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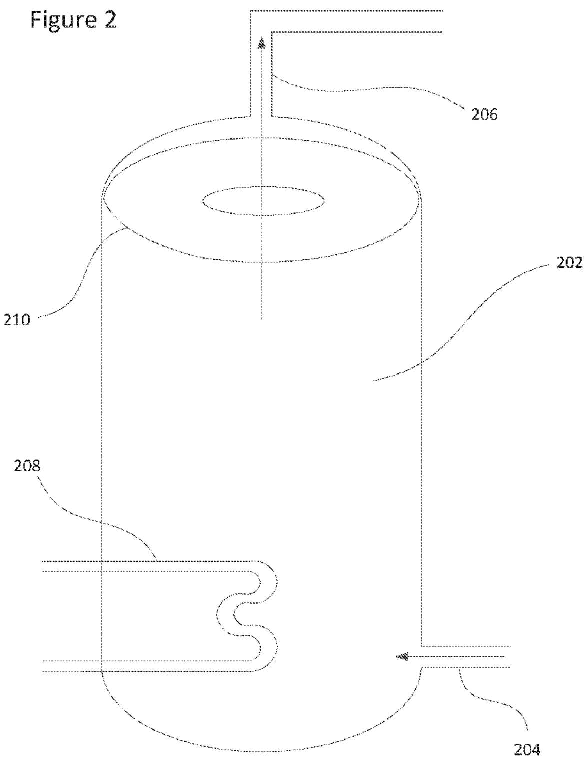
(54) Title: APPARATUS AND METHOD FOR PROTECTING A PRESSURISED FLUID SYSTEM FROM EXCESSIVE PRESSURE

Figure 2



(57) Abstract: Apparatus for protecting a pressurised fluid system from excessive pressure, comprising: a vessel for storing a pressurised fluid; and at least one inflatable element disposed inside the vessel, the element when inflated having a variable volume that can be compressed by a surrounding pressurised fluid inside the vessel such that the volume of the element can compensate a change in volume of the surrounding pressurised fluid.

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Apparatus and method for protecting a pressurised fluid system from excessive pressure

The present invention relates to pressurised fluid systems, such as the type used to supply hot water in a domestic setting. More specifically, the present invention provides an apparatus and method for protecting a pressurised fluid system from excessive pressure, which may occur as a result of the fluid being heated and hence expanding within a pressurised fluid vessel (or tank), in particular a mains-pressurised water vessel, of the system, for example.

Pressurised fluid systems may be used to provide a supply of pressurised fluid for a variety of different applications, both in industrial and domestic settings. For example, a pressurised fluid system may be installed in a residential building to provide a supply of hot water stored under mains water supply pressure. Such a system may comprise a fluid vessel in which a fluid may be stored under mains water supply pressure and heated to a desired temperature to provide a ‘hot’ water supply that is available to be drawn from the vessel, when required. Such pressurised fluid systems may offer an improvement in the water pressures and flow rates that can otherwise be achieved by gravity-based systems.

As fluid stored in a pressurised vessel is heated it increases in volume, by way of thermal expansion, by up to 5%. If this increase in volume is not properly managed somehow, then excessive pressure may build up in the system, particularly in the vessel in which the fluid is being heated and stored, increasing the risk that a wall of the vessel will rupture with potentially catastrophic results.

Simply allowing excess fluid to drain from the system is both wasteful and may be prohibited by regulatory requirements. It is therefore highly desirable for a pressurised fluid system to include an alternative arrangement or facility for managing an increase in the volume of a stored fluid that maintains a safe operating pressure in the vessel.

An example of a known method for managing excessive of pressure of a fluid in a pressurised fluid system is to connect an external expansion vessel in fluid communication to the pressurised fluid vessel. The external expansion vessel accommodates and/or compensates for any increase in volume of the fluid contained in the pressure storage vessel as it is heated.

However, such arrangements can be complicated and cumbersome to install, leading to higher costs, and possibly requiring extra space. Introducing another complex component into the hot water system also means that there are additional potential points of failure in the system.

Aspects and embodiments of the present invention are set out in the appended claims. These and other aspects and embodiments of the invention are also described herein.

According to an aspect of the present invention there is provided an apparatus for protecting a pressurised fluid system from excessive pressure, comprising a vessel for storing a pressurised fluid; and at least one inflatable element disposed inside the vessel, the element when inflated having a variable volume that can be compressed by a surrounding pressurised fluid inside the vessel such that the volume of the element can accommodate and/or compensate a change in volume of the surrounding pressurised fluid.

The vessel of the apparatus may comprise a temperature and/or pressure release valve configured to open when a predetermined temperature and/or pressure is exceeded in the vessel. The valve may be an integrated temperature and pressure release valve, which may be referred to as a “T & P valve”.

The vessel of the apparatus may comprise a pressure reducing valve (“PRV”), whereby to ensure a substantially constant pressure is maintained within the pressurised fluid system against a varying pressure of a replenishing fluid supply to the vessel. In other words, in a domestic setting for example, a pressure reducing valve may be designed to impose a constant pressure within a hot water system against a varying cold mains service pressure. A pressure reducing valve may allow for a smaller inflatable element to be used.

The apparatus may further comprise means for heating a fluid contained in the vessel. Preferably, the means for heating the fluid is at least partially disposed inside the vessel. Such ‘heating means’ may be an immersion element or heat exchanger coil, for example.

The apparatus may further comprise a tether arranged to attach the at least one inflatable element to a wall of the vessel. Preferably, the tether may comprise a conduit fluidly connected to the element, whereby the element can be inflated via the conduit.

According to another aspect of the invention there is provided an apparatus for protecting a pressurised fluid system from excessive pressure, comprising at least one inflatable element; and a conduit fluidly connected to the at least one element, whereby the at least one element can be inflated via the conduit.

The following features may (also) be incorporated into either of the above-described “apparatus”.

The conduit may be integrally formed with the inflatable element to which it may be fluidly connected and/or may have a length of between around 25mm and around 500mm, preferably between around 40mm and around 400mm, and more preferably between around 50mm and around 300mm. The at least one element may be capable of moving freely within a surrounding fluid in the (or a) fluid vessel. Preferably, a valve is provided at an end of the conduit distal to the element. Preferably, the valve comprises a Shrader or Presta type of valve assembly.

The conduit preferably has a substantially constant inner bore diameter, for example wherein the conduit comprises a substantially rigid material.

The at least one element may be expandable by at least 10% of its uninflated volume. Preferably, the at least one element is formed of a material that is more flexible than a material from which a wall of the vessel is constructed. The at least one element may be manufactured from a material approved for contact with potable water. The at least one element may comprise rubber, for example Ethylene Propylene Diene Monomer (EPDM) rubber or a natural rubber. The at least one element may have a wall thickness of between about 0.3mm and about 5mm, preferably between about 0.4mm and about 4mm, and more preferably between about 0.5mm and about 3mm.

Preferably, the at least one element is capable of withstanding a compressive pressure of up to about 1MPa (10 bar), preferably when inflated.

The element may be moulded as a single component. The at least one inflatable element may be substantially torus shaped. The torus shaped element may have an external diameter of between about 200mm and about 800mm, preferably between about 250mm and about 700mm, and more preferably between about 300mm and about 600mm. The torus shaped element may have a generally centrally located hole with a diameter of at least about 50mm, preferably at least about 75mm, and more preferably at least about 100mm.

The at least one element may be arranged to extend between side walls of a fluid vessel (preferably when inflated) such that the at least one element can become lodged in between said side walls. Preferably, the at least one element is arranged to become lodged in between the side walls while being inflated.

The at least one inflatable element may comprise a plurality of chambers, each of which may be arranged to contain a gas. The apparatus may comprise a plurality of inflatable elements. The plurality of elements may be provided in a stacked arrangement.

Alternatively, the at least one element may have a substantially cylindrical shaped body, preferably with tapered ends.

The conduit may be substantially rigid and is arranged so as to be able to secure the at least one element in a fixed position and, preferably, orientation within the vessel, for example in a spaced arrangement relative to the wall of the vessel. A pressure transducer may be arranged to determine the pressure of gas inside the at least one element and/or the fluid vessel.

The plurality of chambers and/or elements may be fluidly connected such that a gas can be introduced into each one via a common conduit. Preferably, the plurality of chambers and/or elements are fluidly connected via one-way valve arrangements, such that once inflated they are isolated from each other.

The element may be an inner-tube for a vehicle, the inner-tube preferably comprising a material approved for contact with potable water.

The apparatus may further comprise an adaptor arranged to fit into a standard immersion element port provided on a wall of a fluid vessel, whereby to secure an end of the conduit to the wall of the vessel.

The adaptor may be an assembly comprising a plate having a threaded boss arranged to be screwed into the port, and a conduit gland arranged to be received by the plate, wherein the plate further comprises a hole for receiving the gland such that the end of the conduit can pass through the gland, whereby it is secured to the gland via a gland nut.

According to another aspect of the invention there may be provided an adaptor for securing a conduit to a port provided on a wall of a fluid vessel, comprising: a plate having a threaded boss arranged to be screwed into the port; and a conduit gland arranged to be received by the plate; wherein the plate further comprises a hole for receiving the gland such that the end of the conduit can pass through the gland, whereby it is secured to the gland via a gland nut.

According to another aspect of the invention there may be provided an adaptor arranged to fit into a port provided on a wall of a vessel arranged to store fluid under pressure, comprising: a threaded boss arranged to be screwed into the port; wherein the adaptor is arranged to provide a fluid connection into the vessel.

The port is preferably a standard immersion element port. The adaptor may further comprise a pressure sensing arrangement arranged to detect the pressure of a fluid contained within the fluid vessel. The pressure sensing arrangement preferably comprises a pressure transducer. The adaptor may further comprise a temperature sensing arrangement for detecting the temperature of a fluid contained within the fluid vessel.

The adaptor may further be arranged to provide a fluid connection to an inflatable element disposed within the fluid vessel. The inflatable element may have a fluid conduit for inflating the inflatable element, and wherein the adaptor may be arranged to form a fluid connection with said conduit, whereby to tether the conduit to the adaptor.

According to another aspect of the invention there may be provided a system comprising a vessel arranged to store fluid under pressure and an analogue pressure gauge fluidly connected to said fluid vessel, wherein the pressure gauge comprises a drag pointer arranged to indicate a maximum pressure of fluid within the vessel.

Preferably, the analogue pressure gauge is directly connected to the vessel. Alternatively, the analogue pressure gauge may be connected to pipework fluidly connected to the vessel. The analogue pressure gauge may alternatively be incorporated into an adaptor secured to a port of the vessel, for example.

According to another aspect of the invention there is provided a method of protecting a pressurised fluid vessel from excessive pressure, the method comprising providing within the vessel an inflatable element filled with a gas, wherein the element has a variable volume such that it can be compressed by surrounding pressurised fluid, whereby the volume of the element can accommodate and/or compensate a change in volume of the pressurised fluid.

According to another aspect of the invention there is provided a method of determining when an inflatable element contained within a pressurised fluid vessel requires inflation, the method comprising: measuring pressure and/or temperature values within the vessel; determining an upper value and a lower value of the measured pressure and/or temperature over a thermal cycle; determining a difference between the upper and lower values; and detecting when the difference between the upper and lower values exceeds a predetermined threshold value; wherein detection of a difference exceeding said threshold value is an indication that inflation of the element may be required.

According to another aspect of the invention there is provided a method of inflating an inflatable element of an apparatus as described above when the element is disposed inside a fluid vessel, the method comprising the steps of: filling the vessel with a fluid; inflating the element with a gas; allowing fluid displaced during inflation of the element to exit the vessel; and measuring the volume of the fluid displaced from the vessel, thereby to determine an increase in volume of the element.

A method of manufacturing an inflatable element as described above, comprising extruding a substantially cylindrical tube of material, preferably wherein the material is a material approved for contact with potable water; cutting the extruded tube to a desired length; connecting together the ends of the tube that have been cut, preferably using heat to fuse them together; creating a hole in the extruded tube, preferably by punching a hole in the tube; and attaching to the hole a conduit for introducing gas into the element, wherein the conduit is provided with a valve at an end that is distal from the element.

Preferably, the conduit has a length of between around 25mm and around 500mm, preferably between around 40mm and around 400mm, and more preferably between around 50mm and around 300mm.

According to another aspect of the invention there is provided a method of manufacturing an inflatable element as described above, comprising using an inner-tube manufacturing process with a material approved for contact with potable water to manufacture the element.

According to another aspect of the invention there is provided a method of monitoring the condition of an inflatable element within a fluid vessel containing a fluid under pressure, the method comprising: determining a physical characteristic of the inflatable element by sensing a measure of the fluid within the fluid vessel.

The method may further comprise monitoring a change in a sensed measure of the fluid within the fluid vessel over a period of time. The method may further comprise calculating a gradient of said change in said sensed measure of fluid over time. The method may further comprise modelling at least one simulated change in a measure of fluid within the fluid vessel over a period of time to calculate a gradient of said change in said measure of fluid over time. The method may further comprise modelling the at least one simulated change in said measure of fluid change based on an initial estimated value of the physical characteristic of the inflatable element.

The method may further comprise comparing the at least one simulated gradient with the sensed gradient. The method may further comprise comparing the at least one simulated gradient with the sensed gradient to determine a degree of similarity between the gradients, preferably using a metric of fit. The method may further comprise determining whether the degree of similarity falls within an acceptable tolerance. The method may further comprise, in response to determining that the degree of similarity falls outside of an acceptable tolerance, modelling one or more additional simulated changes in said measure of fluid using different estimated values for the physical characteristic of the inflatable element for each simulated change, and comparing the one or more simulated gradients with the sensed gradient until a degree of similarity falling within the acceptable tolerance is determined. The method may further comprise logging the estimated value of the physical characteristic that achieved a degree of similarity falling within the acceptable tolerance. Preferably, the period of time over which the change in said sensed measure of fluid is monitored is the period of time for a filling event to occur.

The method may further comprise computing a loss rate of the physical characteristic of the inflatable element over a period of time, preferably measured in weeks or months, based on the estimated value of the physical characteristic determined. The computed loss rate may be used to determine the future date for a likely maintenance event for the inflatable element. The physical characteristic of the inflatable element is preferably its volume, and preferably its inflated volume. Optionally, the sensed measure of fluid is pressure. Optionally, the sensed measure of fluid is temperature.

The method may further comprise detecting when the gradient is a negative gradient. Preferably, the period of time over which the change in said sensed measure of fluid is monitored is the period of time for a draw event to occur. The method may further comprise calculating a flow rate of the fluid during the draw event based on one or more physical characteristics of the inflatable element and the sensed measure of the fluid. Preferably, the sensed measure of the fluid is pressure.

According to another aspect there is provided an apparatus, adaptor and inflatable element as substantially described herein with reference to the accompanying drawings. According to another aspect there is provided a method as substantially described herein with reference to the accompanying drawings.

As used herein, the term “fluid” preferably connotes a liquid or a gas, or even a flowable solid. As used herein, the term “inflate” preferably connotes to fill an expandable structure (e.g. the “at least one element”) with a fluid, preferably air or gas (but equally a liquid) so that it becomes distended. As used herein, the term “torus” preferably connotes a shape defined by a surface or solid formed by rotating a closed curve, especially a circle, about a line which lies in the same plane but does not intersect it (e.g. a “ring doughnut”). As used herein, the term “heating element” preferably connotes an immersion heater or a heat exchanger coil, for example. There may be more than one heating element, which may be powered by electricity or gas. Heat may also be transferred into the vessel via external heat exchangers through straightforward inlet connections. As used herein, the term “vehicle” preferably connotes a motorcycle or a bicycle, but more generally includes any type of vehicle that might use a suitable inner-tube, such as a wheel-barrow, fork-lift truck, sack truck, quad-bike, etc., for example.

Any apparatus feature as described herein may also be provided as a method feature, and vice versa. As used herein, means plus function features may be expressed alternatively in terms of their corresponding structure.

Any feature in one aspect of the invention may be applied to other aspects of the invention, in any appropriate combination. In particular, method aspects may be applied to apparatus aspects, and vice versa. Furthermore, any, some and/or all features in one aspect can be applied to any, some and/or all features in any other aspect, in any appropriate combination. It should also be appreciated that particular combinations of the various features described and defined in any aspects of the invention can be implemented and/or supplied and/or used independently.

At least one exemplary embodiment of the present invention will now be described with reference to the accompanying figures, in which:

Figures 1A and 1B show two different examples of a pressurised fluid vessel having an external expansion vessel;

Figure 2 shows an inflatable element disposed within a pressurised fluid vessel according to a first embodiment of the present invention;

Figure 3 shows an inflatable element according to a second embodiment of the present invention.

Figure 4 shows the inflatable element of Figure 3 disposed inside a pressurised fluid vessel;

Figure 5 shows a pressurised fluid vessel having a pressure monitoring system; and

Figures 6A to 6D show an assembly for tethering an inflatable element to a wall of the vessel;

Figures 7A and 7B show two different examples of adaptors arranged to fit a port of a storage vessel;

Figures 8A and 8B show the exemplary adaptor embodiments of Figures 7A and 7B connected with an inflatable element;

Figure 9 shows the exemplary arrangement of 8A in use in a storage vessel;

Figure 10A shows another alternative embodiment of an inflatable element;

Figure 10B shows the embodiment of Figure 10A tethered to a wall of a storage vessel, in use;

Figure 11 shows yet a further embodiment of an inflatable element in use in a water tank;

Figure 12 shows a close up view of the further embodiment of an inflatable element in use;

Figure 13 illustrates an alternative arrangement of the yet further embodiment of the inflatable element in use;

Figure 14 illustrates another alternative arrangement of the further embodiment of the inflatable element in use;

Figure 15 illustrates a method for monitoring the state of the inflatable element in use;

Figure 16 is an exemplary plot of measured pressure data against time taken from an exemplary system, in use;

Figure 17 shows an analytical method of estimating the volume of an expansion vessel, in use;

Figure 18 shows a numerical method of estimating the volume of an expansion vessel, in use; and

Figure 19 shows an exemplary plot of pressure data against time obtained for a simulated system, in use.

Figures 1A and 1B each show an example of a typical fluid storage vessel 102 suitable for storing a fluid under pressure. The vessel 102 has a fluid inlet 104 and a fluid outlet 106. A heating element 108 is disposed internally towards the base of the vessel 102 for heating a fluid entering via the inlet 104. Arrows are illustrated to show the direction of fluid flow in and out of the vessel 102 via the inlet 104 and outlet 106, respectively. The vessel 102 may be used to store a heated fluid, wherein cold fluid entering the vessel 102 via the inlet 104 (from the mains water supply, for example) is heated within the vessel 102 by the heating element 108. Once heated, the fluid can be drawn from the vessel 102 via the outlet 106. A typical application might be to heat and store heated water for use in a domestic setting, for example, wherein water is stored in the vessel 102 under pressure of the mains water supply.

To compensate for an expansion in the volume of fluid caused by heating, an external expansion tank 110 may be fluidly connected to the fluid storage vessel 102. In the exemplary arrangement shown in Figure 1A, the expansion tank 110 is connected to the vessel 102 via the outlet 106 through which heated fluid is drawn for use. In the, perhaps more common, exemplary arrangement shown in Figure 1B, the expansion tank 110 is connected to the vessel 102 via the inlet 104 to the vessel 102 through which the vessel 102 is filled. It will be appreciated that the expansion tank 110 may be fluidly connected to the vessel 102 via another suitable fluid conduit (not shown).

The expansion tank 110 comprises a pressurised cylinder having an internal volume that is divided into two separate compartments 112, 114 by a flexible membrane (or ‘diaphragm’) 116. The first compartment 112 fluidly connected to the pressurised fluid storage vessel 102; the second compartment 114 contains gas (typically air) under pressure. In use, the first compartment 112 of the expansion tank is pressurised by fluid entering via a fluid inlet (not shown), supplied by the mains water supply, for example.

In use, as fluid stored in the vessel 102 is heated its volume increases. The increased volume of fluid is compensated by a deformation of the membrane 116 in the expansion tank 110, which distends into the second compartment 114. The air contained in the second compartment 114 is more compressible than the fluid in the expansion tank 110, and hence the air is caused to be compressed by the volume of fluid increasing, as it is heated, for example. The expansion tank 110 acting to absorb the increased volume of fluid in this way therefore allows excessive pressure in the fluid storage vessel 102 to be avoided.

The heated fluid is therefore stored in the vessel 102 under pressure so that a draw event (such as opening a hot water tap or faucet, for example) causes heated fluid to exit the vessel 102 via the outlet 106. As heated fluid is drawn from the vessel 102, a pressure difference between the fluid supply to the inlet 104 (e.g. mains water supply) and atmospheric pressure causes fluid from the fluid supply to enter the fluid vessel 102 to replenish the fluid that has been drawn.

Figure 2 shows a fluid storage vessel 202 of similar construction to the fluid storage vessel 102 of Figure 1, having a fluid inlet 204, a fluid outlet 206 and a heating element 208 disposed within the vessel 202.

Also disposed inside the vessel 202 is an inflatable element 210, which in this example is torus shaped. The inflatable element 210 may be inflated by air, or another suitable gas, and disposed inside the vessel 202 during manufacture, for example.

The inflatable element 210 is, ideally, dimensioned so that it may be lodged between sidewalls of the vessel 202, such that it remains in-situ during transport, for example. If the inflatable element 210 is not retained by the sidewalls of the vessel 202, the hole provided at the centre of the inflatable element 210 ensures that the fluid outlet 206 will not become blocked should the inflatable element 210 have positive buoyancy relative to fluid stored in the vessel 202, causing it to rise to the top of the vessel 202. Furthermore, the torus shape of the inflatable element 210 of this particular embodiment advantageously allows it to fit into the dome-shaped top of the vessel 202, which allows for a greater utilisation of the space within the vessel 202 to store heated fluid.

In another embodiment (not shown), an inflatable element may be configured such that it secures itself into position as it is inflated against the inside wall(s) of a vessel. This would prevent the element from moving around in the vessel during transit, for example. The inflatable element may be further configured to become free once under pressure (compressed), such that it can float to the top of the vessel.

Figure 3 shows another embodiment of an inflatable element 310 for use in a fluid storage vessel, the element being generally torus shaped with a generally centrally located hole 320. The inflatable element 310 has a conduit 330 attached to allow inflation of the inflatable element 310. The conduit, preferably, has a length between 50mm and 300mm, though other lengths may be considered. The conduit, preferably, may be configured such that it can be bent upon itself without a substantial fluid restriction being created in the conduit 330. A free ‘distal’ end of the conduit (i.e. an end not attached to the inflatable element 310) is provided with a valve 332.

The torus shaped inflatable element 310 is characterised by two diameters: a first ‘major’ diameter, d_1; which is the centreline diameter of the torus; and a second ‘minor’ diameter, d_2, which is the diameter of the circle that forms the torus. The diameters d_1, d_2 are chosen to ensure that the inflatable element 310 can contain sufficient gas to absorb (i.e. to compensate for) an increase in the volume of the fluid when heated. Preferably, the external (outer) diameter (d_1+d_2) of the inflatable element lies between about 300mm and 600mm. The minimum inner diameter of the inflatable element 310 (in other words, the diameter of the generally central hole provided in the inflatable element 310) is, preferably, around 100mm (to prevent any head losses). A similarly dimensioned hole would, ideally, be suitable for all external diameters, though the diameter of the hole is of course not limited to this dimension. Some exemplary volumes for an inflatable element 310 when in the form of a torus (or ‘ring doughnut’) are provided in Annex A.

As mentioned above, the diameters d_1, d_2 are also chosen so that the element 310 does not unnecessarily occupy too much of the useful volume inside a vessel. In particular, the diameters d_1, d_2 are, preferably, chosen so that the diameter of the central hole 320 (given by d_1-d_2) in the element 310 is at least equal to the diameter of a centrally located fluid outlet provided at the top of a fluid storage vessel. This is to prevent restriction (or even blockage) of the flow of heated fluid out of the vessel. A fluid outlet on a vessel used in a domestic setting in the UK may be around 22mm in diameter, for example. Of course, it will be understood that the diameter of the central hole 320 can be configured according to different sized fluid outlets, as required.

Figure 4 shows the inflatable element 310 disposed within a fluid storage vessel 402 having a fluid inlet 404, a fluid outlet 406 and a heating element 410, similar to the fluid storage vessels of Figures 1 and 2.

In this embodiment, the inflatable element 310 is tethered, preferably by a conduit 330, to a plate 338 having a threaded boss 334. Gas can be passed into the inflatable element 310 via the valve 332 provided as part of the plate 338 and threaded boss 334 arrangement. The threaded boss 334 is configured to fit a standard immersion port size (for example, of diameter 38mm (1½“), 44.5mm (1¾“), or 57mm (2¼“) in the UK) provided on a wall of the vessel 402. Advantageously, this arrangement enables an inflatable element 310 to be ‘retro-fitted’ into a vessel 402 after its manufacture by inserting an uninflated inflatable element 310 through a suitable port 440, and then securing it to the port 440 via the threaded boss 334 before inflating the inflatable element 310 via the valve 332. The port 440 may, preferably, be an immersion heater port. This arrangement will be described in more detail further on, with reference to Figure 6.

A gas contained in the inflatable element 310 is more compressible than the fluid, such as water for example, stored in the vessel 402. Thus, in use, any expansion of fluid, through it being heated for example, resulting in a change (i.e. increase) in volume of fluid is absorbed by the inflatable element 310 being compressed. In other words, as the fluid in the vessel 402 expands, the inflatable element 310 is compressed. Importantly, this protects the vessel 402 against excessive pressure that might otherwise be present in the vessel 402.

Variations in the volume of the fluid inside the vessel 402 over a thermal cycle of the fluid (for example, the fluid being heated, allowed to cool, then (re)heated, etc.), can be accommodated by the expansion and compression of the inflatable element 310. More specifically, as fluid stored in the vessel 402 is heated by the heating element 410, its volume increases. This increased volume causes additional pressure to be applied to the outer surface of the inflatable element 310, which compresses the air contained inside it. The volume of the inflatable element 310 is reduced accordingly, by an amount approximately equal to the increase in volume of the water in the vessel. In practice, the vessel 402 may itself expand to accommodate some of the increased volume, in which case the change in volume of the inflatable element 310 may not exactly reflect the change in volume of the fluid. While the pressure of the gas inside the inflatable element 310 increases, it is configured to be able to withstand this increase in pressure without rupture.

The effects of other pressure variations within the fluid, such as water hammer or other shockwaves for example, can also be reduced by use of the inflatable element 310 in this way. The pressure variations cause the inflatable element 310 to expand and contract, absorbing the changes and reducing the risk of damage to the rest of the fluid supply system, including the vessel 402.

A challenge of installing an inflatable element 310 into a pre-manufactured vessel 402 (i.e. ‘retrofitting’ the inflatable element 310) is to ensure that the inflatable element 310 is adequately inflated during assembly/replacement. This can be achieved by filling the inflatable element 310 with a predetermined volume of gas, for example using a pre-filled gas cylinder containing the desired amount of gas.

In a domestic installation, for example, where the inflatable element 310 is being inflated for the first time or is being replaced, it may be impractical to deliver an accurate volume of air without using specialist equipment.

To overcome this problem the following method can be used. Upon installation of a vessel 402 containing a deflated ring (i.e. “inflatable element”), the fluid inlet 404 is opened and the vessel 402 is filled with (typically cold) fluid. When the vessel 402 is full, the fluid inlet 404 is closed. An outlet connection tube (not shown) can then be fitted to a fluid outlet 406 of the vessel 402. The inflatable element 310 is then inflated, which displaces fluid from the vessel 402 via the fluid outlet 406 and into the outlet connection tube. By monitoring the volume of displaced fluid, the volume of gas in the inflatable element 310 can be determined. Once a predetermined volume of fluid has been displaced, it will be known that the inflatable element 310 contains a desired amount of gas. The outlet connection tube can then be removed from the fluid outlet 406 and installation of the rest of the fluid system can then proceed as normal.

The fluid storage vessel 302, 402 is pressurised with fluid. For example, when the fluid is water, the vessel 402 is pressurised to the mains water supply pressure. In practice, many mains hot water vessels often have a pressure reducing valve and so the pressure of the fluid contained within a vessel 302, 402 can be configured as required.

A pressure of 0.3 MPa (3 bar) is quite typical in a pressurised fluid storage vessel used in a domestic setting in the UK, for example. However a pressure of 0.10 MPa (1 bar) would likely be adequate for most requirements. If the fluid system is to operate without a pressure reducing valve, the inflatable element 310 would need to accommodate pressure as high as 0.70 MPa (7 bar) (a figure that the mains service pressure in the UK can reach at night when there is minimal use). Consequently the inflatable element 310 might have to be considerably larger than if used in combination with a pressure reducing valve.

The inflatable element 310 is, preferably, manufactured from a material suitable for use with potable water, ideally comprising rubber. Advantageously, this allows heated water stored in a vessel 302, 402 to be used for human consumption. Such a material would have to comply with regulatory standards, for example the Water Regulation Advisory Scheme (“WRAS”) UK.

Ideally, a WRAS approved Ethylene Propylene Diene Monomer (EPDM) (M-class) rubber with a rating of at least 60°C (preferably 85°C) would be used. An example of such a material is the Zenith™ PWS EPDM rubber compound provided by Zenith™ Industrial Rubber Products PVT. LTD, though many other examples will be familiar to those skilled in the art. The rubber may be vulcanised. Natural rubbers have, however, been found to be less brittle and may therefore be preferred for certain arrangements.

By providing an internal expansion vessel in this way the number of moving parts in the system is reduced, leading to an increase in reliability as there are fewer parts to fail. The ease of installation such a system is also greatly improved.

The inflatable element 310 also allows for a more efficient utilisation of space. Pressurised vessels 302, 402 in the domestic setting in particular are usually installed in a cupboard or other restricted space. An external expansion tank takes up a lot of this space, reducing the amount of space available for the vessel 302, 402. This can make installation more difficult, as well as reducing the available amount of hot water. The inflatable element of the present invention does not suffer from these drawbacks, since it is internal to the vessel.

The relative simplicity of the inflatable element 310 means that its cost to manufacture is far less than that of an external expansion tank. The cost of installing a pressurised fluid vessel containing an inflatable element 310 is also greatly reduced.

In another embodiment (not shown), the inflatable element may comprise a vehicle inner-tube manufactured, ideally, from an approved material suitable for use with potable water, such as a WRAS approved material, as discussed above. An inner-tube is provided with a conduit for inflation, wherein the conduit may comprise a valve stem and a valve assembly, preferably of the “Schrader” or “Presta” type. This embodiment may provide the advantage of using existing inner-tube manufacturing processes to manufacture suitable inflatable elements from a WRAS approved material (e.g. rubber) at a low cost and high production volume. A motorcycle, bicycle, quad-bike, fork-lift truck, wheel-barrow or sack truck, for example, are all vehicles that may use an inner-tube of a size, shape and configuration that may be suitable for use with the present invention.

In yet another embodiment (not shown), a separate length of conduit may be provided to tether an element to a wall of the vessel, wherein the separate length of conduit may, ideally, be removably attachable to the element. In the alternative embodiment (not shown) discussed above, the separate length of ‘tethering’ conduit would, preferably, be fluidly connected to the conduit, for example the inflation valve of the (inner-tube) element, rather than forming an integral part of it, such that the element may be inflated via the tethering conduit.

Figure 5 shows a fluid storage vessel 502 having disposed within it an inflatable element 310, very similar to the arrangement shown in Figure 4. In addition, the vessel 502 in this embodiment further comprises a pressure monitoring system 550. The pressure monitoring system 550 comprises a pressure sensor 552 installed on a sidewall of the vessel 502, wherein the pressure sensor 552 is, preferably, adapted to fit into a standard immersion heater port 540-2 (for example by integration with a threaded boss similar to that used with the valve assembly), and a control unit 554.

Over time, gas may gradually leak from the inflatable element 310, which may result in the situation that the volume of gas in the inflatable element 310 will be insufficient to absorb the changing volume of fluid during heating and cooling cycles. This could result in the excess pressure in the system causing the fluid storage vessel 502 to rupture. It is possible to top up the volume of gas contained in the inflatable element 310 by inflating it using the valve 532. However, it is difficult to know when the inflatable element 310 requires inflating, and an over-inflated inflatable element 310 would take up valuable usable volume in the vessel 502, not to mention run the risk of bursting the inflatable element 310.

The pressure sensor 552 enables the controller 554 to observe changes in pressure as the fluid in the vessel 502 heats and cools repeatedly. The pressure sensor 552 may also be equipped with a temperature sensor (not shown), which would enable the controller 554 to monitor the temperature of the fluid in order to determine its thermal cycle. When the inflatable element 310 is fully (i.e. optimally) charged, the pressure change inside the vessel 502 over one thermal cycle will be small since there will be an optimum amount of gas to accommodate the expansion. However, should the volume of the inflatable element 310 decrease, the change in pressure inside the vessel 502 will rise over each thermal cycle. The controller 554 monitors the change in pressure and raises an alarm in the event that the change in pressure exceeds a predetermined threshold, advising that the inflatable element 310 requires inflation. This predetermined threshold would, ideally, in practice be significantly lower than mechanical pressure relief valve settings that are required for a particular vessel being used. The determination of pressure relief valve settings for a particular vessel diameter with a known wall thickness can be derived from look-up tables - for example, Table 4 from BS7206:1990 - which are well known to a person skilled in the art.

Figures 6A to 6D show an embodiment of an assembly arranged to tether an inflatable element 310 to a fluid vessel 402, 502. Figure 6A is an exploded view of the assembly, which includes a plate 338 having a threaded boss 334 arranged to be screwed into a port (not shown) on a wall of the fluid vessel 402, 502, and a conduit gland 340. The threaded boss 334 has an outer hexagonal-shaped key feature to enable it to be tightened using a conventional immersion spanner (not shown). The body of the gland 340 (preferably sized between M3 and M8), is screwed into the plate 338, as shown in Figure 6B. The gland 340 has gland fingers 342 with a, preferably rubber, sealing ring inside (not shown). A gland nut 344 is provided to screw onto the body of the gland 340.

During assembly, the uninflated inflatable element 310 is inserted into the vessel 402, 502 before being inflated. As shown in Figure 6C, a valve stem 336 on the free end of the tether 320 is then threaded through the threaded boss 334 and gland 340. Within the gland 340 assembly, a rubber ring (not shown) inside the gland fingers 342 provides a seal around the valve stem 336. Once the threaded boss 334 is tightened into the standard immersion heater port 440, 540 provided in a wall of the vessel 402, 502, the gland nut 344 is fastened onto the body of the gland 340 to tighten the gland fingers 342 around the internal sealing ring (not shown) to ensure the assembly is fully water tight.

In the embodiments described herein, the inflatable element 310 is manufactured from a single moulded piece. It will be appreciated by those skilled in the art that this does not need to be the case for the inflatable element 310 to work as described. The inflatable element 310 can alternatively be formed from multiple moulded pieces, ideally fluidly connected so that they can be inflated via a common conduit but individually contained such that rupture of the inflatable element 310 at a single point will not deflate the entire element 310. Such an arrangement may improve the robustness of the inflatable element

310 to deflation.

Alternatively, an inflatable element may comprise multiple (for example, torus shaped) elements (e.g. gas pockets / compartments) stacked one on top of another. Alternatively, multiple inflatable elements may be nested radially. The inflatable element 310 may be formed from multiple parts tethered together. Those multiple parts may be of equal size and shape, or may be different sizes and shapes. For example, the inflatable element 310 may be formed form multiple parts each of which are a “slice” of the inflatable element 310.

The gas filling the ring is, preferably, air, but any gas that is more compressible than the fluid surrounding it in a vessel would be suitable. Preferably, the gas is an inert gas.

The inflatable element 310 (or any of the parts that make up the inflatable element 310) can be coated in a self-sealing coating, either internally of externally to reduce the effect of punctures on the inflatable element 310.

In the exemplary embodiments described herein, the inflatable element has been generally described herein as torus shaped. It will of course be understood that the inflatable element could be of any size, shape, configuration, material or structure, provided that when inflated with a gas it was capable of absorbing or accommodating/compensating for an increase in volume of a fluid stored within a pressurised fluid vessel (caused by that fluid being heated, for example), according to the present invention.

Figures 7A and 7B illustrate two alternative embodiments of adaptors 732, 733 for securing to a port (not shown) of a fluid pressure (“storage”) vessel via a plate 736, 737 having a threaded boss 734, 735, similar to the adaptor 338 previously described. These adaptors 732, 733 may be utilised for monitoring the internal pressure of a pressurised “storage” vessel (not shown), preferably in which an internal expansion vessel as described above is installed.

An adaptor (not shown) having a pressure transducer and threaded boss arrangement alone (i.e. one that does not accommodate a conduit of an inflatable element) may also be provided for monitoring the pressure of a pressurised "storage" vessel having an external expansion vessel or an internal expansion vessel that does not need to be topped up, or is otherwise inflated.

As described above, the adaptor 732, 733 may be arranged to enable an internal expansion vessel (i.e. an "inflatable element") to be inflated. In Figure 7A, the adaptor 732 has a pressure transducer 738 arranged in-line with a conduit or valve (not shown) for inflating an expansion vessel (not shown), whereby the inflation conduit or valve passes through the body of the pressure transducer 738. An electrical connector 740 is provided for supplying power to the pressure transducer 738 and, optionally, for carrying a signal. In Figure 7B, the adaptor 733 has a pressure transducer arranged off-set from a valve 743 provided for inflating a pressure vessel (not shown). An electrical connector 741 is provided for supplying power to the pressure transducer 739 and, optionally, for carrying a signal.

It may also be desirable to obtain a temperature measurement around the adaptors 732, 733. Thus, a temperature sensor 746, 747 may be provided, for example being arranged on the surface of the plate 736, 737 of each adaptor 732, 733 as shown in Figures 7A and 7B, for obtaining a temperature reading indicative of the temperature of the stored fluid. This may be useful to assist with physical modelling (preferably together with measured pressure data) used to infer a volume of the expansion vessel, as will be described later.

The adaptors 732, 733 are of course not limited for use with a torus-shaped element. Figures 8A and 8B illustrate the adaptors 732, 733 of Figures 7A and 7B, respectively, provided with an inflatable element 730, 731 having a (conventional) balloon-shape type, though the shape of the inflatable element 730, 731 is not so limited. The inflatable element 730, 731 in each of Figure 8A and 8B is tethered to a port plug of a pressurised storage vessel (not shown) via a conduit of the inflatable element 730, 731.

In Figure 8A, a conduit (not shown) fluidly connected to the inflatable element 730 passes through the plate 736 of the adaptor 732 and pressure transducer 738, thereby tethering the inflatable element 730 to the adaptor 732. The fluid conduit terminates at a valve 744, such as a Shrader or Presta type valve for example, that is provided for inflation purposes.

In Figure 8B, a conduit 743 fluidly connected to the inflatable element 731 passes through the plate 737 of the adaptor 733 and thereby tethers the inflatable element 731 to the adaptor 733. The pressure transducer 739 is coupled to the plate 737 of the adaptor 733 with an off-set configuration such that it is separate from the conduit 743. The fluid conduit terminates at a valve 745, such as a Shrader or Presta type valve for example, that is provided for inflation purposes.

Figure 9 illustrates the adaptor 732 and balloon-shaped inflatable element 730 of Figure 8A in use. The adaptor 732 is secured to the upper pressure relief dome 908 of a pressurised fluid storage vessel (not shown). The threaded boss 734 of the adaptor 732 is screwed into the threaded port 910 in the relief dome 908 to secure the adaptor 732 in place. A conduit (not visible) of the inflatable element 730 passes through the adaptor 732 and pressure transducer 738, which is arranged in an in-line configuration and hence the inflatable element 730 is tethered to the wall of the pressurised storage vessel. The conduit may be secured to the adaptor by way of a securing nut on the end of the valve 744, for example. A compression fitting compression may urge a sealing O-ring (not shown) against the inside of the port plug 910, creating an air-tight and water-tight seal.

Figures 10A and 10B illustrate another example of an embodiment of an inflatable element 1000. In this embodiment, the inflatable element 1000 has the shape of an elliptical torus. A conduit 1002 is provided that is fluidly connected to the interior of the inflatable element 1000. The conduit 1002 passes into the inflatable element 1000 through a sealing O-ring 1004 attached to the outer surface of the inflatable element 1000. In the embodiment shown, the sealing O-ring 1004 has a circular shape, though the skilled person will appreciate that a variety of shapes are possible. The conduit 1002 is threaded at either end to facilitate the securing of the inflatable element 1000 to a side wall of a fluid storage vessel 1006 and the attachment of a valve to the end of the conduit 1000. The conduit 1002 may however have a threaded portion provided at a distal end from the inflatable element 1000, with its proximal end being secured to the inflatable element 1000 with adhesive, for example or other ‘permanent’ means. Figure 10B illustrates how this alternative inflatable element 1000 may be secured to a relief dome 1008 of a storage vessel 1006, in use.

Figures 11 and 12 illustrate a further embodiment of an inflatable element 1100 secured to the wall of a fluid storage vessel 1108. In this further embodiment, the inflatable element 1100 is generally tubular-shaped, with tapered sealed ends. A conduit 1102 is fluidly connected to the interior of the inflatable element 1100 to enable it to be inflated.

The inflatable element 1100 may be introduced (ideally un-inflated) into the fluid storage vessel via a port plug 1112 provided in a side wall of the vessel 1108, through which the conduit 1102 passes. The inflatable element 1100 is thereby secured to the wall of the vessel 1108 by the conduit 1102. A sealing O-ring 1114 is positioned between the body of the inflatable element 1100 and the port plug 1112, and through which the conduit 1102 also passes. A securing nut 1116 attached to the conduit 1102 fixes the inflatable element 1100 in place. The securing nut 1116 urges the sealing O-ring 1114 against the inside of the port plug 1112, creating an air-tight and water-tight seal between the inflatable element 1100 and the port plug 1112.

In the examples shown, the conduit may be manufactured from a rigid material, such as metal or plastic, and may terminate in a sealing valve, for example a Shrader or Presta car type valve. The conduit may take the form of an extended valve tube, which may be about 5-6mm in diameter and between about 50-100mm in length, for example, in order to accommodate (e.g. extend past) any thermal insulation provided around the outside of a storage vessel.

Figure 13 illustrates an alternative arrangement of the further embodiment of the inflatable element 1100. In this exemplary arrangement, a conduit 1122 is provided in the form of an elbowed pipe. The conduit 1122 is secured to a port plug 1112 on the side wall of a fluid storage vessel 1108 by means of a compression fitting. The conduit 1122 end that lies outside the vessel 1108 terminates in a valve, for example a Shrader or car type valve. Inside the vessel 1108, the conduit 1122 extends in a substantially horizontal direction from the port plug 1112 to an elbow 1118. This horizontal extension into the vessel 1108 ensures that the side-walls of the vessel 1108 are clear for a helical coil heat exchanger (not shown). In some embodiments, the conduit 1122 extends a distance of between about 100mm to 250mm into the vessel 1108 from the vessel side wall.

At the elbow 1114, the conduit 1122 is bent into a substantially vertical direction, and joins the lower part of inflatable element 1100. The inflatable element 1100 is thus positioned away from the side wall of the vessel 1108, and aligned in the vertical direction to minimise the obstruction of fluid flow within the vessel 1108.

Figure 14 illustrates another alternative arrangement of the further embodiment of the inflatable element in use. In this embodiment, the inflatable element 1100 has the conduit 1102 extending outwardly from approximately midway along the body of the inflatable element 1100. The inflatable element 1100 is secured to the top pressure relief dome through a port plug 1112. The inflatable element 1100 is secured to the top pressure relief dome in a similar way to a standard vertical entry immersion boss.

Although not shown, an analogue pressure gauge may also be fluidly connected to the storage vessel or nearby plumbing of such a system, preferably a pressure gauge having a ‘drag pointer’. A drag pointer is arranged to track the variation in pressure from the gauge needle but it does not return with the (spring-loaded) needle once the pressure drops or is removed. Such a gauge can therefore be used to track the highest pressure that the system has experienced in service. A plumber visiting the system (or any other interested party) could glance at the gauge to verify that the maximum pressure encountered is safely below the maximum operating pressure of the system.

A method of estimating the volume of an expansion vessel (e.g. the inflatable element described herein) contained within a pressurised fluid vessel, and other aspects, will now be described. For example, a simple pressure monitoring algorithm for predicting the condition of the expansion vessel a future date for maintenance of the expansion vessel to be required is as follows:

1. Measure maximum signal recorded after a heating event over cyclic period of time

(e.g. each day);
2. Over a duration (e.g. weeks or months) of time in service, compute the trajectory of pressure rise;
3. Calculate a time (or date) in future at which the pressure within the expansion vessel will breach a safe operating limit, based on pressure relief valve characteristics; and
4. Using step 3, recommend a suitable maintenance date.

Figure 15 illustrates a method for monitoring the inflatable element in use, for example to determine a draw event and/or to estimate a maintenance schedule. The pressure inside a fluid storage vessel may be monitored by a pressure monitoring system 550 such as that shown in Figure 5, which includes a pressure sensor 552. During use, the pressure inside the fluid storage vessel varies, which is detected 1300 by a pressure sensor. Applying 1302 a low pass signal filter to pressure data collected by the pressure sensor can remove higher frequency noise and fast pressure variations from the pressure data, for example those caused by shockwaves during the refilling process. The gradient of the changing pressure with respect to time (i.e. a “pressure gradient”) is then calculated 1304, which is the derivative of the detected pressure with respect to time (dP/dT).

Figure 16 illustrates an exemplary plot of measured pressure data against time, illustrating a pressure change that occurs in a storage vessel during use. A negative gradient indicates a “draw” event during which fluid is drawn from the vessel. A positive gradient indicates a filling event during which the vessel is (re)filled.

If a positive pressure gradient 1406 (dP/dt) is detected by the pressure monitoring system, the volume of the inflatable element can be estimated 1312, 1314 using the pressure gradient 1406. The positive pressure gradient that is measured during system recovery after a draw event reflects the volume of air within the vessel. This is because the amount of gas within the vessel determines its associated compliance. The volume of stored air determines the relationship between vessel displacement, i.e. for the internal expansion arrangement the degree to which it contracts due to surrounding water pressure, and the consequent pressure rise within the stored gas. In essence, this determines the effective spring rate associated with the vessel - if the system is considered to be a mass spring damper. In such an analogy, pressure is equivalent to a force (distributed over an area) and damping is equivalent to the pressure drop throughout the system as a function of flow rate.

If the mains pressure and system pressure drop are known, a model of the system can be parameterised in which the response of the system to the termination of a draw event can be characterised by the consequent response in system pressure over time. Since the response of the system is determined by the effective spring rate of the expansion vessel, which in turn is a function of its volume, the pressure gradient can be used to infer the volume during termination of a draw event.

The larger the volume of air within the inflatable element (i.e. the “expansion vessel”), the more compliant it will be when fully expanded. For a large volume, on termination of a draw event, it will take a long time for the pressure to stabilise back to the mains pressure since it will take longer to fully compress the air. This will manifest itself as a small positive pressure gradient. For a small inflatable element volume, the compliance will be less (i.e. stiffer) since the vessel’s internal pressure will rise rapidly as it is compressed. On termination of a draw event, it will therefore take less time for the system to recover back to steady state which manifests itself as a large positive pressure gradient. The volume of the inflatable element can be estimated directly through comparison with experiment (where an inflatable element within a fluid storage vessel is subjected to increasing water pressure whilst the volumetric flow required to induce this pressure is monitored).

The volume can also be estimated using a pressure-volume relationship deduced for the vessel on the basis of its geometry and ideal gas laws (or a more complex model incorporating finite element or membrane theoretical analysis of the rubber walls to account for its stiffness).

The relationship between volume of the inflatable element and temperature during heating (when there are no draw events) can (also) be characterised by analysing the system in three stages, making the assumption that conditions are at steady state and that ideal gas laws apply. It is assumed that the contribution to the internal pressure within the inflatable element from the inflatable element's elastic walls is negligible.

Stage 1 – Dry state, P_d, V_d, T_d

The inflatable element can be inflated into an empty fluid storage vessel. At this stage the pressure within the inflatable element is equal to the atmospheric pressure since the element's walls are highly elastic therefore P_d is 1 bar (0 bar gauge). The temperature is at ambient assuming steady state, $T_d \approx 20^{o}C$.

Stage 2 – Filled state, P_f, V_f, T_f

On filling, the fluid storage vessel is pressurised to the mains water service pressure. In practice, many mains hot water cylinders often have a pressure reducing valve and so this figure can be chosen by design. A figure of 3 bar is popular on the market, however 1 bar would likely be adequate for most system requirements.

Once filled and pressurised, the volume of the inflatable element in the filled state, V_f, becomes:

$$V_f = \left(\frac{P_d V_d}{T_d}\right)\frac{T_f}{P_f}$$

Stage 3 – Heated state, P_h, V_h, T_h

As the cylinder is heated, the water expands by Vex due to the relationship between temperature and density which we have foreknowledge of. The heated volume of the inflatable element therefore becomes:

$$V_h = V_f - V_{ex}$$

Allowing the heated pressure to be determined by:

$$P_h = \left(\frac{P_f V_f}{T_f}\right)\frac{T_h}{V_h}$$

Using the above relationships, it is possible can determine the filled volume of the inflatable element, V_f, and how it changes over time whilst the fluid storage vessel is in service.

Having estimated the volume of the inflatable element, the filling event is timestamped and stored in a database, along with the estimated volume of the inflatable element 1314.

The pressure monitoring system then determines whether the estimated volume of the inflatable element is below a pre-determined threshold 1316. An estimated volume below this threshold indicates that the inflatable element requires maintenance 1318. If the estimated volume is above this threshold, then the system is determined to be functioning properly 1320.

In addition, the rate of volume loss and pressure rise per heating cycle is calculated 1322, and used to predict the date at which the estimated volume will fall below the threshold, and therefore a predicted maintenance date 1324.

The volume loss from the inflatable element is likely to be gradual, for example a loss of 50% of volume over 10 years might be expected. By periodically logging an estimate of the inflatable element (i.e. the “expansion vessel”) volume (e.g. over a period of weeks and months), the loss rate of its volume can be determined. The consequent increase in pressure that will arise after each heating event can also be observed.

Therefore, as the rate of increasing pressure/decreasing volume of the inflatable element is known from the above process, it is possible to schedule when the inflatable element needs to be recharged with gas during a maintenance visit. This is achieved by projecting the increasing pressure ahead in time and predicting the point at which the inflatable element’s pressure relief valve would exhaust (ideally, with subtraction of some safety margin).

Figure 17 illustrates an exemplary ‘analytical’ method of deriving (“estimating”) the volume of an inflatable element during use based on the geometry of the inflatable element during use and the physical characteristics of the hot water system in which it operates.

Upon first usage of a particular inflatable element within a fluid storage vessel, the pressure in the vessel is monitored via a pressure sensor. The pressure as a function of time (P(t)) is recorded during a filling event. A low pass filter is applied to the recorded pressure data to remove higher frequency noise and fast pressure variations from the pressure data, for example those caused by shockwaves during the filling process. The gradient of the pressure with respect to time is then calculated. If it is negative, the system re-applies the low pass filter. If the gradient is positive, then the variation in the gradient of the pressure with respect to time is monitored as the pressure asymptotes towards the pressure of the mains supply feeding the vessel (i.e. a mains pressure). This avoids the influence of downstream pressure drops on the pressure data.

A dynamical model characterised by a set of model parameters is then fitted to the measured pressure data (and pressure gradient data) to of the system pressure. For example, by iteratively experimenting with values for the volume of the vessel assumed by the dynamic model, it is possible to obtain a number of simulated pressure gradients, which are then compared against the pressure gradient obtained using the measured pressure data. When a match within a pre-set tolerance is achieved (e.g. using a metric of fit such as ‘Richardson squared’), the estimated volume used for that model can be extracted.

An optimisation algorithm, such as a gradient descent algorithm applied to an error cost function, for example, is used to fit the model to measured pressure data and determine the optimal parameters. An error cost function is defined which acts a metric for measuring the difference between the dynamical model with a particular set of model parameters and the pressure data, with a lower value of the error cost function indicating a closer fit of the simulated model to the measured data. An initial set of model parameter values are used in the model to determine an initial error cost. A gradient of the error cost function with respect the model parameters being optimised is then calculated, either numerically or using a known closed form. This gradient is used to calculate new values of the parameters being optimised using the gradient descent method. The process is then repeated with the new values for the model parameters, and iterated until the values of the parameters that minimise the error cost function are found. These are the optimum values for fitting the model to the data.

In a preferred embodiment, the dynamical model is a forced harmonic oscillator, and the system can be modelled by an analytical approach using the equation:

$$P(t) = P_m a \cos\left(\sqrt{\frac{a}{b}}\, t\right), \tag{1.1}$$

Where:

- a is a characteristic of the system spring rate, which is known for a new system;
- b is a characteristic of the system inertia, which is initially unknown and depends on variables including the vessel volume and intermediate pipework; and
- P_m is the asymptotic mains pressure.

Fitting the pressure data to this form during the first usage of the inflatable element in the system determines the (initially unknown) parameter b, and allows for the initial volume of the inflatable element to be baselined.

In subsequent service usage, the pressure continues to be monitored during draw and fill events substantially as described in relation to Figure 16. When the pressure gradient is determined to be positive 1406 the variation in the gradient of the pressure with respect to time is monitored. Once the ‘mains pressure’ asymptote is approached, the same dynamical model characterised by the set of model parameters as used in the first usage is fitted to the pressure data using an optimisation approach to regress the data to a closed form model solution.

In embodiments where the dynamical model is a forced harmonic oscillator, modelled by equation 1.1, the parameter a has already been determined by the first usage fitting, and a new value for the parameter b is determined by this regression.

From the new parameter, or parameters, determined in the regression and the known geometry of the vessel, an estimated volume of the inflatable element can be derived. This estimated volume can be fed back into the ‘pressure monitoring’ algorithm illustrated in Figure 15 to determine whether maintenance is required and also to estimate a maintenance date.

Figure 18 shows a physical model of a water storage system, which model may be computer-implemented, for example. Figure 19 is an exemplary plot of simulated pressure data against time, obtained using a physical model such as that illustrated in Figure 18, for example.

A numerical algorithm (or method) for estimating a maintenance schedule for an expansion vessel based on the estimated volume of the expansion vessel, incorporating the physical model of Figure 18, is outlined below:

1. Measure a pressure signal received from a vessel during start and termination of a draw event (i.e. a positive gradient);
2. Run a physical model of the system using an initial guess of the volume of the expansion vessel (as illustrated in Figure 18);
3. Compare a simulated pressure response (e.g. Figure 19) to a measured pressure response (e.g. Figure 16 – portion 1406)_using a metric of fit (such as 'Richardson squared');
4. Check to see whether the measured and simulated results agree within an acceptable tolerance;
5. If measurements and simulation don't agree, repeat steps 1 to 4 with new, directed guesses for the expansion vessel volume until convergence is achieved;
6. Once convergence has achieved, log estimated vessel volume;
7. Over a duration (e.g. weeks or months) of time in service, compute the loss rate of the expansion vessel volume based on values derived from above steps; and
8. Project vessel volume loss rate and consequent pressure rise to determine likely maintenance schedule requirement.

Additionally, if the temperature of the fluid in the vessel is detectable, the temperature(s) may be fed into the pressure loss model 1809 and/or the vessel stiffness model 1816 of the algorithm in Figure 18, for example.

Turning again to Figures 15 and 16, a negative pressure gradient 1402 indicates a draw event 1400, whereby fluid is removed from the storage vessel. This can lead to a sudden drop in the pressure inside the vessel. A negative gradient 1402 (dP/dt) can be used to classify the flow rate out of the vessel and the associated activity. For instance, the gradient for a shower use event will have a larger magnitude (e.g. be steeper) than that for a wash-hand basin event. An algorithm can therefore use the pressure gradient 1402 along with knowledge of the inflatable element’s physical characteristics to produce a log of flow rates at different times of day, which may be useful for calculating usage and energy requirements at different times, for example.

Calculation of the flow rate can be achieved by recording the onset of the draw event 1306, determining the pressure gradient 1308 during the draw event and relating the pressure gradient 1308, and then logging the event with a timestamp and a flow rate 1310.

After a draw event, the fluid removed from the vessel during the draw event 1400 is replaced and, optionally, heated to the required temperature. This filling event 1404 leads to an increase in the pressure within the vessel until the system pressure returns to the steady state pressure. The positive gradient 1406 (dP/dt) can be used to characterise the health of the inflatable element. The magnitude of the gradient 1406 is at its lowest after a draw event 1400. As gas within the inflatable element escapes over time, the gradient increases, along with the maximum steady state pressure when the system is at full temperature. Therefore, a steep gradient 1406 indicates that the volume of the element is low.

In more detail, just prior to a draw event, the pressure within the tank recorded by the sensor is stabilised at the mains water pressure. As soon as a tap is opened, water flows through the intermediary pipework to the tank and out towards the taps. At each stage before the tap, there are various sources of pressure drop due to constrictions associated with plumbing elbows, the inlet to the tank and pipe and tank walls within the plumbing system. The size of each of these pressure drops is proportional to the flow rate. At the onset of a draw event, the pressure rapidly drops and slowly converges towards a new, lower steady state pressure (in this instance 1 bar). The system pressure drop in this instance is 1.5 bar (since the original steady state pressure was 2.5 bar). The reason for the slow convergence is a combination of the distributed inertia associated with the water stored within the system along with the vessel which expands in response to the dropping pressure thus acting as a stabilising influence. By simply detecting the pressure drop (i.e. by observing a negative pressure gradient) it is possible to determine that a draw event has taken place.

Flow rate can then be quantified by establishing the relationship between the system pressure drop (i.e. the mains pressure before draw event minus steady state mains pressure during the draw event) and the flow rate through it. To do this, we examine the way the system recovers once a draw event has finished. In the example of Figure 16, this begins to happen from about 48 seconds to about 100 seconds. The system pressure begins rising back towards the mains pressure. The reason the system does not recover instantly is because the gas within the expansion vessel compresses to accommodate the water. However, by knowing the initial volume and physical characteristics of the pressure vessel, using anything from simple ideal gas laws to a detailed finite element model or experimental calibration, we can have foreknowledge of the vessel’s volume as a function of pressure. Taking the derivative of the pressure signal with respect to time therefore gives us the volume flow rate at each instance in time as the system recovers. At the same time, the relationship between flow rate and pressure drop for the intermediary pipework to the tank up to the location of the pressure sensor can be established. The relationship between pressure drop and flow rate are then both known, which can be used to discern the steady state flow rate of the system during a draw event. This method is preferred for draw events that are long enough for the system to converge to steady state.

For shorter draw events, where steady state hasn’t been attained, a physical model of the system can be used that accounts for the distributed inertia of the water within the system. This model can be parameterised by measuring the time constant associated with the system achieving steady state. Using both the steady state relationship between volume flow rate and the pressure drop along with the characterisation of system inertia from the system time constant, the flow rate for any pressure signal can be discerned using a fully parameterised model of the system.

The pressure monitoring methods may be performed by a microcontroller as part of the system, which are ideally mains powered, preferably with a battery back-up. The microcontroller may be hard-wired into the system or it may be configured for wireless communication. The microprocessor may be configured to issue an alert should it detect that an action is required, such as maintenance to (e.g. inflating) an inflatable element disposed within the vessel as described herein, for example.

While the invention as described herein occasionally refers to a system comprising a pressurised vessel (or tank) in the context of providing a domestic hot water supply, it will be appreciated by those skilled in the art that the invention may extend to a pressurised vessel containing a fluid for many different domestic or industrial applications.

Although not illustrated herein, an expansion vessel may contain an inflatable element that is filled with fluid (e.g. water) that itself is compressed within a pressurised fluid contained within the expansion vessel (e.g. air), such that said inflatable element is inflated and subsequently compressed within the vessel. Such an expansion vessel may be situation external to a fluid storage vessel, but may still fall within the scope of the present invention.

Thus, it will be understood that the present invention has been described above purely by way of example, and modifications of detail can be made within the scope of the invention.

Each feature disclosed in the description, and (where appropriate) the claims and drawings may be provided independently or in any appropriate combination.

Reference numerals appearing in the claims are by way of illustration only and shall have no limiting effect on the scope of the claims.

Annex A

Assuming an infinitely stiff vessel, and an upper limit of 0.6MPa (6 bar) for a pressurised fluid storage vessel heated to 60C from an initial temperature of 20C and pressure of 0.3MPA (3 bar), the following sizes of inflatable element 310, in the form of a torus shape, may be appropriate for the following UK standard sizes of vessel:

BS Standard Ref number	Tank Volume (litres)	Inflated Element Volumes - heated (litres)
0	98	11.3
1	74	8.6
2	98	11.3
3	116	13.4
4	86	10.0
5	98	11.3
6	109	12.6
7	120	13.9
8	144	16.7
9	166	19.2
9E	210	24.3
10	200	23.2
11	255	29.5
12	290	33.6
13	370	42.8
14	450	52.1

It should be noted that these are probably conservative values since, in practice; a degree of expansion within the body of the vessel will absorb a significant degree of additional volume.

Claims

1. Apparatus for protecting a pressurised fluid system from excessive pressure, comprising:

a vessel for storing a pressurised fluid; and

at least one inflatable element disposed inside the vessel, the element when inflated having a variable volume that can be compressed by a surrounding pressurised fluid inside the vessel such that the volume of the element can compensate a change in volume of the surrounding pressurised fluid.

2. An apparatus according to Claim 1, wherein the vessel comprises a temperature and/or pressure release valve configured to open when a predetermined temperature and/or pressure is exceeded within the vessel.

3. An apparatus according to Claim 1 or 2, wherein the vessel comprises a pressure reducing valve, whereby to ensure a substantially constant pressure is maintained within the pressurised fluid system.

4. An apparatus according to any of Claims 1 to 3, further comprising means for heating fluid contained in the vessel.

5 An apparatus according to Claim 4, wherein the means for heating the fluid is at least partially disposed inside the vessel.

6. An apparatus according to any of Claims 1 to 5, further comprising a tether arranged to attach the at least one element to a wall of the vessel.

7. An apparatus according to Claim 6, wherein the tether comprises a conduit fluidly connected to the at least one element, whereby the at least one element can be inflated via the conduit.

8. Apparatus for protecting a pressurised fluid system from excessive pressure, comprising:

at least one inflatable element; and

a conduit fluidly connected to the at least one element, whereby the at least one element can be inflated via the conduit.

9. An apparatus according to Claim 7 or 8, wherein the conduit is integrally formed with the element to which it is fluidly connected and has a length of between around 25mm and around 500mm, preferably between around 40mm and around 400mm, and more preferably between around 50mm and around 300mm.

10. An apparatus according to any of Claims 7 to 9, further comprising a valve assembly provided at an end of the conduit distal to the element.

11. An apparatus according to any of Claims 7 to 10, wherein the conduit has a substantially constant inner bore diameter, for example wherein the conduit comprises a substantially rigid material.

12. An apparatus according to any preceding claim, wherein the at least one element is capable of moving freely within a surrounding fluid in the (or a) fluid vessel.

13. An apparatus according to any preceding claim, wherein the at least one element is expandable by at least 10% of its uninflated volume.

14. An apparatus according to any preceding claim, wherein the at least one element is formed of a material that is more flexible than the material from which a wall of the vessel is constructed.

15. An apparatus according to any preceding claim, wherein the at least one element is manufactured from a material approved for contact with potable water.

16. An apparatus according to according Claim 13 to 15, wherein the at least one element comprises rubber, for example Ethylene Propylene Diene Monomer (EPDM) rubber.

17. An apparatus according to any preceding claim, wherein the at least one element has a wall thickness of between about 0.3mm and about 5mm, preferably between about 0.4mm and about 4mm, and more preferably between about 0.5mm and about 3mm.

18. An apparatus according to any preceding claim, wherein the at least one element is capable of withstanding a compressive pressure of up to about 1MPa (10 bar) when inflated.

19. An apparatus according to any preceding claim, wherein the at least one element is moulded as a single component.

20. An apparatus according to any preceding claim, wherein the at least one element is arranged to extend between side walls of a fluid vessel such that the at least one element can be lodged in between said side walls.

21. An apparatus according to any preceding claim, wherein the element has an external diameter of between about 200mm and about 800mm, preferably between about 250mm and about 700mm, and more preferably between about 300mm and about 600mm.

22. An apparatus according to any preceding claim, wherein the element is substantially torus shaped.

23. An apparatus according to Claim 22, wherein the torus shaped element has a generally centrally located hole with a diameter of at least about 50mm, preferably at least about 75mm, and more preferably at least about 100mm.

24. An apparatus according to any preceding claim, comprising a plurality of inflatable elements.

25. An apparatus according to any preceding claim, wherein the plurality of elements are provided in a stacked arrangement.

26. An apparatus according to any preceding claim, wherein the at least one element has

a substantially cylindrical shaped body, preferably with tapered ends.

27. An apparatus according to any of Claims 7 to 26, wherein the conduit is substantially rigid and is arranged so as to be able to secure the at least one element in a fixed position and, preferably, orientation within the vessel, for example in a spaced arrangement relative to the wall of the vessel.

28. An apparatus according to any preceding claim, wherein the at least one element comprises a plurality of chambers, each of which is arranged to contain a gas.

29. An apparatus according to Claim28, wherein the plurality of chambers and/or elements are fluidly connected such that a gas can be introduced into each one via a common conduit.

30. An apparatus according to Claim 29, wherein the plurality of chambers and/or elements are fluidly connected via one-way valve arrangements, such that once inflated they are isolated from each other.

31. An apparatus according to any preceding claim, wherein the element is an inner-tube for a vehicle, preferably wherein the inner-tube comprises a material approved for contact with potable water.

32. An apparatus according to any preceding claim, further comprising an adaptor arranged to fit into a port provided on a wall of a fluid vessel, for example a standard immersion element port, the adaptor having a threaded boss arranged to be screwed into the port, wherein the adaptor is arranged to provide a fluid connection into the vessel.

33. An adaptor arranged to fit into a port provided on a wall of a vessel arranged to store fluid under pressure, comprising:

a threaded boss arranged to be screwed into the port;

wherein the adaptor is arranged to provide a fluid connection into the vessel.

34. An apparatus according to Claim 32 or 33, wherein the adaptor further comprises a

pressure sensing arrangement arranged to detect the pressure of a fluid contained within the fluid vessel.

35. An apparatus according to Claim 34, wherein the pressure sensing arrangement comprises a pressure transducer.

36. An apparatus according to any of Claims 32 to 35, wherein the adaptor further comprises a temperature sensing arrangement for detecting the temperature of a fluid contained within the fluid vessel.

37. An apparatus according to any of Claims 32 to 36, wherein the adaptor is further arranged to provide a fluid connection to an inflatable element disposed within the fluid vessel.

38. An apparatus according to Claim 37, wherein the inflatable element has a fluid conduit for inflating the inflatable element, and wherein the adaptor is arranged to form a fluid connection with said conduit, whereby to tether the conduit to the adaptor.

39. An apparatus according to Claim 38, wherein the adaptor is arranged to receive an end of the conduit therethrough, such that the end of the conduit can secured to adaptor external of the fluid vessel.

40. An apparatus according to any of Claims 33 to 39, further comprising at least one inflatable element arranged to be disposed within a fluid storage vessel, the apparatus being configured such that the inflatable element can be inflated when disposed within the fluid storage vessel, preferably after the apparatus has been secured to a fluid vessel.

41. A system comprising a vessel arranged to store fluid under pressure and an analogue pressure gauge fluidly connected to said fluid vessel, wherein the pressure gauge comprises a drag pointer arranged to indicate a maximum pressure of fluid within the vessel.

42. A system according to Claim 41, wherein the analogue pressure gauge is directly connected to the vessel.

43. A method of protecting a pressurised fluid vessel from excessive pressure, the method comprising disposing within the vessel an inflatable element filled with a gas, wherein the element has a variable volume such that it can be compressed by surrounding pressurised fluid, whereby the volume of the element can compensate a change in volume of the pressurised fluid.

44. A method of determining when an inflatable element contained within a pressurised fluid vessel requires inflation, the method comprising:

measuring pressure and/or temperature values within the vessel;

determining an upper value and a lower value of the measured pressure and/or temperature over a thermal cycle;

determining a difference between the upper and lower values; and

detecting when the difference between the upper and lower values exceeds a predetermined threshold value;

wherein detection of a difference exceeding said threshold value is an indication that inflation of the element may be required.

45. A method of inflating an inflatable element of an apparatus according to any of Claims 7 to 40 when the element is disposed inside a fluid vessel, the method comprising the steps of:

filling the vessel with a fluid;

inflating the element with a gas;

allowing fluid displaced during inflation of the element to exit the vessel; and

measuring the volume of the fluid displaced from the vessel, thereby to determine the volume of the element.

46. A method of manufacturing an inflatable element according to any of Claims 1 to 30, comprising:

extruding a substantially cylindrical tube of material, preferably wherein the material is a material approved for contact with potable water;

cutting the extruded tube to a desired length;

connecting together the ends of the tube that have been cut, preferably using heat to fuse them together;

creating a hole in the extruded tube; and

attaching to the hole a conduit for introducing gas into the element, wherein the conduit is provided with a valve at an end that is distal from the element.

47. A method according to Claim 46, wherein the conduit has a length of between around 25mm and around 500mm, preferably between around 40mm and around 400mm, and more preferably between around 50mm and around 300mm.

48. A method of monitoring the condition of an inflatable element within a fluid vessel containing a fluid under pressure, the method comprising:

determining a physical characteristic of the inflatable element by sensing a measure of the fluid within the fluid vessel.

49. A method according to Claim 48, comprising monitoring a change in a sensed measure of the fluid within the fluid vessel over a period of time.

50. A method according to Claim 49, comprising calculating a gradient of said change in said sensed measure of fluid over time.

51. A method according to any of Claims 48 to 50, comprising modelling at least one simulated change in a measure of fluid within the fluid vessel over a period of time to calculate a gradient of said change in said measure of fluid over time.

52. A method according to Claim 51, further comprising modelling the at least one simulated change in said measure of fluid change based on an initial estimated value of the physical characteristic of the inflatable element.

53. A method according to any of Claims 51 to 53, comprising comparing the at least one simulated gradient with the sensed gradient.

54. A method according to Claim 53, comprising comparing the at least one simulated gradient with the sensed gradient to determine a degree of similarity between the gradients.

55. A method according to Claim 54, wherein the degree of similarity is determined using a metric of fit.

56. A method according to Claim 55, comprising determining whether the degree of similarity falls within an acceptable tolerance.

57. A method according to Claim 56, comprising, in response to determining that the degree of similarity falls outside of an acceptable tolerance, modelling one or more additional simulated changes in said measure of fluid using different estimated values for the physical characteristic of the inflatable element for each simulated change, and comparing the one or more simulated gradients with the sensed gradient until a degree of similarity falling within the acceptable tolerance is determined.

58. A method according to Claim 56 or 57, comprising logging the estimated value of the physical characteristic that achieved a degree of similarity falling within the acceptable tolerance.

59. A method according to any of Claims 49 to 58, wherein the period of time over which the change in said sensed measure of fluid is monitored is the period of time for a filling event to occur.

60. A method according to any of Claims 48 to 59, further comprising computing a loss rate of the physical characteristic of the inflatable element over a period of time, preferably measured in weeks or months, based on the estimated value of the physical characteristic determined.

61. A method according to Claim 60, comprising using the computed loss rate to determine the future date for a likely maintenance event for the inflatable element.

62. A method according to any of Claims 48 to 61, wherein the physical characteristic of the inflatable element is its volume, preferably its inflated volume.

63. A method according to any of Claims 48 to 62, wherein the sensed measure of fluid is pressure.

64. A method according to any of Claims 48 to 63, wherein the sensed measure of fluid is temperature.

65. A method according to any of Claims 48 to 50, further comprising detecting when the gradient is a negative gradient.

66. A method according to Claim 65, wherein the period of time over which the change in said sensed measure of fluid is monitored is the period of time for a draw event to occur.

67. A method according to Claim 65 or 66, comprising calculating a flow rate of the fluid during the draw event based on one or more physical characteristics of the inflatable element and the sensed measure of the fluid.

68. A method according to Claim 66, wherein the sensed measure of the fluid is pressure.

69. An apparatus substantially as described herein and illustrated in the accompanying drawings.

70. An adaptor substantially as described herein and illustrated in the accompanying drawings.

71. An inflatable element substantially as described herein and illustrated in the accompanying drawings.

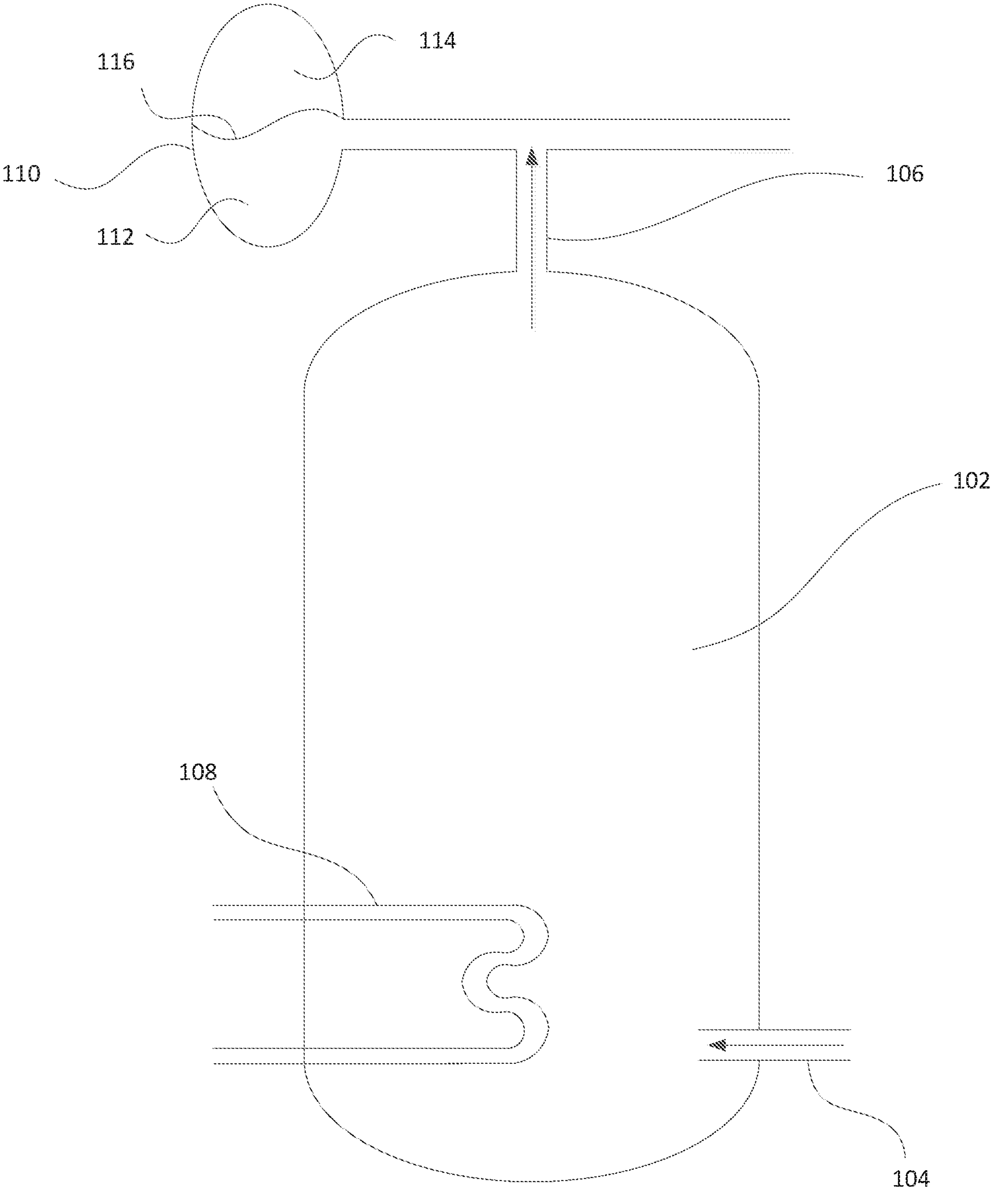

Figure 1A

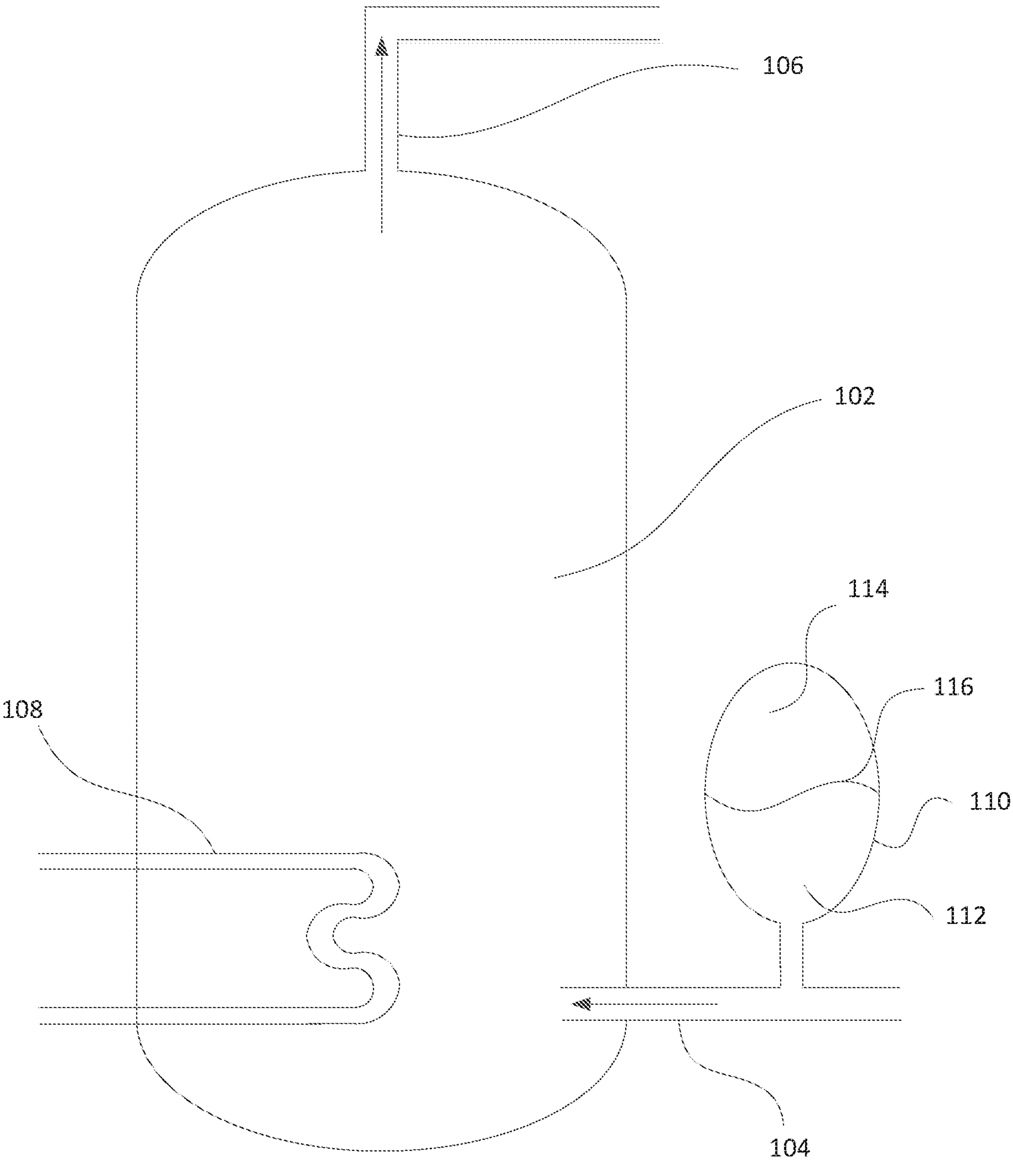

Figure 1B

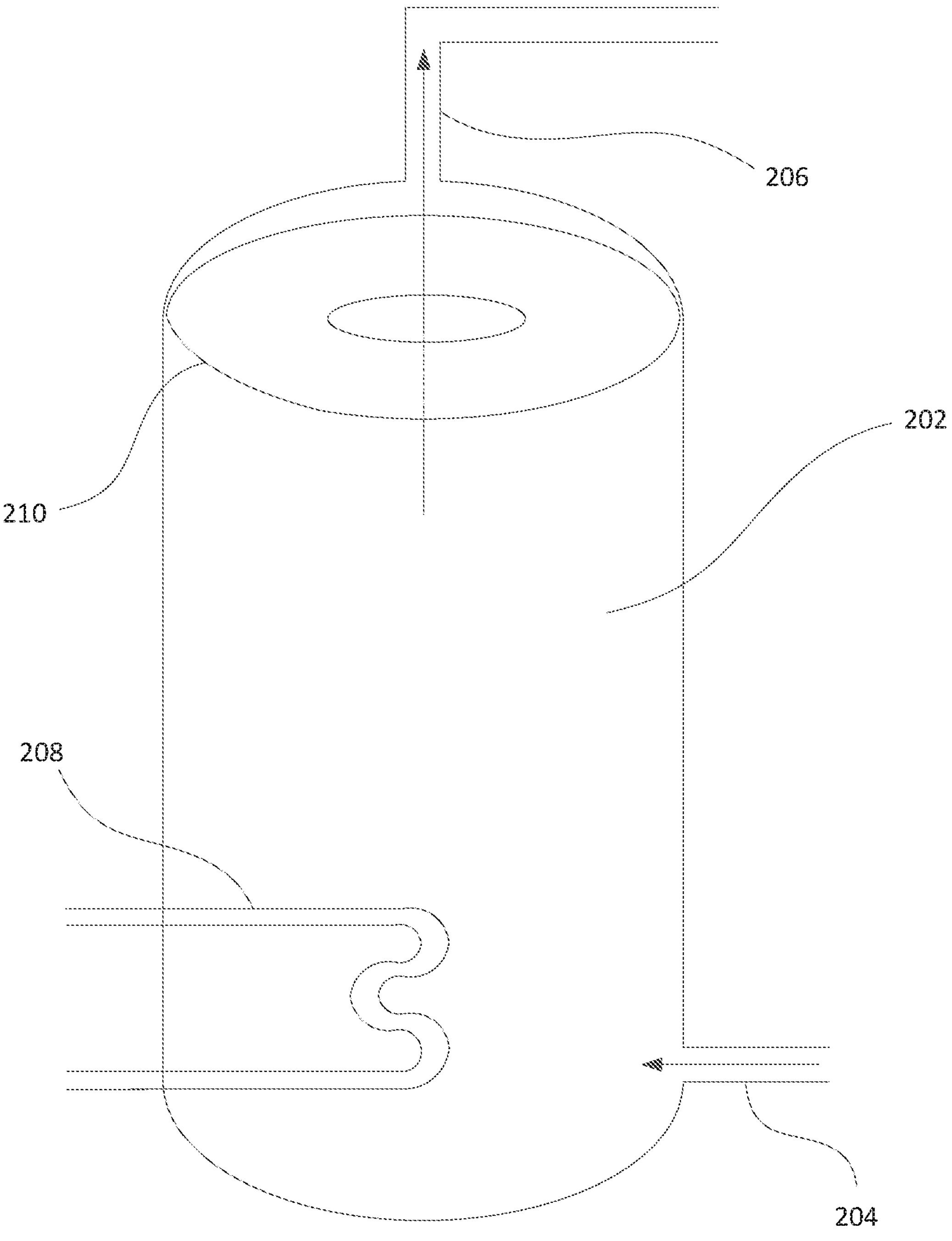

Figure 2

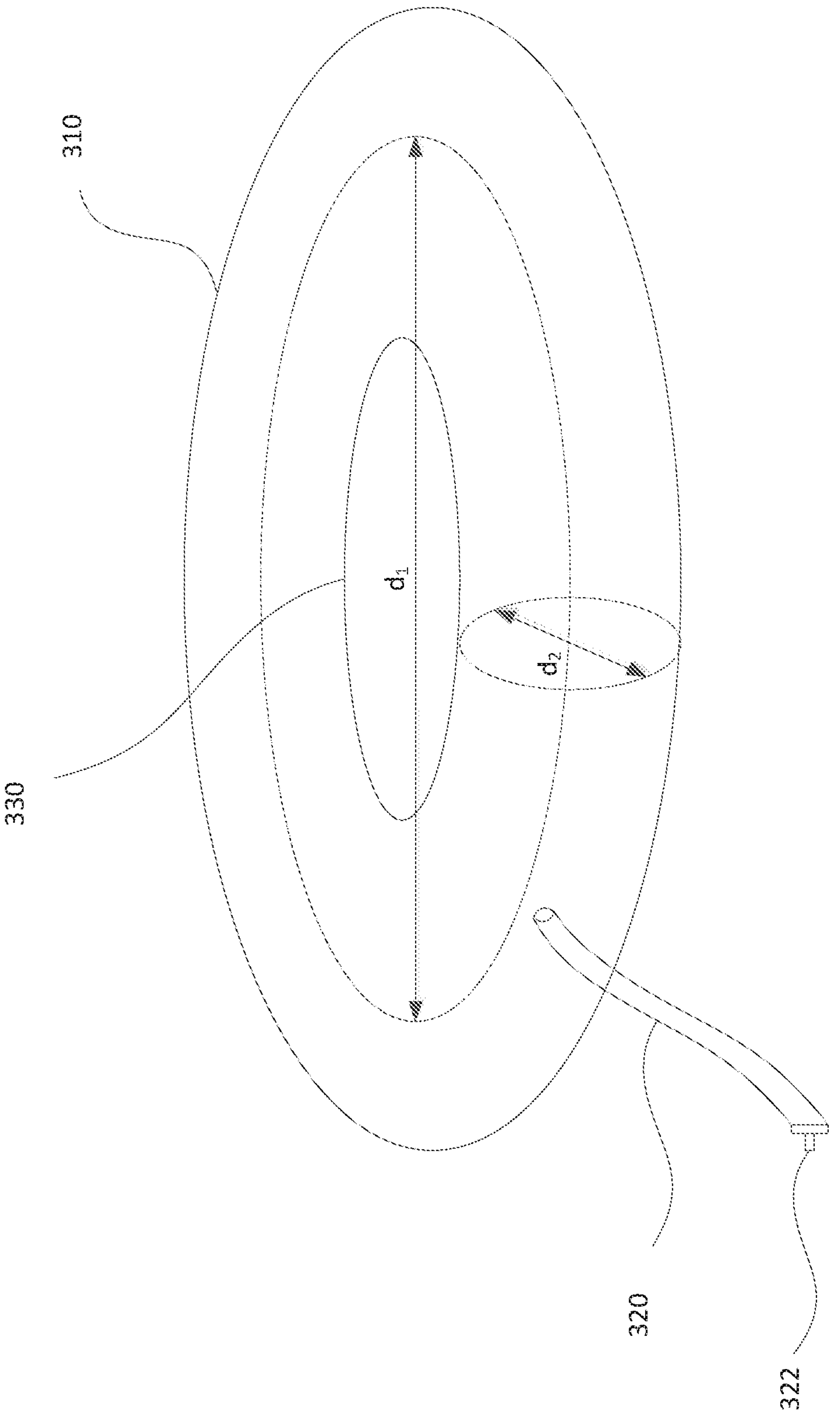

Figure 3

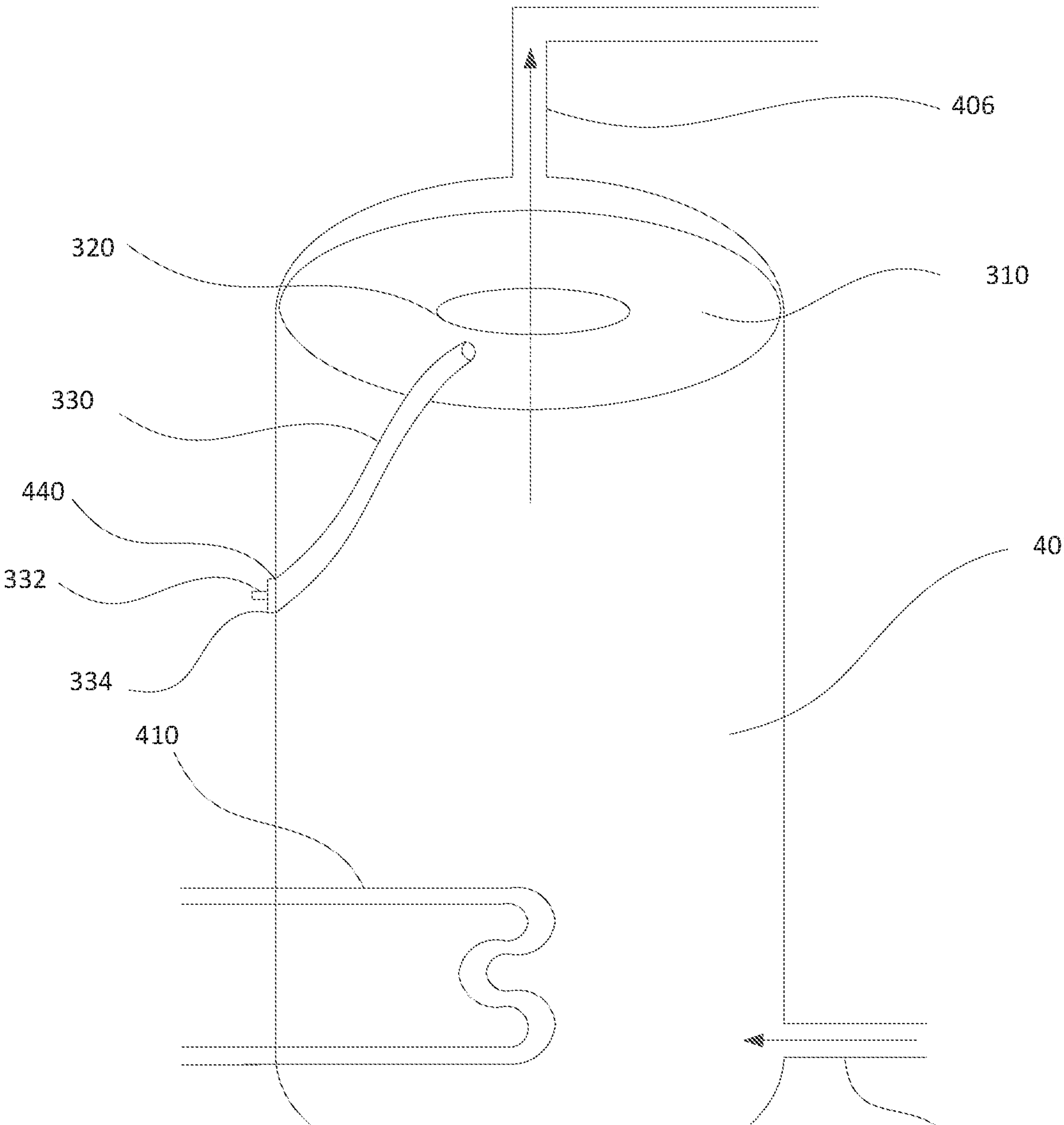

Figure 4

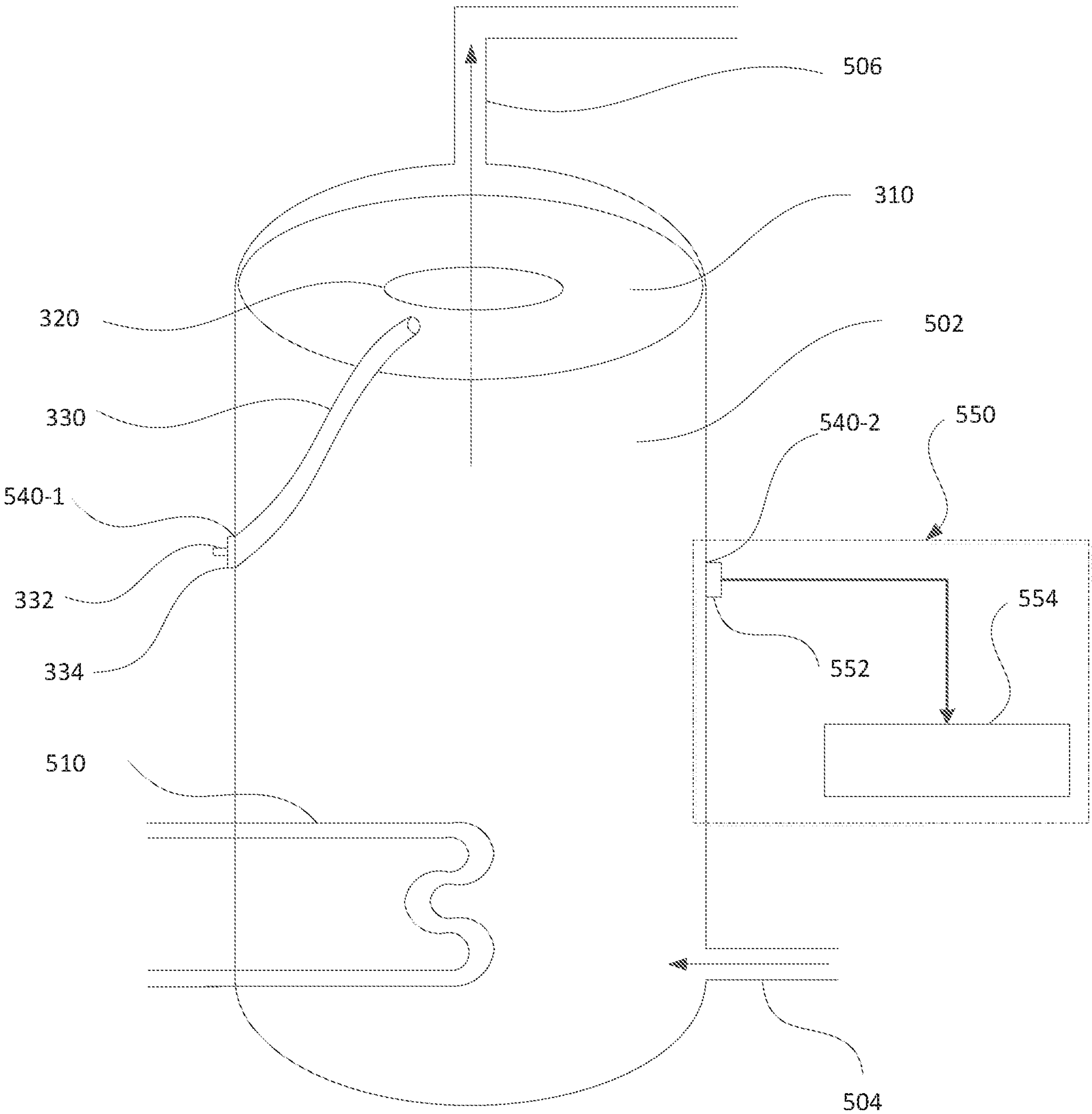

Figure 5

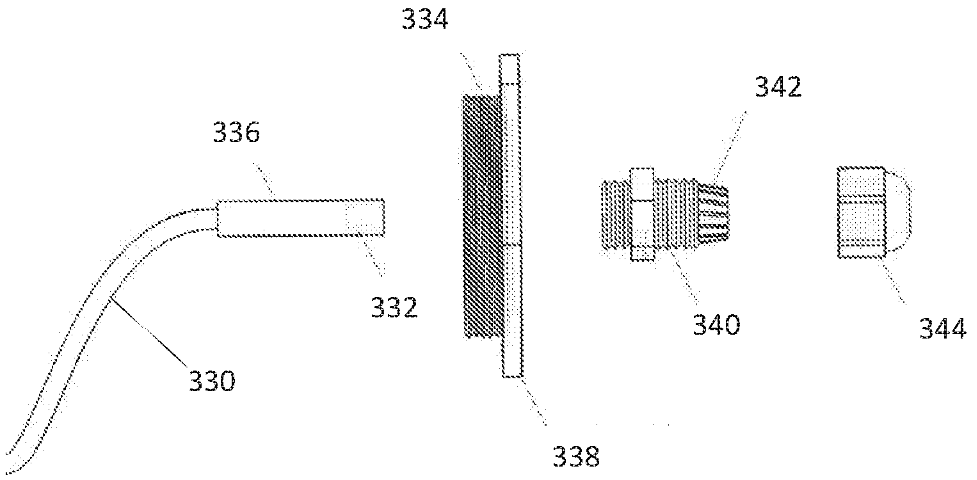

Figure 6A

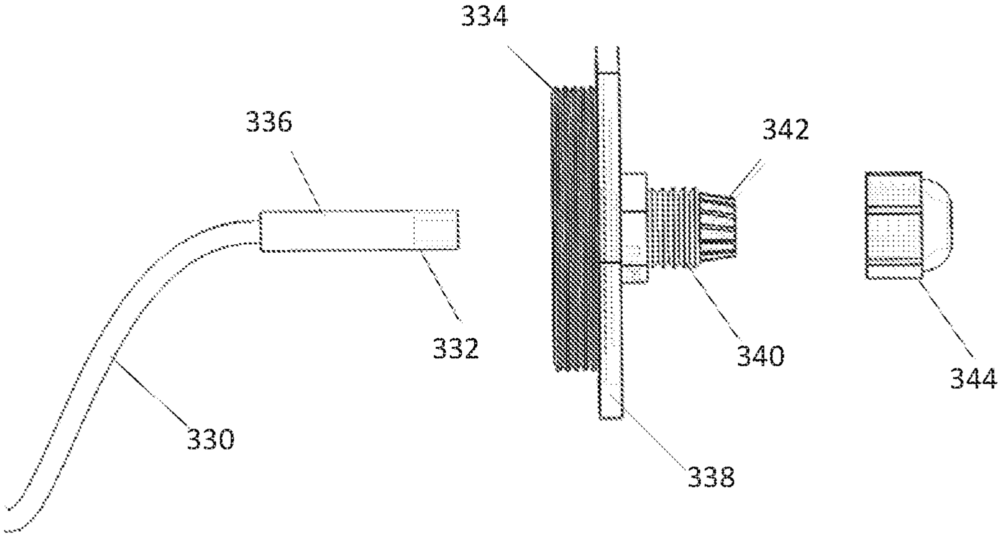

Figure 6B

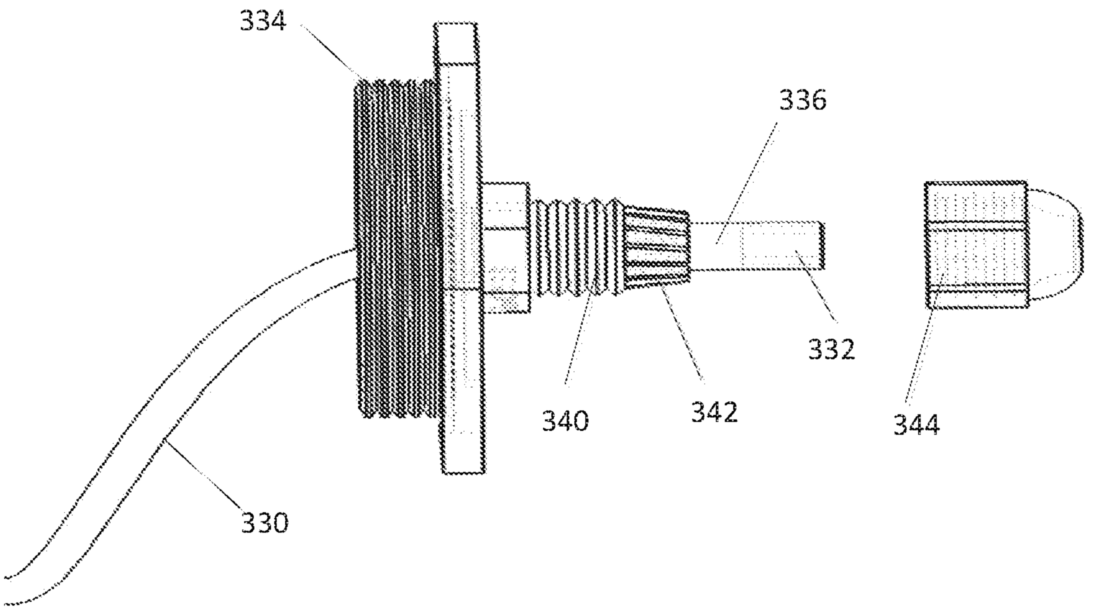

Figure 6C

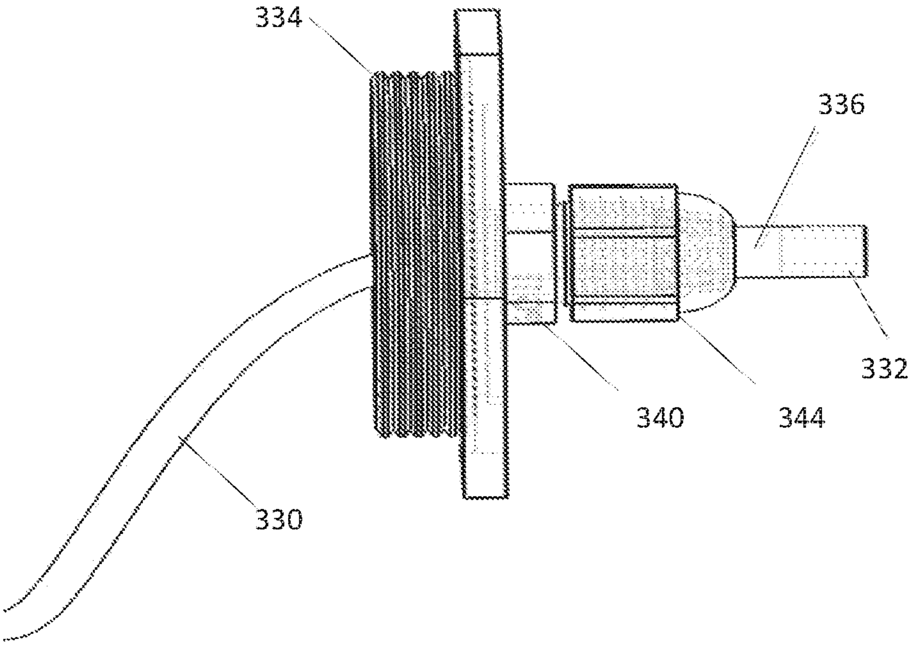

Figure 6D

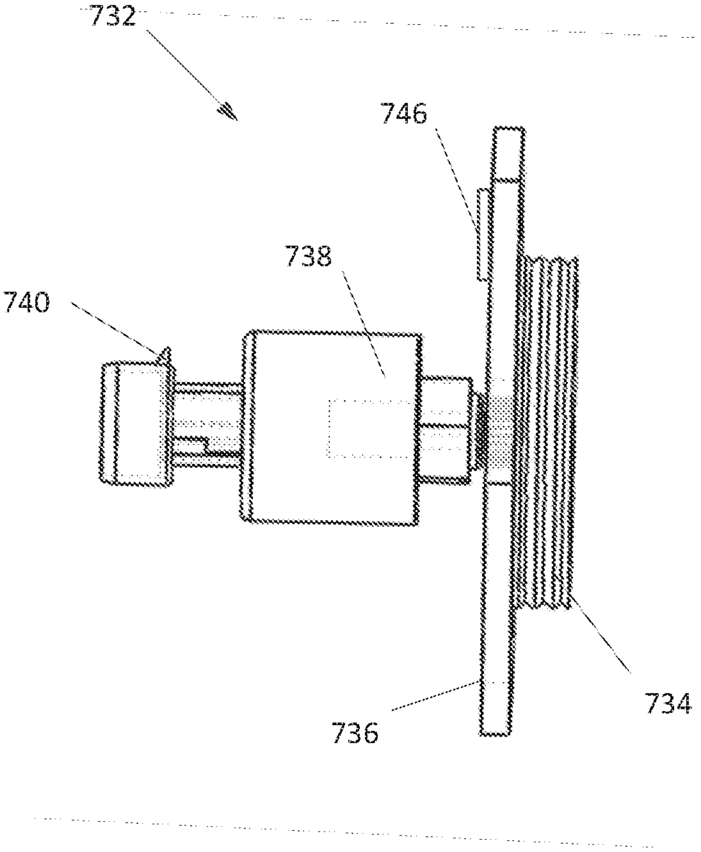

Figure 7A

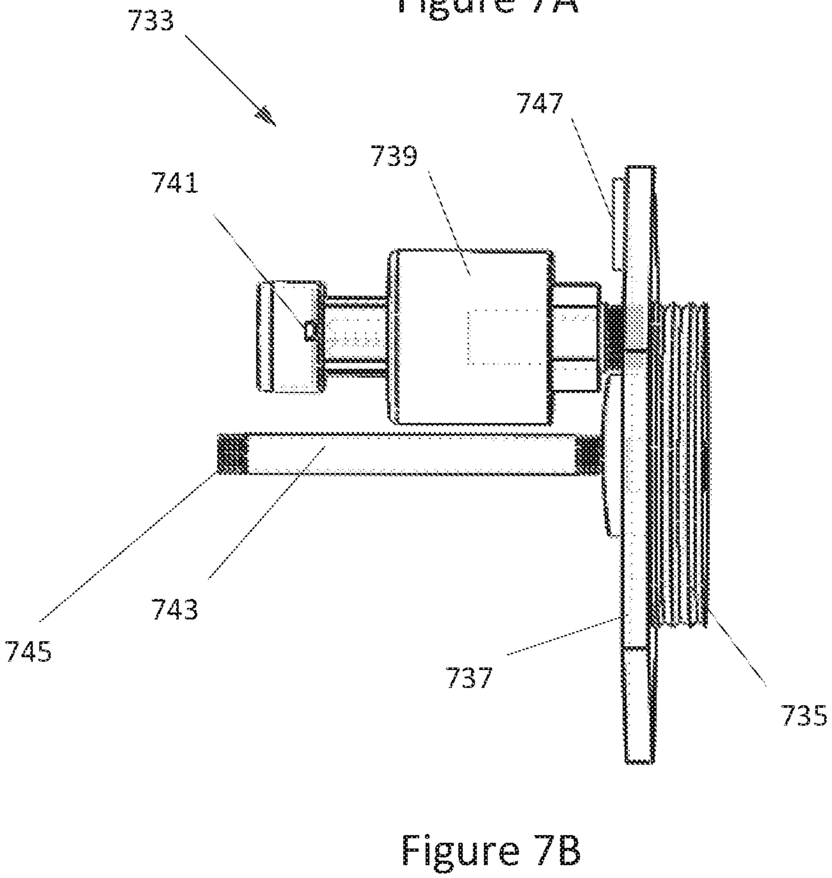

Figure 7B

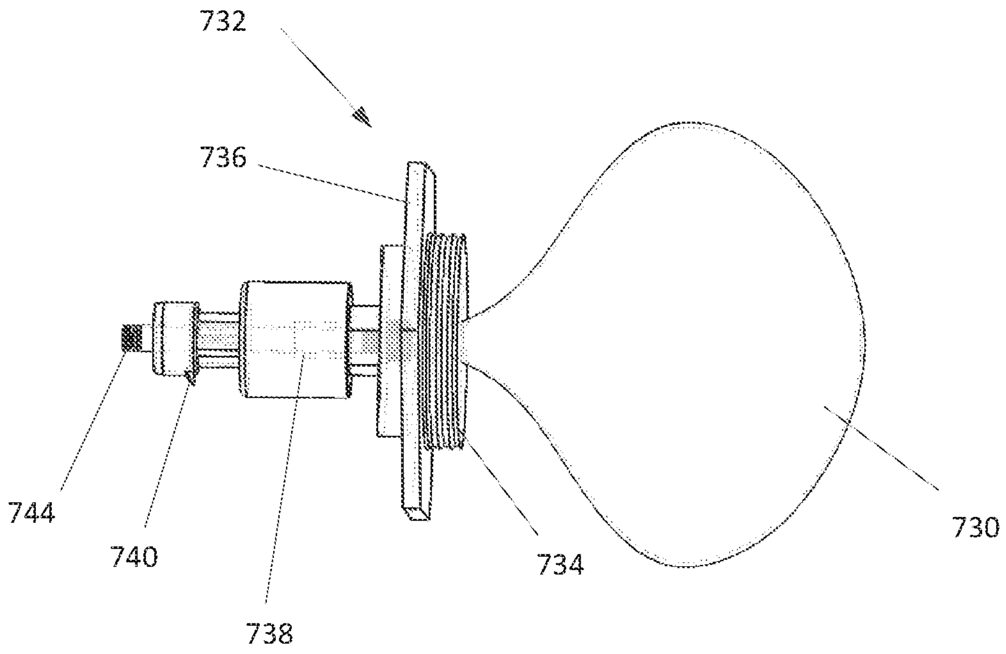

Figure 8A

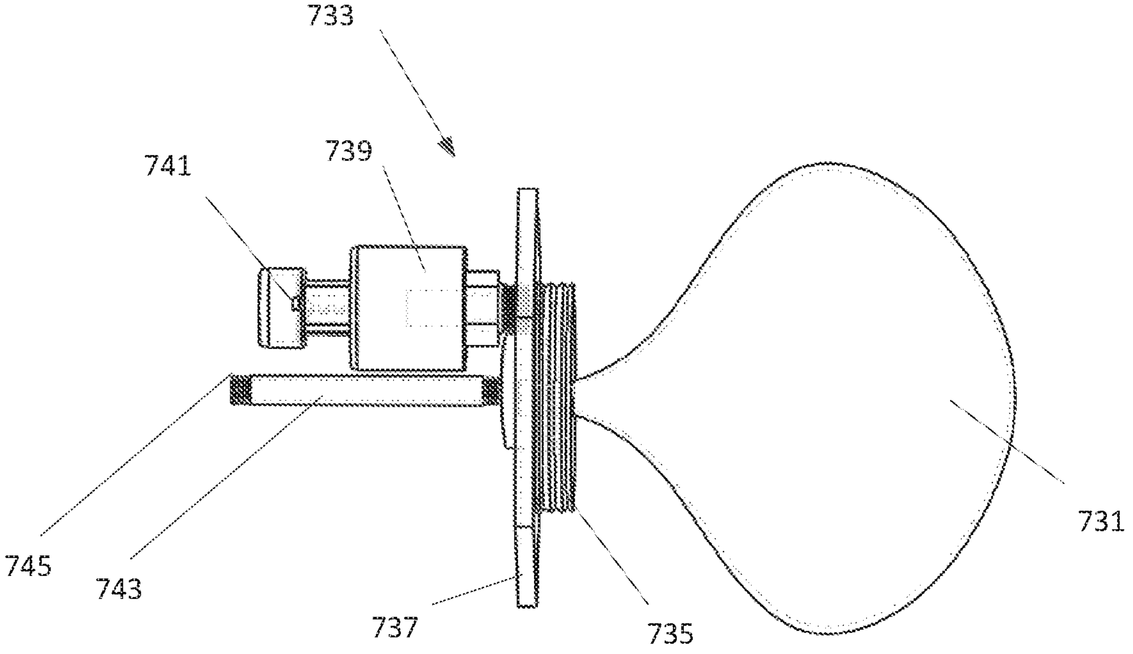

Figure 8B

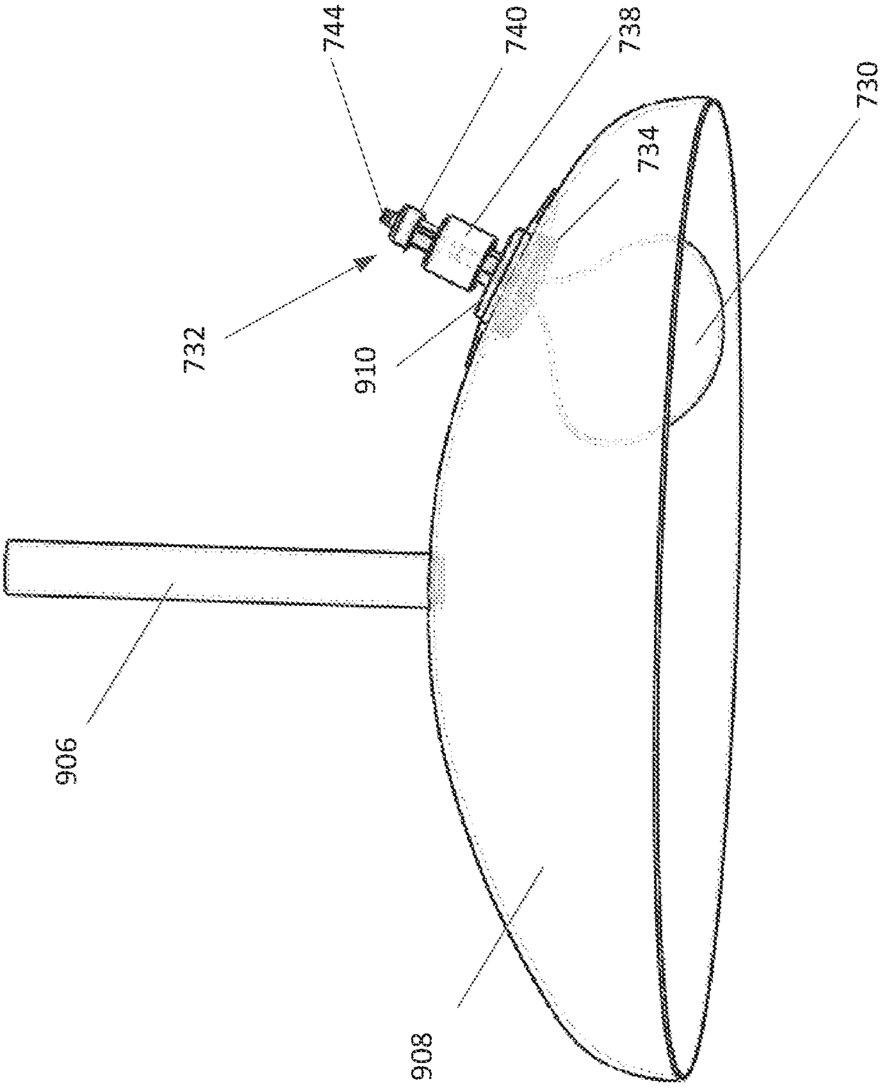

Figure 9

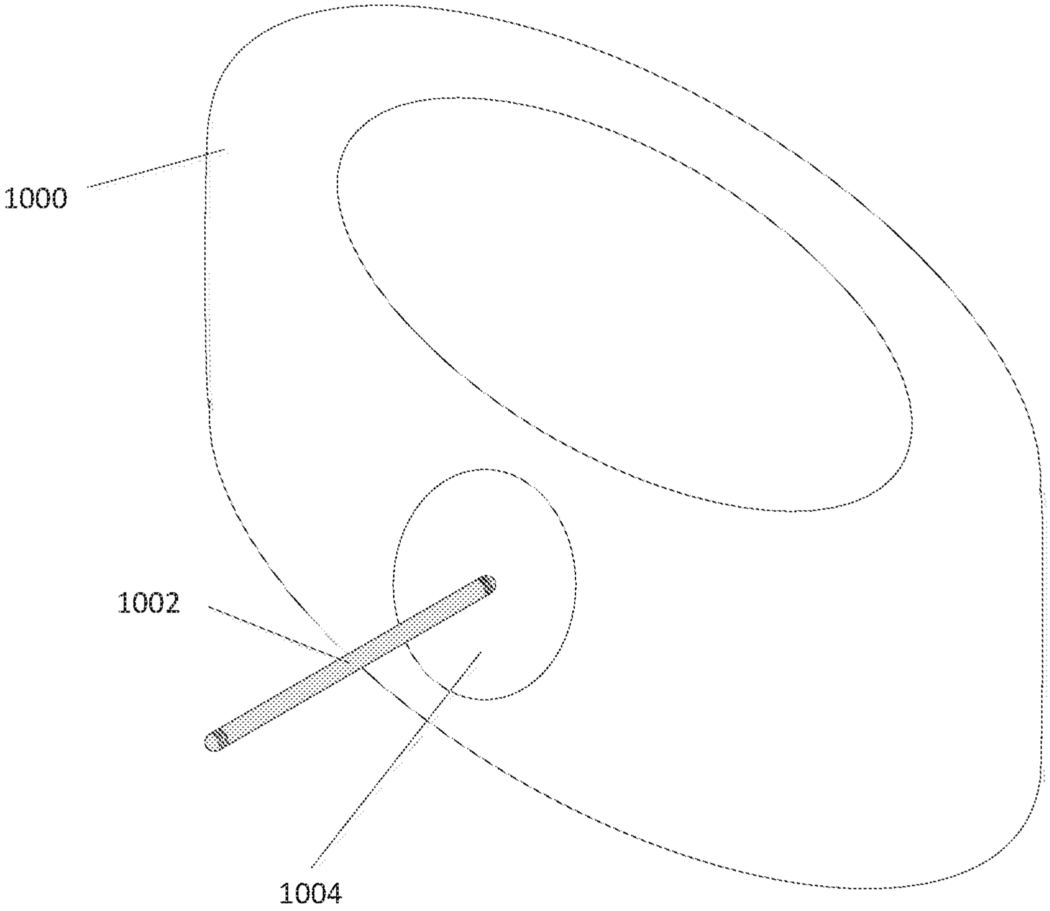

Figure 10A

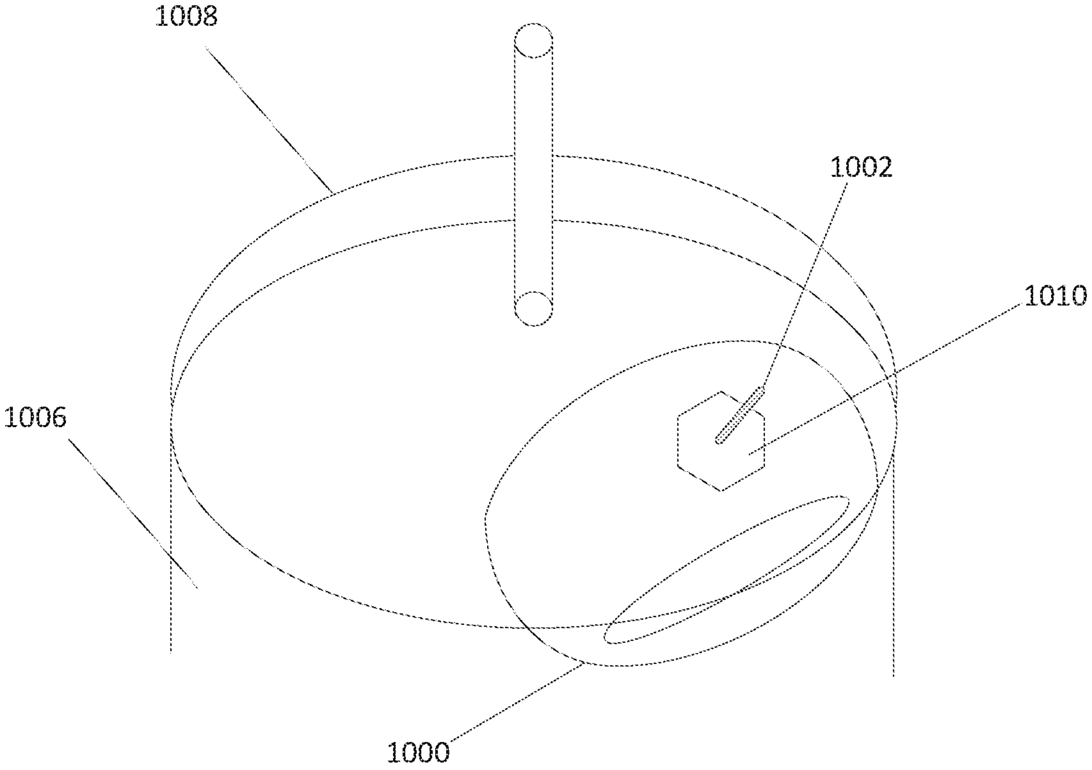

Figure 10B

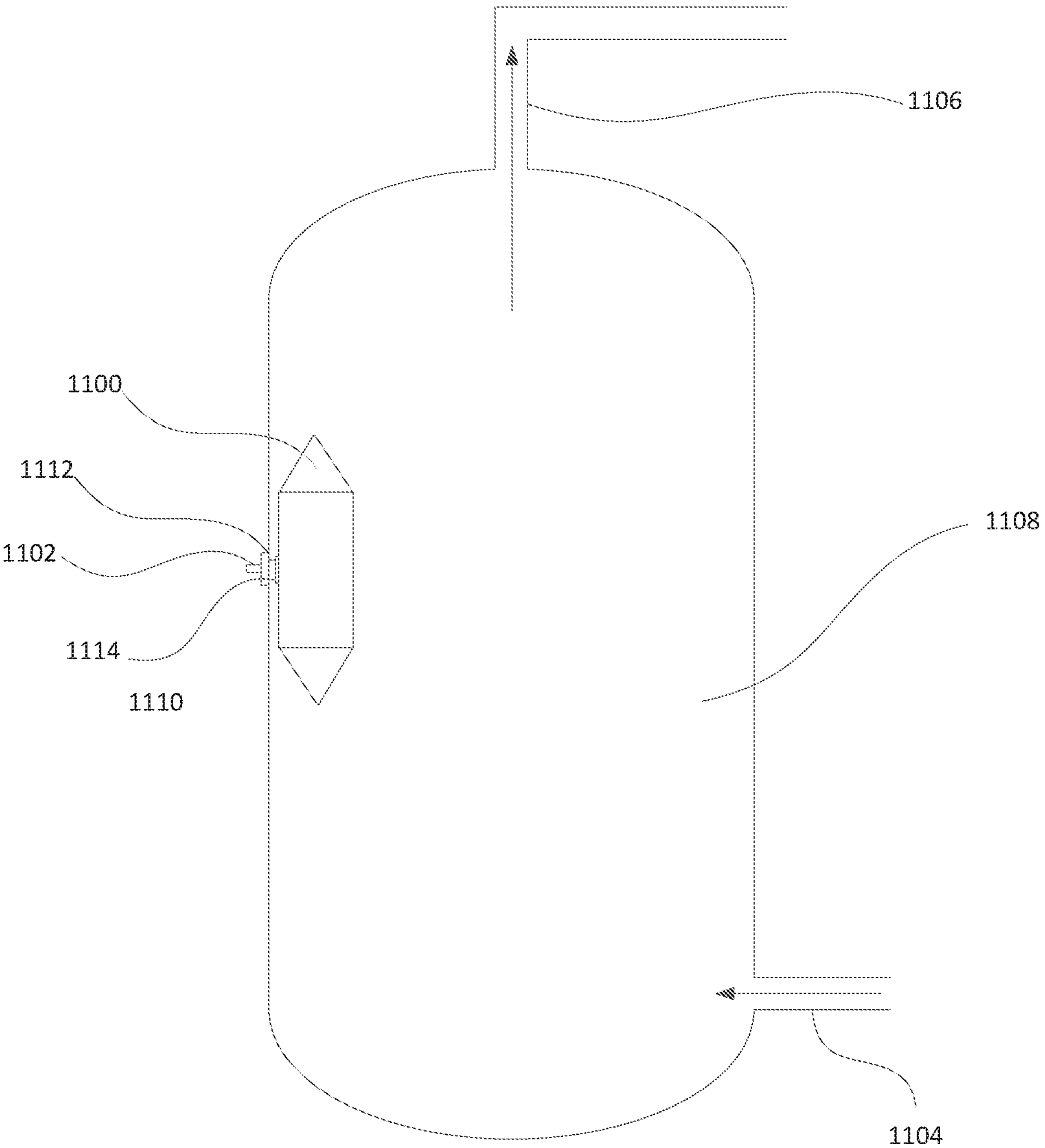

Figure 11

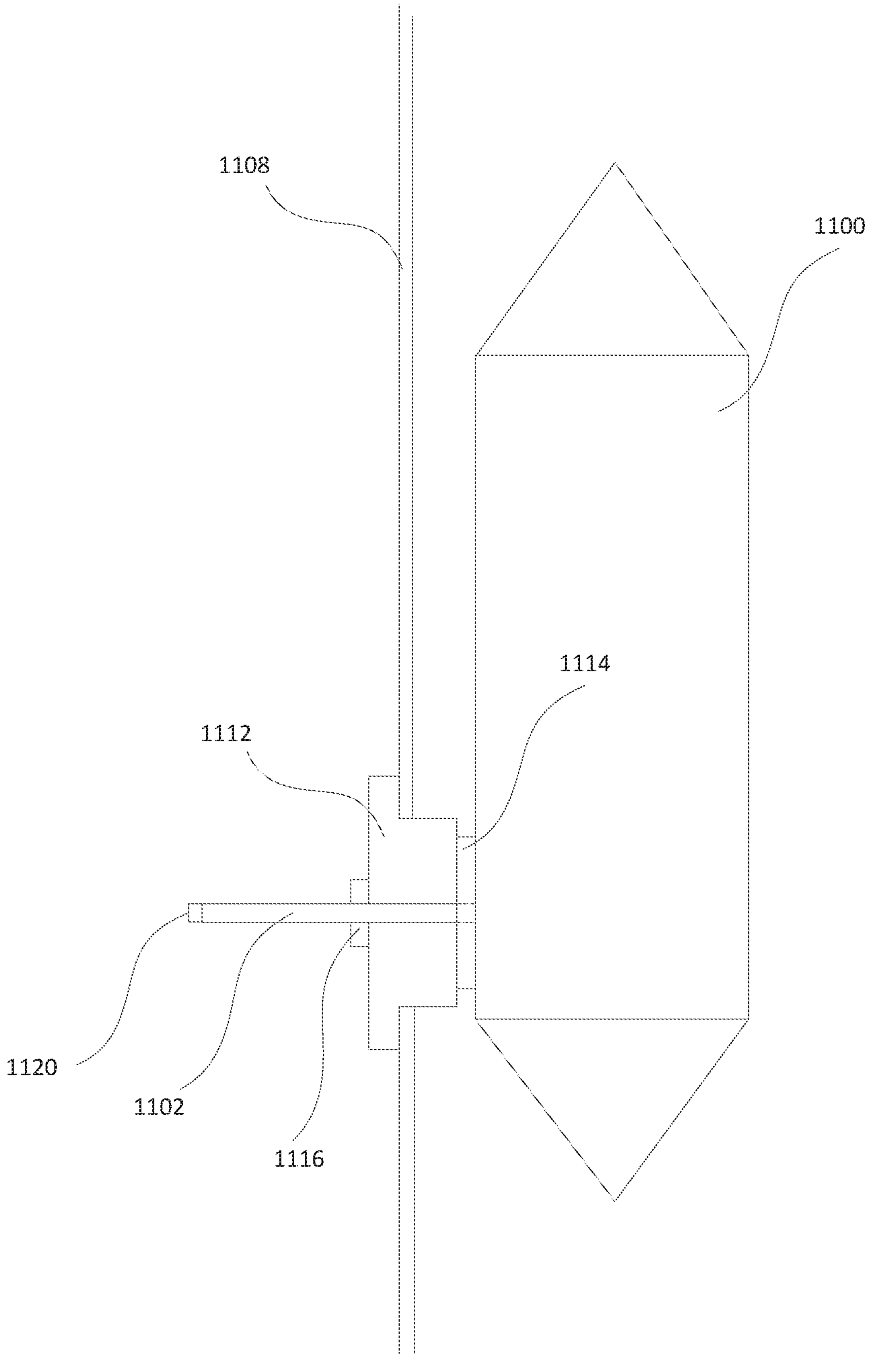

Figure 12

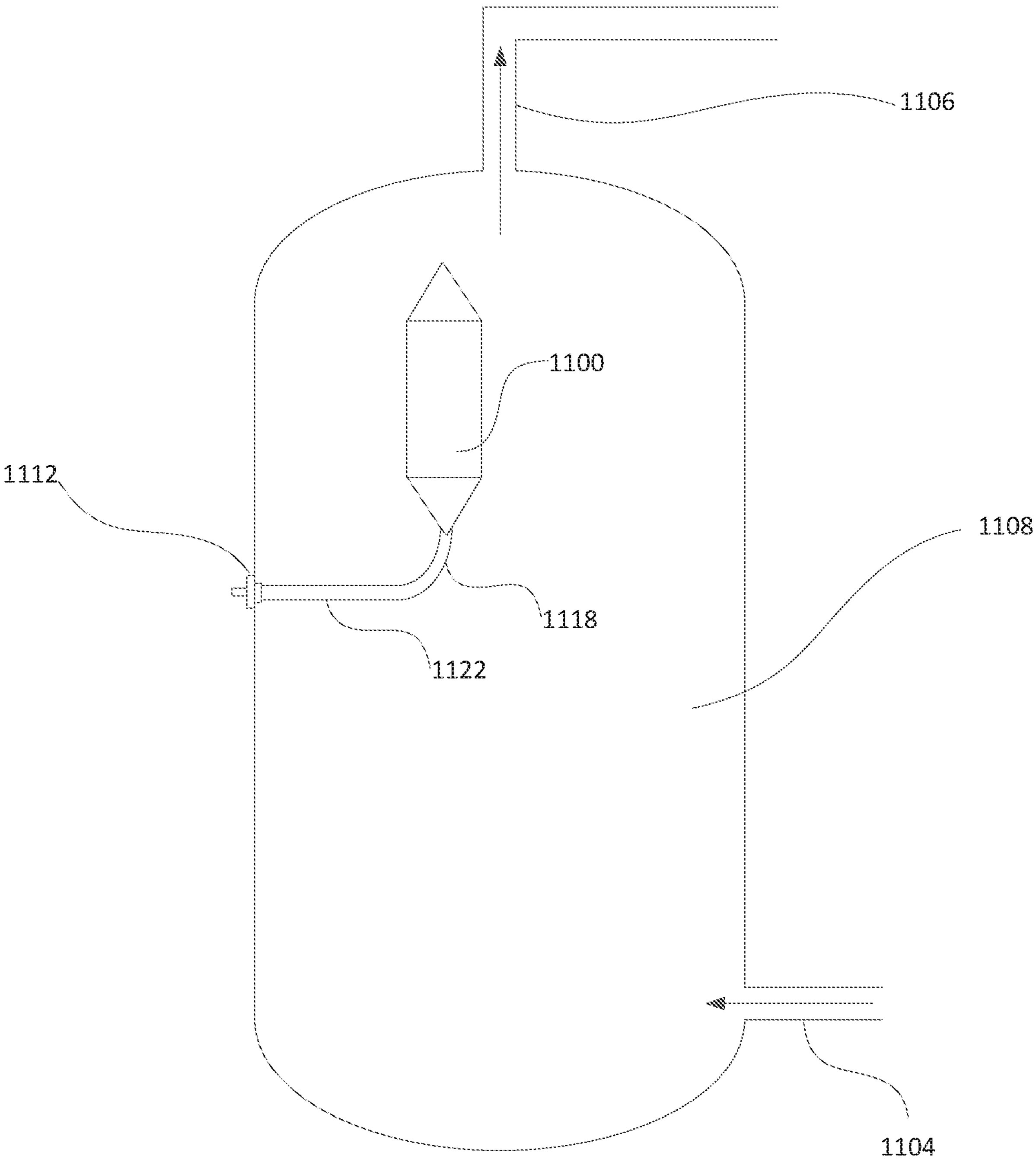

Figure 13

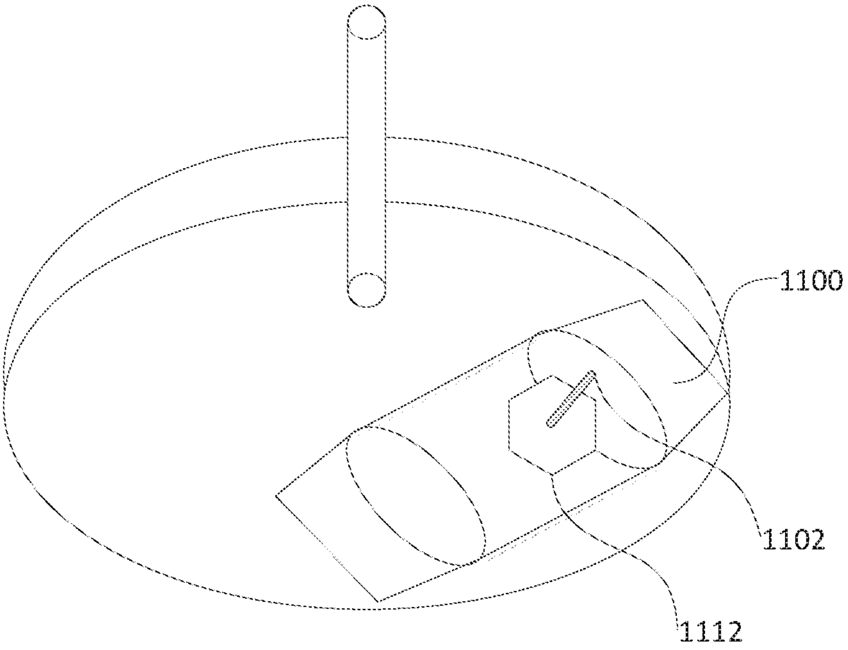

Figure 14

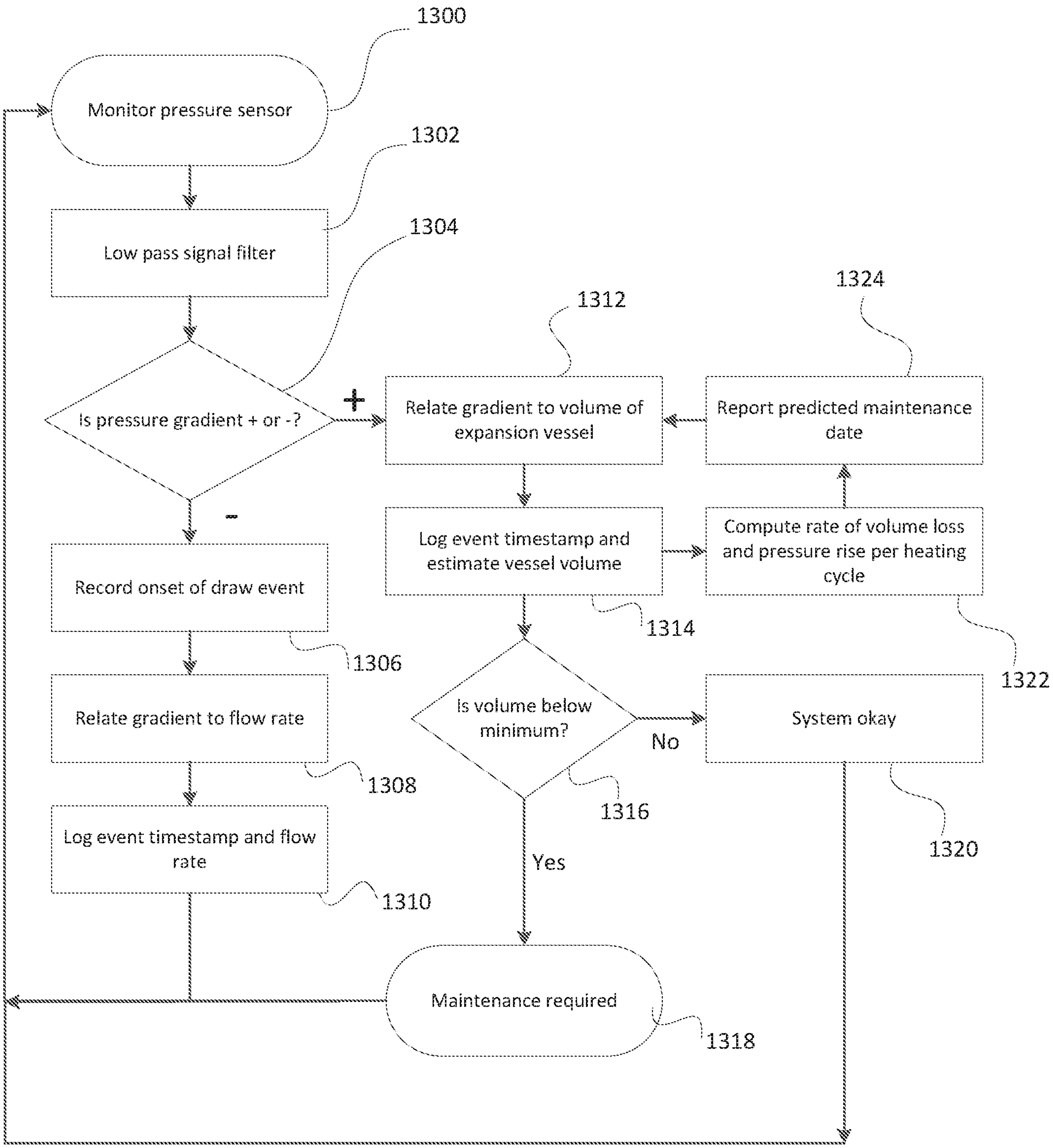
1300
Monitor pressure sensor
1302
Low pass signal filter
1304
Is pressure gradient + or -?
+
-
Record onset of draw event
1306
Relate gradient to flow rate
1308
Log event timestamp and flow rate
1310
1312
Relate gradient to volume of expansion vessel
1324
Report predicted maintenance date
Log event timestamp and estimate vessel volume
1314
Compute rate of volume loss and pressure rise per heating cycle
1322
Is volume below minimum?
1316
No
System okay
1320
Yes
Maintenance required
1318

Figure 15

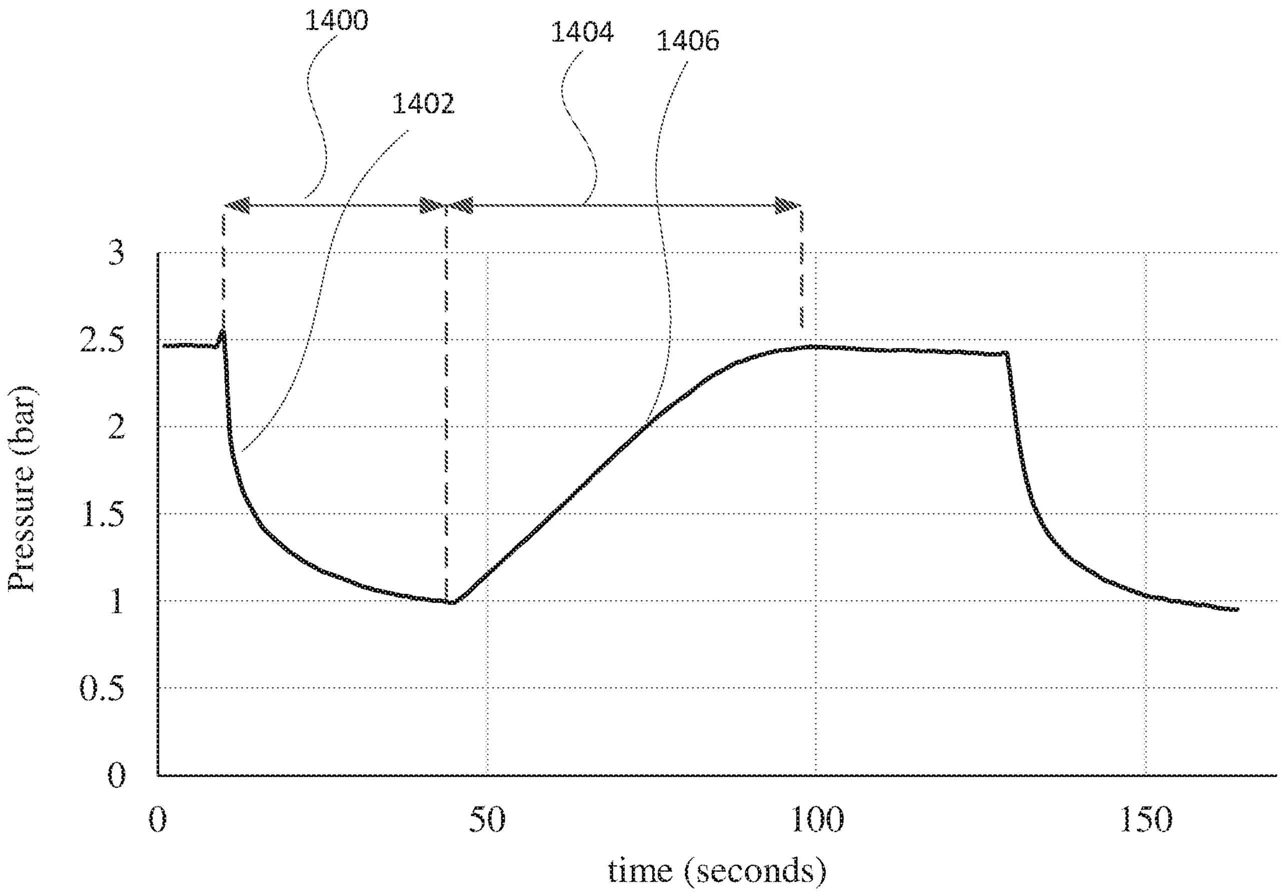
1400
1402
1404
1406
3
2.5
2
1.5
1
0.5
0
Pressure (bar)
0
50
100
150
time (seconds)

Figure 16

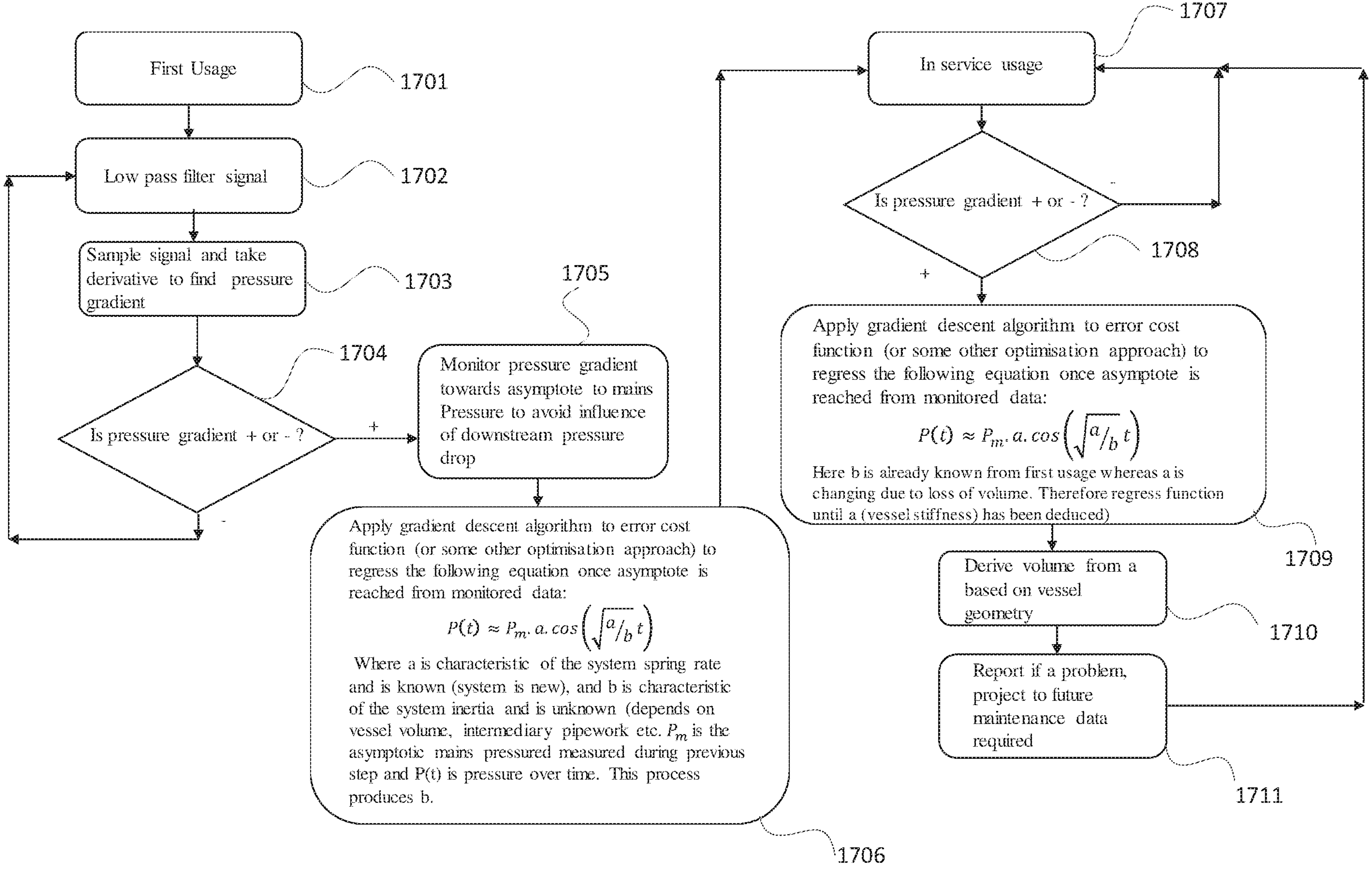
First Usage
1701
Low pass filter signal
1702
Sample signal and take derivative to find pressure gradient
1703
1704
Is pressure gradient + or - ?
+
-
1705
Monitor pressure gradient towards asymptote to mains Pressure to avoid influence of downstream pressure drop
Apply gradient descent algorithm to error cost function (or some other optimisation approach) to regress the following equation once asymptote is reached from monitored data:
$P(t) \approx P_m. a. cos\left(\sqrt{a/_b}\, t\right)$
Where a is characteristic of the system spring rate and is known (system is new), and b is characteristic of the system inertia and is unknown (depends on vessel volume, intermediary pipework etc. P_m is the asymptotic mains pressured measured during previous step and P(t) is pressure over time. This process produces b.
1706
In service usage
1707
Is pressure gradient + or - ?
-
+
1708
Apply gradient descent algorithm to error cost function (or some other optimisation approach) to regress the following equation once asymptote is reached from monitored data:
$P(t) \approx P_m. a. cos\left(\sqrt{a/_b}\, t\right)$
Here b is already known from first usage whereas a is changing due to loss of volume. Therefore regress function until a (vessel stiffness) has been deduced)
1709
Derive volume from a based on vessel geometry
1710
Report if a problem, project to future maintenance data required
1711

Figure 17

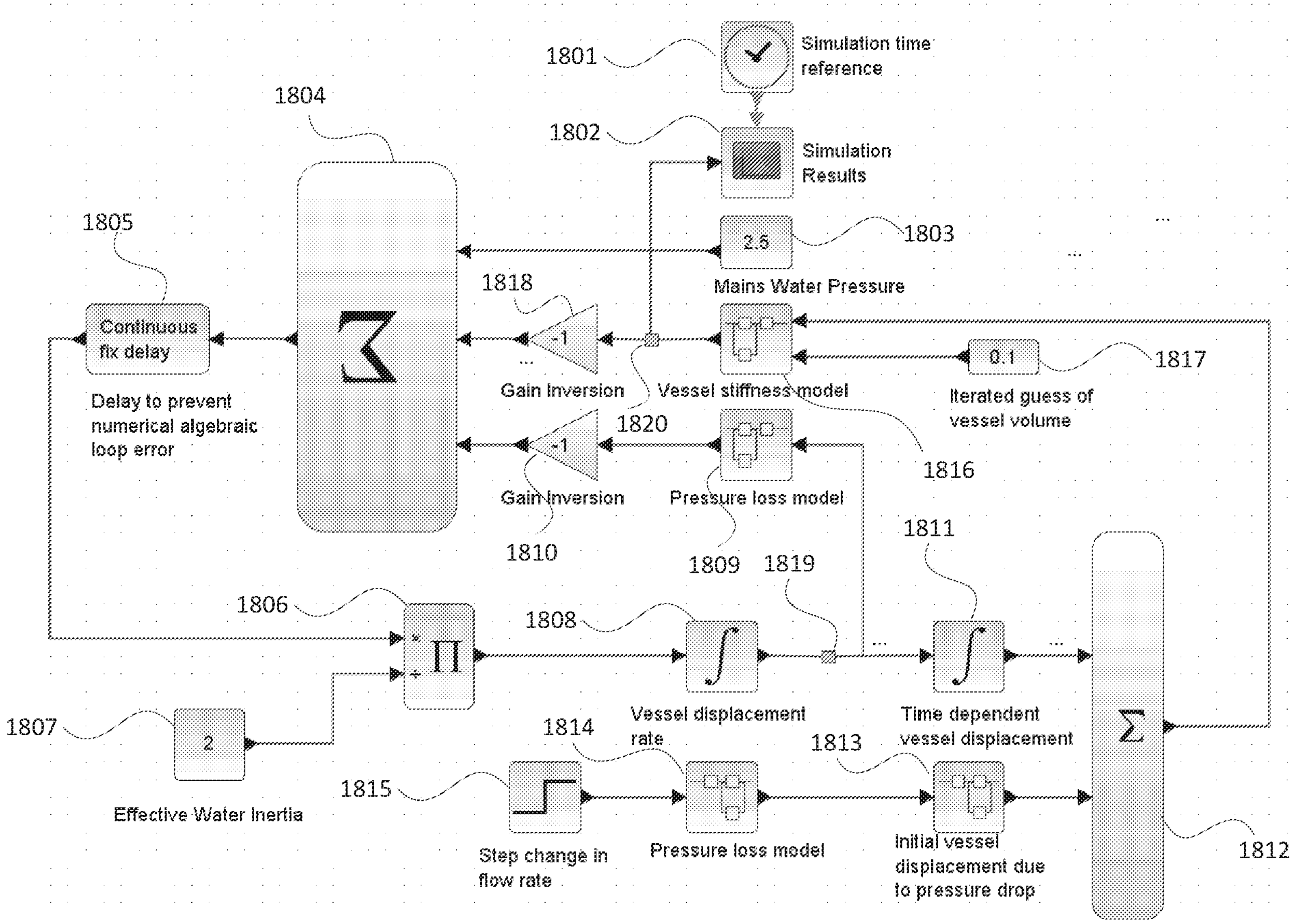
1801
Simulation time reference
1802
Simulation Results
1803
2.5
Mains Water Pressure
1804
Σ
1805
Continuous fix delay
Delay to prevent numerical algebraic loop error
1818
-1
Gain Inversion
1816
Vessel stiffness model
1817
0.1
Iterated guess of vessel volume
1820
-1
Gain Inversion
1810
Pressure loss model
1809
1806
Π
1807
2
Effective Water Inertia
1808
Vessel displacement rate
1819
1811
Time dependent vessel displacement
1812
Σ
1814
1815
Step change in flow rate
Pressure loss model
1813
Initial vessel displacement due to pressure drop
...

Figure 18

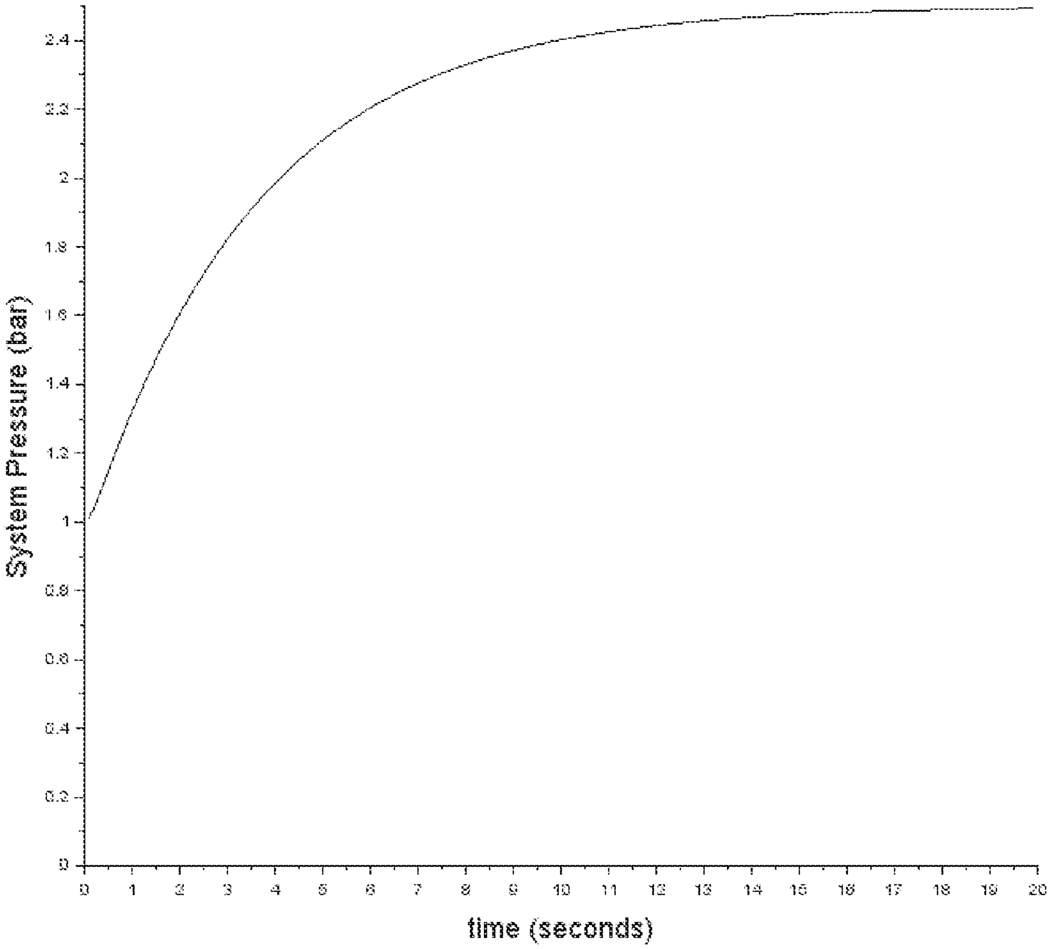
System Pressure (bar)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
time (seconds)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Figure 19