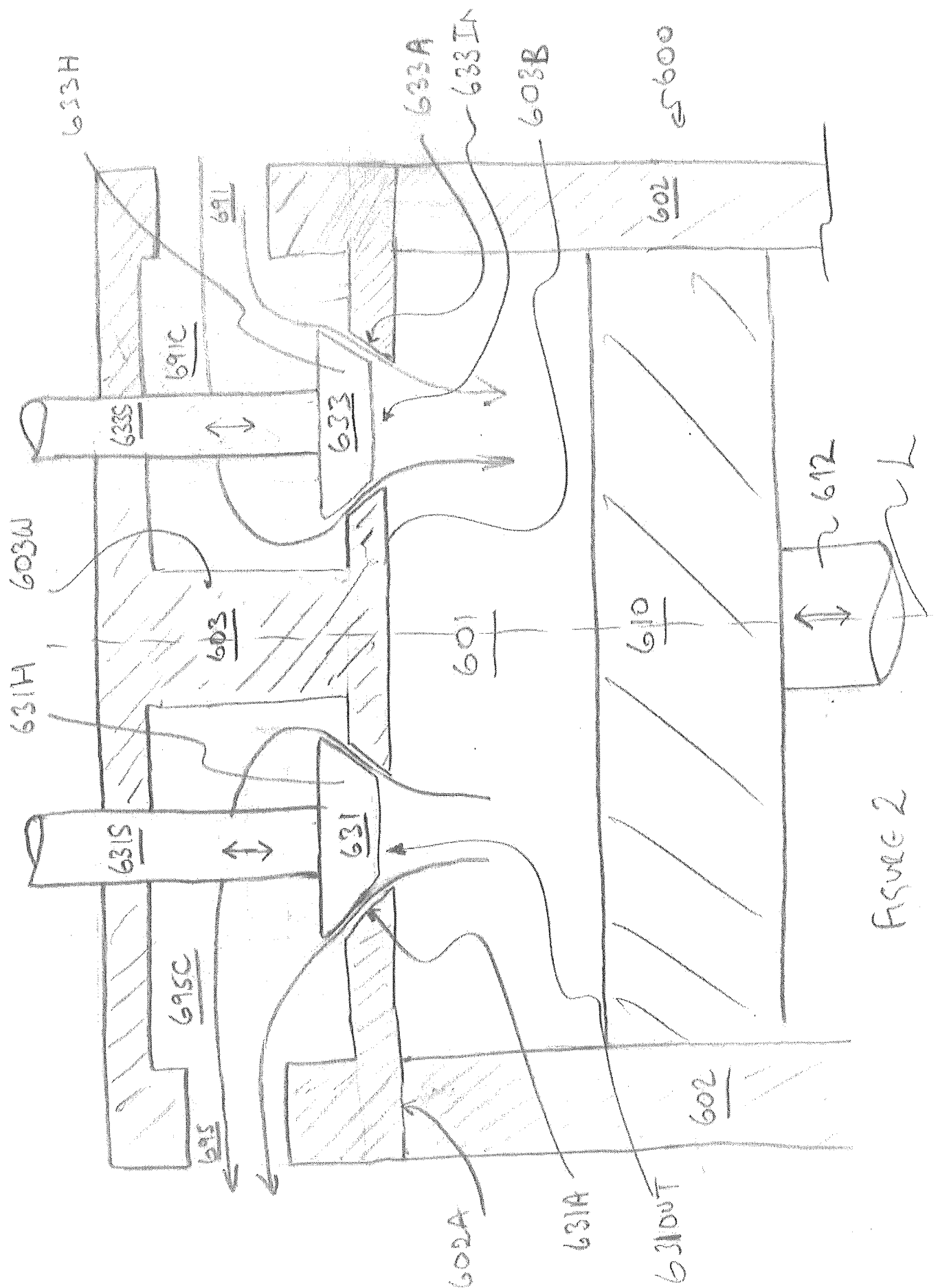
22. Apparatus as claimed in claim 20 or 21 wherein the control means is operable to control the valve means to allow a flow of fluid into the pump chamber from the fluid inlet when the at least a portion of the compression member is substantially at the first position thereby to reduce a magnitude of a force required to so move the compression member.

23. Apparatus as claimed in claim 2 or any one of claims 3 to 22 depending through claim 2 wherein the control means is arranged to open the outlet valve as the at least a portion of the compression member moves from the second position to the first position and to close the outlet valve when the at least a portion of the compression member is substantially at the first position thereby to increase the amount of fluid exhausted through the outlet valve.

24. Apparatus as claimed in any preceding claim coupled to first and second respective different volumes and arranged to pump gas from a first volume to the second volume.
25. Apparatus as claimed in any preceding claim wherein the linear drive assembly comprises a coupling rod coupled to the compression member, the drive assembly being arranged to drive the coupling rod to and fro in a substantially straight line along a direction coincident with a longitudinal axis of the coupling rod.
26. Apparatus as claimed in any preceding claim wherein the drive assembly comprises a piezoelectric drive portion.
27. Apparatus as claimed in any preceding claim wherein the drive assembly comprises an electromagnetic drive portion.
28. Apparatus as claimed in any preceding claim wherein the linear drive assembly is in fluid communication with the compression member.
29. Apparatus as claimed in claim 28 wherein the linear drive assembly is provided in a vacuum-tight package whereby it is sealed from an environment external to the apparatus.
30. Apparatus as claimed in claim 2 or any one of claims 3 to 29 depending through claim 2 wherein the closure member of the inlet valve is operable to open in a direction away from the pump chamber.
31. Apparatus as claimed in any preceding claim wherein the apparatus is a vacuum pump.
32. A pumping assembly comprising at least first and second fluid pump apparatus as claimed in any preceding claim.
33. An assembly as claimed in claim 32 wherein a fluid outlet of the first pump apparatus is in fluid communication with a fluid inlet of the second pump apparatus wherein the first and second pump apparatus are coupled in series.
34. An assembly as claimed in claim 32 or 33 wherein respective compression members of the first and second pump apparatus are arranged to reciprocate along a common axis.

35. An assembly as claimed in claim 32 or 33 wherein respective compression members of the first and second pump apparatus are arranged to reciprocate along respective parallel axes.
36. An assembly as claimed in claim 32 or 33 wherein respective compression members of the first and second pump apparatus are arranged to reciprocate along non-parallel axes.
37. An assembly as claimed in claim 36 wherein respective compression members of the first and second pump apparatus are arranged to reciprocate along substantially orthogonal axes.
38. An assembly as claimed in any one of claims 32 to 37 wherein the respective compression members are arranged to reciprocate either in phase or in anti-phase with respect to one another.
39. A method of dry pumping a gaseous fluid by means of dry pumping apparatus comprising:
- drawing fluid through a fluid inlet into a pump chamber via valve means when at least a portion of a compression member is translated in a first direction and exhausting fluid from the pump chamber through a fluid outlet via valve means when said at least a portion of the compression member is translated in a second direction opposite the first,
 - the method comprising actuating the valve means by actuator means under the control of control means to perform at least one selected from amongst the functions of allowing fluid to be drawn from the fluid inlet via the valve means into the pump chamber and allowing fluid to be exhausted from the pump chamber via the valve means through the fluid outlet,
 - the method further comprising driving the at least a portion of the compression member to and fro within the pump chamber by means of a linear drive assembly.
40. Fluid pump apparatus, an assembly or a method substantially as hereinbefore described with reference to the accompanying drawings.





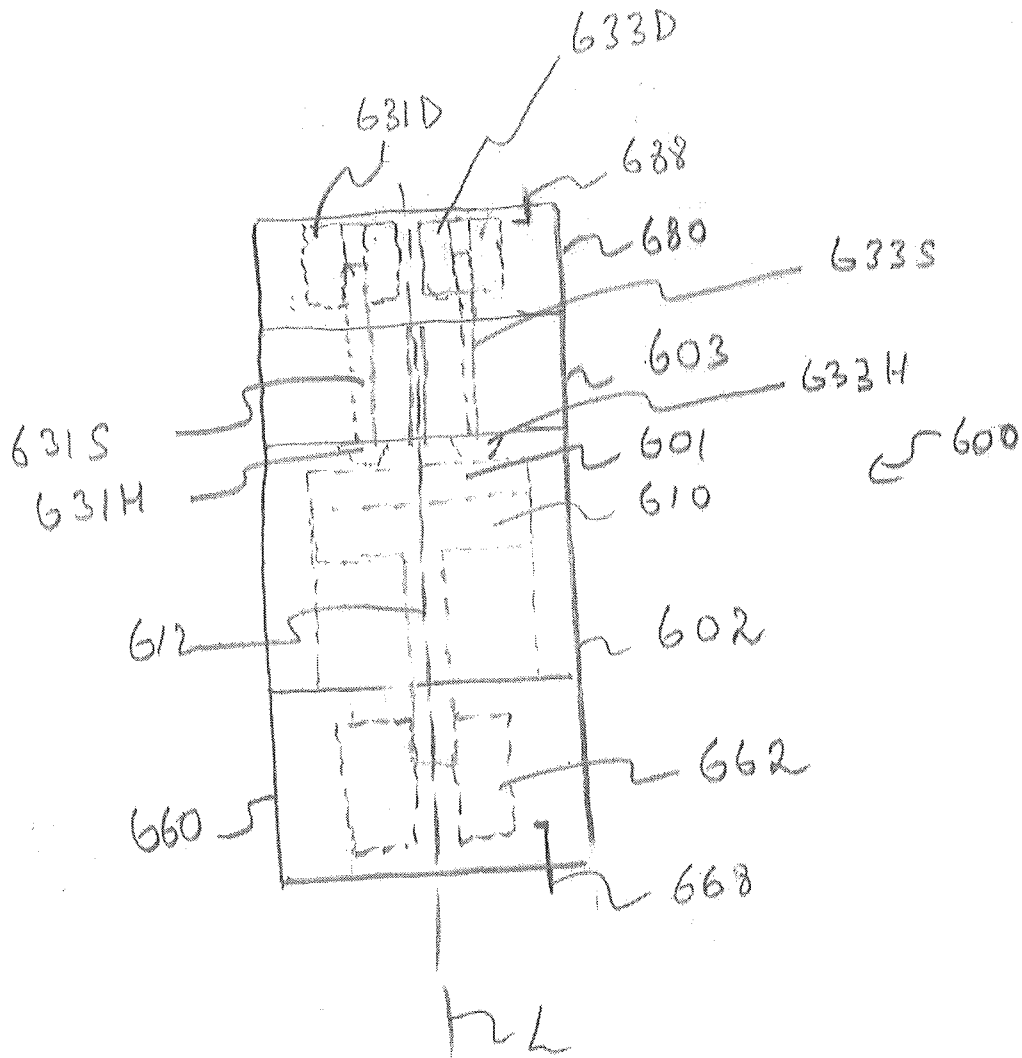


Figure 3

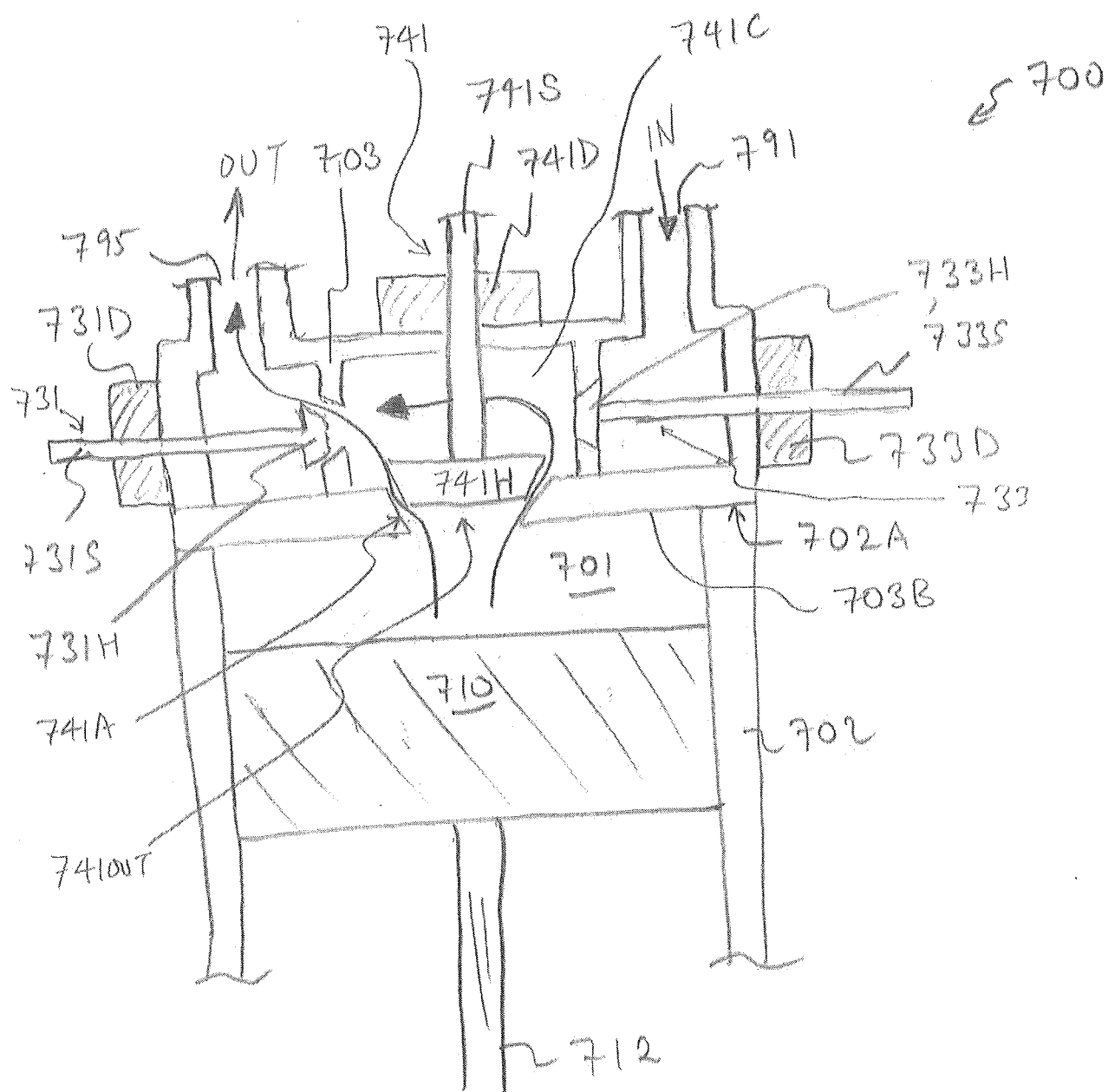


FIGURE 4

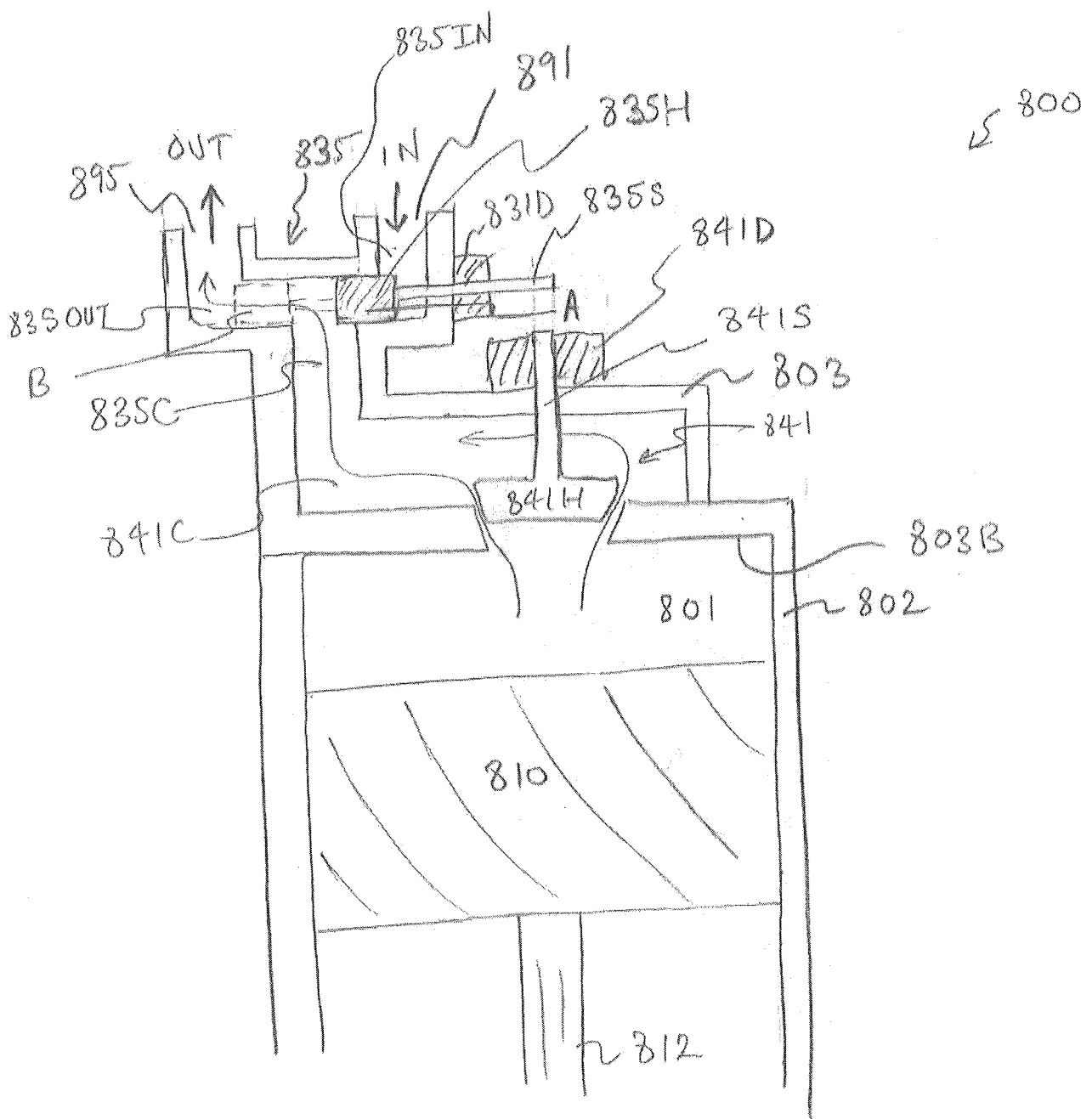


FIGURE 5

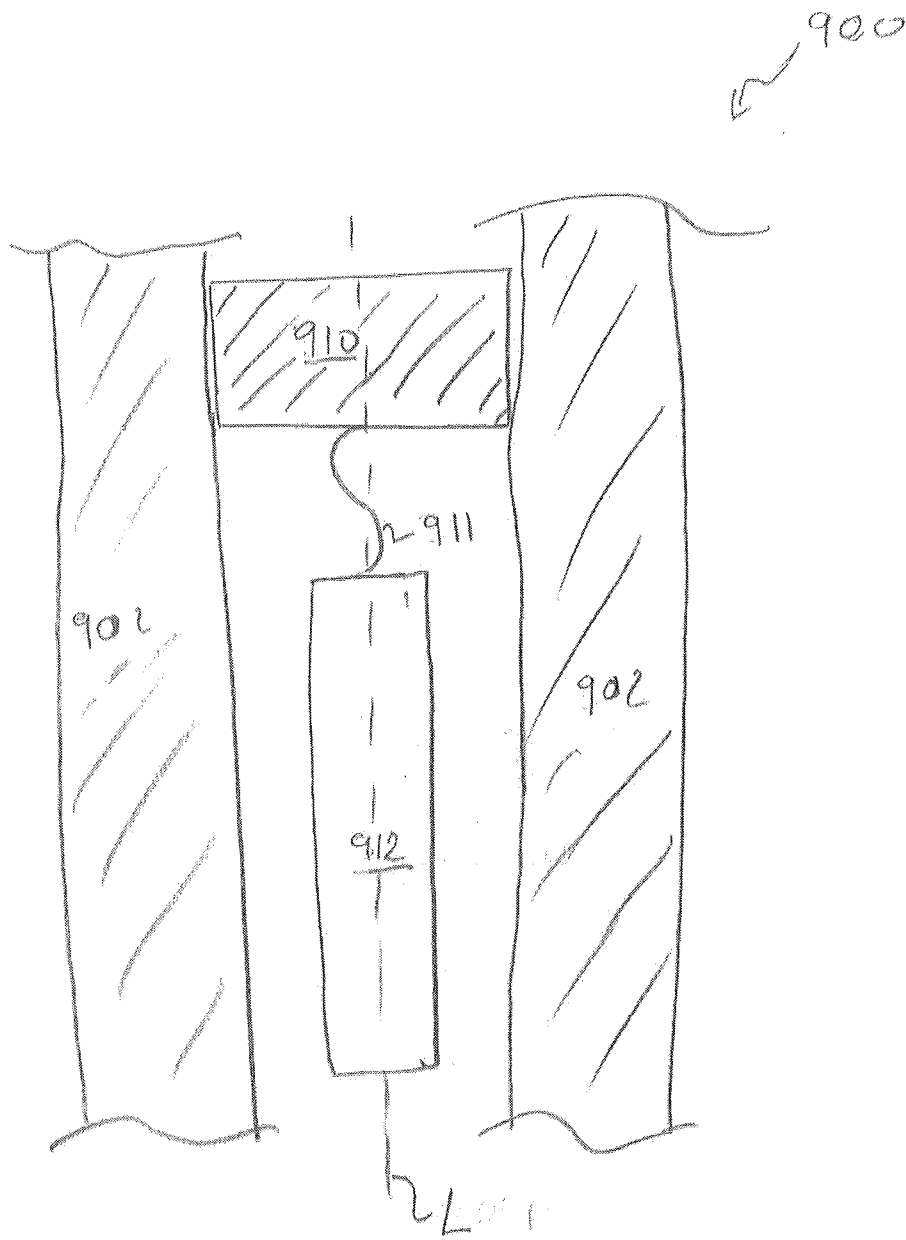


FIG. 6

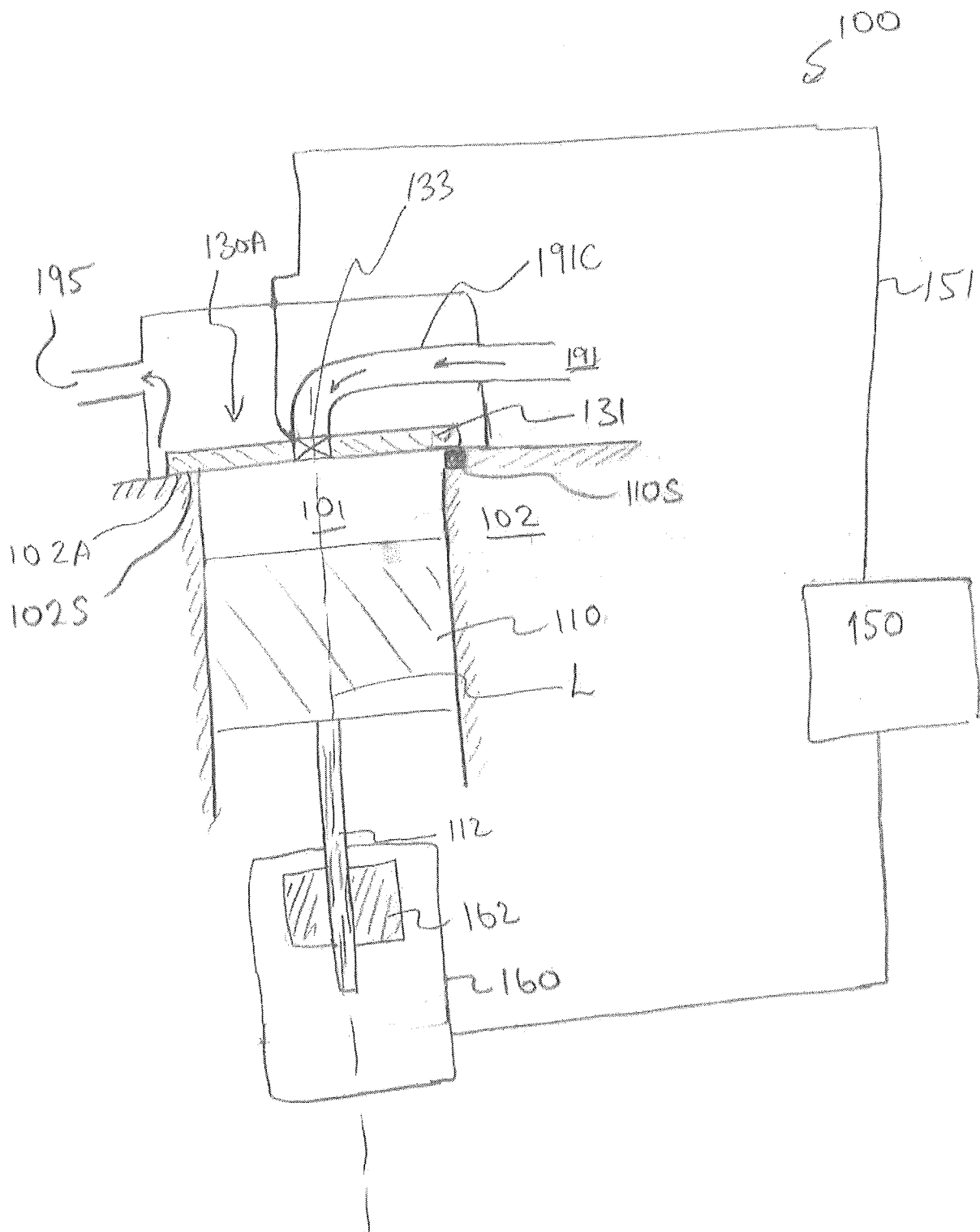


Figure 7