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(54) **CONTROL UNIT FOR AN ENERGY STORAGE SYSTEM**

(57) A controller (401) for controlling pressure in at least one multi-segment compressed pressure vessel (100) of an energy handling system is described. The multi-segment compressed pressure vessel (100) thereby comprises at least an inner segment (201) and an outer segment (101) substantially fully encompassing the inner segment (201). The controller (401) comprises a data input (402) for receiving data related to the pressure (302, P1) in the inner segment (201) and data related to the pressure (301, P2) in the outer segment (101), and a processor (404) being programmed for deriving control signals for controlling the pressure in the multi-segment compressed pressure vessel (100) in imbalance taking into account the data related to the pressure (302, P1) in the inner segment (201) and of the data related to the pressure (301, P2) in the outer segment (101)..

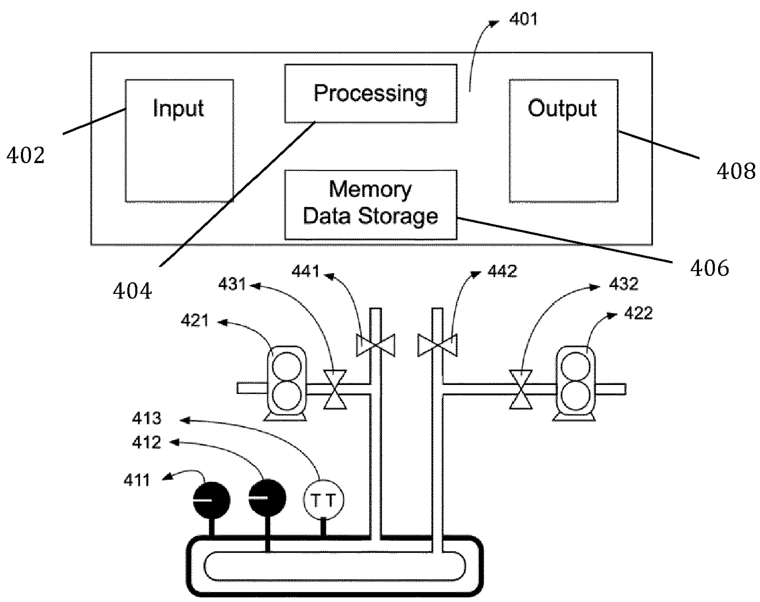

FIG. 3

Processed by Luminess, 75001 PARIS (FR)

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Description

Technical field of the invention

[0001] The present invention relates to the field of energy storage and/or energy handling. More particularly, the present invention relates to energy storage and/or handling systems comprising segmented pressure vessels, as well as to controllers and methods for controlling energy storage and/or handling.

Background of the invention

[0002] Energy storage systems using dual segment pressure vessels as structural elements such as the one described in US patent US11181235B2 attempt to solve the difficulties in storing large amounts of energy in a cost-effective manner. Compressed gas, more specifically hydrogen gas, is widely viewed as one of the most viable options for storing renewable energy.

[0003] A pressure vessel with multiple segments, as described in US11181235B2, is a valid solution to the issues gaseous or liquid hydrogen poses in more traditional single segment pressure vessels. These issues mainly comprise the behaviour of hydrogen in relation to materials used for high pressure vessels (usually made from carbon steel), in function of the long service life (for example minimum 20 years).

[0004] However, the balancing of the two gases (hydrogen gas and a secondary gas, such as nitrogen or carbon dioxide), is a topic that must be carefully considered for the technology described in US11181235B2. It mentions the two gases should be 'balanced' with regards to their respective pressures. However, due to the nature of renewable energy sources, and its irregular supply of energy and thus hydrogen gas from the electrolyser(s), it is paramount adequate safety margins are in place for controlling the pressures in each section of the vessel. Figure 1 shows a cross-section of such 2 segmented cylindrical pressure vessel. The objective typically is to have a rather thin wall for the inner segment.

[0005] Balancing the pressures (i.e. setting them exactly equal) introduces a number of problems with regard to the operational safety of the vessel. Consequently, controlling the pressure in the multi-segment vessels of an energy storing and/or handling system still require improvement. There is thus still a need in the art for devices and methods for addressing control of pressure in multi-segment pressure vessels in an energy storing and/or handling system.

Summary of the invention

[0006] It is an object of the present invention to provide good methods and systems for controlling pressure in multi-segment pressure vessels in an energy storing and/or handling system.

[0007] It is an advantage of embodiments of the present invention that automated control of pressure in multi-segment pressure vessels can be obtained, whereby the pressures are within predetermined safety values but whereby at the same time good or optimum efficiency is obtained in storing and/or handling energy.

[0008] The above objective is accomplished by a method and apparatus according to the present invention.

[0009] In one aspect, the present invention relates to a controller for controlling pressure in at least one multi-segment compressed pressure vessel of an energy handling system, the multi-segment compressed pressure vessel thereby comprises at least an inner segment and an outer segment substantially fully encompassing the inner segment, the controller comprising a data input for receiving data related to the pressure in the inner segment and data related to the pressure in the outer segment, and a processor being programmed for deriving control signals for controlling the pressure in the multi-segment compressed pressure vessel in imbalance taking into account the data related to the pressure in the inner segment and of the data related to the pressure in the outer segment.

[0010] It is an advantage of embodiments of the present invention that the separation wall between the inner segment and the outer segment can be relatively thin, thus allowing compressed pressure vessels to have a relatively low weight, less material usage, easier assembly (e.g. welding) and lower cost. It is an advantage of embodiments of the present invention that efficient but still safe energy handling can be obtained, even with multi-segment compressed pressure vessels having a relatively low weight due to a relatively thin thickness of the separation wall between the inner segment and the outer segment.

[0011] In some embodiments, controlling of the pressure in the multi-segment compressed pressure vessel may be controlling the pressure in the inner segment to be significantly higher than the pressure in the outer segment.

[0012] Controlling the pressure in the multi-segment compressed pressure vessel may comprise controlling the pressure in the multi-segment compressed pressure vessel as function of a differential pressure between the inner segment and the outer segment of the multi-segment compressed pressure vessel.

[0013] The controller may be configured for controlling the pressure in the inner segment to be substantially higher than the pressure in the outer segment. It is an advantage of embodiments of the present invention that a higher operational margin for the complete multi-segment vessel, as well as each segment itselves, is obtained for controlling the pressure in the multi-segment compressed pressure vessel.

[0014] The data input may be configured for receiving a pressure in the inner segment and/or a gas pressure in the outer segment. It is an advantage of embodiments of the present invention that an increased range of operation can be obtained in which safety is guaranteed.

[0015] The multi-segment compressed pressure vessel may be adapted for storing or handling hydrogen gas in the inner segment.

[0016] The controller may be configured for controlling the pressure in one, more or all of the segments of the at least one multi-segment compressed pressure vessel.

[0017] The controller may be configured for controlling the pressure in one, more or all of the multi-segment compressed pressure vessels of the energy handling system.

[0018] The controller may be configured for controlling the pressure in the at least one multi-segment compressed pressure vessel, taking into account at least one of a thickness, material and diameter of a separation wall between the inner segment and the outer segment of the at least one multi-segment compressed pressure vessel.

[0019] The controller may be configured for controlling the pressure in the at least one multi-segment compressed pressure vessel, taking into account a temperature of the at least one multi-segment compressed pressure vessel.

[0020] The controller may furthermore comprise a data output for outputting control signals for controlling pressure in the multi-segment compressed pressure vessel.

[0021] The controller may be configured for controlling one or more of a start-up process, a filling process, an emptying process, a process for dealing with imbalance, a process for storing of gasses, and a process for leak detection in the at least one multi-segment compressed pressure vessel.

[0022] The controller may be configured for determining a filling process based on the control signals determined by furthermore taking into account predicted or forecasted internal temperature changes.

[0023] In another aspect of the present invention, an energy handling system is disclosed, the energy handling system comprising at least one multi-segment compressed pressure vessel and comprising a controller according to the first aspect, the controller being for controlling gas pressures in the at least one multi-segment compressed pressure vessel.

[0024] A wall thickness of a wall between an inner segment and an outer segment of the multi-segment compressed pressure vessel may be smaller than 15mm, e.g. less than 12mm, e.g. less than 9mm.

[0025] It is an advantage of embodiments of the present invention that assembly of multi-segment compressed pressure vessels can be performed efficiently and accurately due to the limited thickness of the walls, e.g. inner wall, between an inner and outer segment.

[0026] In yet another aspect, the present invention relates to a method for controlling pressure in at least one multi-segment compressed pressure vessel of an energy handling system, the method comprising

obtaining data related to the pressure in the inner segment and data related to the pressure in the outer segment, and deriving control signals for controlling the pressure in the multi-segment compressed pressure vessel in imbalance taking into account the data related to the pressure in the inner segment and of the data related to the pressure in the outer segment.

[0027] Such controlling may comprise dynamically controlling the pressure in the at least one multi-segment compressed pressure vessel based on the data related to the pressure in the inner segment and the data related to the pressure in the outer segment.

[0028] Such controlling may comprise deriving control signals based on a differential pressure between the inner segment and the outer segment of the multi-segment compressed pressure vessel.

[0029] In some embodiments, controlling of the pressure in the multi-segment compressed pressure vessel may be controlling the pressure in the inner segment to be significantly higher than the pressure in the outer segment. Significantly higher may be higher with a value corresponding with the operational margin.

[0030] Said controlling may comprise controlling one or more of a start-up process, a filling process, an emptying process, a process for dealing with imbalance, a process for storing of gasses, and a process for leak detection in the at least one multi-segment compressed pressure vessel.

[0031] Particular and preferred aspects of the invention are set out in the accompanying independent and dependent claims. Features from the dependent claims may be combined with features of the independent claims and with features of other dependent claims as appropriate and not merely as explicitly set out in the claims.

[0032] Although there has been constant improvement, change and evolution of devices in this field, the present concepts are believed to represent substantial new and novel improvements, including departures from prior practices, resulting in the provision of more efficient, stable and reliable devices of this nature.

[0033] The above and other characteristics, features and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the invention. This description is given for the sake of example only, without limiting the scope of the invention. The reference figures quoted below refer to the attached drawings.

Brief description of the drawings

[0034]

FIG. 1 is a cross section of a multi-segment pressure vessel, as known from prior art.
FIG. 2 illustrates the different pressure zones applicable for a 2 two segmented pressure vessel
FIG. 3 shows a schematic overview of the components of an exemplary control unit and all the equipment of a multi-segmented pressure vessel, according to an embodiment of the present invention.
FIG. 4 shows main communication directions of data and commands in the data transfer between components of a control unit and equipment on a multi-segmented pressure vessel, according to an embodiment of the present invention.
FIG. 5 illustrates an example of a Startup process flow diagram, according to an embodiment of the present invention.
FIG. 6 illustrates an example of a Filling process flow diagram, according to an embodiment of the present invention.
FIG. 7 illustrates an example of an Emptying process flow diagram, according to an embodiment of the present invention.
FIG. 8 illustrates an example of a process flow diagram at an Imbalance situation and how to restore to the safer pressure balance, according to an embodiment of the present invention.
FIG. 9 illustrates an example of a Storing process flow diagram, according to an embodiment of the present invention.
FIG. 10 illustrates a schematic overview of components of the control unit and their connection to an external data source for weather data, historical or forecasted.
FIG. 11 illustrates an example of a Leak detection process flow diagram, according to an embodiment of the present invention.
FIG. 12 illustrates an example of a filling level prediction process flow diagram, according to an embodiment of the present invention.

[0035] In the different figures, the same reference signs refer to the same or analogous elements.

Description of illustrative embodiments

[0036] The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto but only by the claims. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes. The dimensions and the relative dimensions do not correspond to actual reductions to practice of the invention.

[0037] Furthermore, the terms first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequence, either temporally, spatially, in ranking or in any other manner. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other sequences than described or illustrated herein.

[0038] Moreover, the terms top, bottom, over, under and the like in the description and the claims are used for descriptive purposes and not necessarily for describing relative positions. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other orientations than described or illustrated herein.

[0039] It is to be noticed that the term "comprising", used in the claims, should not be interpreted as being restricted to the means listed thereafter; it does not exclude other elements or steps. It is thus to be interpreted as specifying the presence of the stated features, integers, steps or components as referred to, but does not preclude the presence or addition of one or more other features, integers, steps or components, or groups thereof. The term "comprising" therefore covers the situation where only the stated features are present and the situation where these features and one or more other features are present. The word "comprising" according to the invention therefore also includes as one embodiment that no further components are present. Thus, the scope of the expression "a device comprising means A and B" should not be interpreted as being limited to devices consisting only of components A and B. It means that with respect to the present invention, the only relevant components of the device are A and B.

[0040] Similarly, it is to be noticed that the term "coupled" should not be interpreted as being restricted to direct connections only. The terms "coupled" and "connected", along with their derivatives, may be used. It should be understood that these terms are not intended as synonyms for each other. Thus, the scope of the expression "a device A coupled to a device B" should not be limited to devices or systems wherein an output of device A is directly connected to an input of device B. It means that there exists a path between an output of A and an input of B which may be a path including other devices or means. "Coupled" may mean that two or more elements are either in direct physical or electrical contact, or that two or more elements are not in direct contact with each other but yet still co-operate or interact with each other.

[0041] Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment, but may. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner, as would be apparent to one of ordinary skill in the art from this disclosure, in one or more embodiments.

[0042] Similarly it should be appreciated that in the description of exemplary embodiments of the invention, various features of the invention are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims following the detailed description are hereby expressly incorporated into this detailed description, with each claim standing on its own as a separate embodiment of this invention.

[0043] Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments are meant to be within the scope of the invention, and form different embodiments, as would be understood by those in the art. For example, in the following claims, any of the claimed embodiments can be used in any combination.

[0044] Furthermore, some of the embodiments are described herein as a method or combination of elements of a method that can be implemented by a processor of a computer system or by other means of carrying out the function. Thus, a processor with the necessary instructions for carrying out such a method or element of a method forms a means for carrying out the method or element of a method. Furthermore, an element described herein of an apparatus embodiment is an example of a means for carrying out the function performed by the element for the purpose of carrying out the invention.

[0045] In the description provided herein, numerous specific details are set forth. However, it is understood that embodiments of the invention may be practiced without these specific details. In other instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an understanding of this description.

[0046] The invention will now be described by a detailed description of several embodiments of the invention. It is clear that other embodiments of the invention can be configured according to the knowledge of persons skilled in the art without departing from the technical teaching of the invention, the invention being limited only by the terms of the appended claims.

[0047] Where in embodiments of the present invention reference is made to an energy handling system, reference may be made to an energy harvesting construction. The energy handling system or energy harvesting construction may for example be configured for handling energy e.g. obtained from solar energy, wind energy, wave energy, another form of green energy or more generally other type of energy. The energy harvesting construction may in some embodiments be configured for using energy e.g. obtained from solar panels, wind mills, wave energy systems or alike for generating hydrogen, for producing ammonia, methane or nitric acid, or for other chemical or physical processes.

[0048] Where in embodiments of the present invention solar panels are mentioned, reference may be made to thermal solar panels wherein solar energy conversion is based on heating of a substance by solar energy, reference may be made to photovoltaic cells, or more generally reference may be made to any type of system converting solar energy into another type of energy. Furthermore, as indicated above, applications according to embodiments of the present invention also allow conversion of other energy types, such as wind, wave, or alike.

[0049] In one aspect, the present invention relates to a controller for controlling gas in one or more multi-segment compressed pressure vessels of an energy handling system. Such a multi-segment compressed pressure vessel may for example be a dual compressed pressure vessel, such as the one described in US11181235B2, although embodiments are not limited thereto, and also compressed pressure vessels with more than two segments may be used. An exemplary multi-segment compressed pressure vessel, with which the controller of the first aspect can be used is shown in FIG. 2. The inner segment of the multi-segment compressed pressure vessel typically may comprise a port for filling or emptying the inner segment and the outer segment, wherein the outer segment also may comprise a port for filling or emptying the outer segment with a secondary gas. The outer segment may be substantially fully encompassing the inner segment.

[0050] The compressed pressure vessels referred to may be constructive elements of the energy handling system or construction. This means that the compressed pressure vessels in some embodiments may be load carrying vessels, e.g. allowing to carry the load of the energy handling system or even of further constructions positioned on such an energy handling system.

[0051] According to the first aspect, the present invention relates to a controller, also referred to as a control unit, for controlling pressure in at least one multi-segment compressed pressure vessel of an energy handling system. The multi-segment compressed pressure vessel thereby comprises at least an inner segment and an outer segment substantially fully encompassing the inner segment. The control unit comprises a data input for receiving data related to the pressure in the inner segment and data related to the pressure in the outer segment. The control unit furthermore comprises a processor being programmed for deriving control signals for controlling the pressure in the multi-segment compressed pressure vessel in imbalance taking into account the data related to the pressure in the inner segment and of the data related to the pressure in the outer segment. Such controlling may in some embodiments comprise dynamically controlling the pressure in the at least one multi-segment compressed pressure vessel based on the data related to the pressure in the inner segment and the data related to the pressure in the outer segment. Such controlling may comprise deriving control signals based on a differential pressure between the inner segment and the outer segment of the multi-segment compressed pressure vessel. In some embodiments, controlling also may comprise dynamically controlling the pressure in the multi-segment compressed pressure vessel as function of the data related to the pressure in the inner segment and of the data related to the pressure in the outer segment.

[0052] In some embodiments, controlling the pressure in the multi-segment compressed pressure vessel as function of the data related to the pressure in the inner segment and the data related to the pressure in the outer segment, comprises controlling the pressure in the multi-segment compressed pressure vessel as function of a differential pressure between the inner segment and the outer segment of the multi-segment compressed pressure vessel.

[0053] The data related to the pressure may be a pressure in the segment, may be a flow rate of gas into or out of the segment, or any other data allowing to determine the gas pressure in the segment.

[0054] In some embodiments, controlling the pressure in the multi-segment compressed pressure vessel comprises controlling the pressure in the inner segment and/or controlling the pressure in an outer segment, or if more than two segments are present controlling in one, more or all of the segments of the multi-segment compressed pressure vessel.

[0055] The controller may be adapted for controlling the pressure in one, more or all of the multi-segment compressed pressure vessels used or present in the energy handling system.

[0056] The controller may be adapted for controlling the pressure in the at least one multi-segment compressed pressure vessel, taking into account a thickness of a separation wall between the inner segment and the outer segment.

[0057] The controller may be adapted for controlling the pressure in the at least one multi-segment compressed pressure vessel, taking into account a temperature of the multi-segment compressed pressure vessel.

[0058] Further standard or optional features of embodiments of the present invention will now be discussed with reference to FIG. 3 and further, without being limited thereto.

[0059] According to embodiments of the present invention, the controller 401, also referred to as control unit, comprises a data input 402 for receiving pressure related information regarding the pressure in the inner segment and/or the outer segment of the multi-segment pressure vessel. The data input may be of any suitable type. A communication component for communicating with other components in any suit able way also may be provided. As shown in FIG. 3, the controller 401 also comprises a processor 404. The controller 401 furthermore may comprise a memory/data storage 406 for storing data. The controller typically also comprises a data output 408 for outputting data to e.g. valves, pumping and/or compressing systems, actuators or alike, for controlling the process according to the processed data. The processor 404 used may be a general purpose processor, comprising specific software for performing tasks as set out in embodiments of the present invention, or may be a specific processor developed or configured for performing such tasks. The processor 404 may be a single processor, a set of processors, may be local, may be cloud based or more generally may be of any suitable type.

[0060] In some embodiments, the pressure related information may be relative or absolute pressure values for the inner segment and/or the outer segment. According to one embodiment, the controller 401 receives or reads pressure values from pressure sensors, continuously, at regular and/or predetermined moments in time, or when prompted. The pressure sensors 411, 412 may in one example be of a type that generates an electric (voltage) signal. Such sensors can be piezoelectric, sealed, vacuum, strain gauge, capacitive, etc. The signals from the pressure sensors may in some embodiments be sent by either a transmitter integrated in the pressure sensor, or by a standalone transmitter. Transmission may occur via a wired connection, such as PROFIBUS, PROFINET, Ethernet, ..., or wirelessly, such as over LoRA, NBIoT, LTE-M, WiFi, Bluetooth,... Alternatively or in addition thereto, the pressure related information also may be a flow sensor for measuring a flow in or out the inner/outer segment. Such information may, e.g. in combination with historical data, also allow for determining pressures in the segments.

[0061] In some embodiments, the pressure related information may furthermore involve temperature data, since the pressure typically is a function of temperature and since external effects of changes of temperature may be taken into account or may be used to control the system differently. The latter will be illustrated further in this description. A temperature sensor 413 therefore may be present in the system or communication with a temperature sensor may be provided. The data input 402 thus may be configured for receiving temperature information from a temperature sensor 413.

[0062] According to embodiments of the present invention the controller may be configured for controlling valves and/or pumps for allowing gas to enter or leave the inner and/or outer segments of the multi-segment pressure vessel. In some examples, the valves may be globe valves, segment valves, pinch valves, butterfly valves, ball valves, or any commonly used control valves. The valves may be electrically or pneumatically driven by an actuator, which may be part of the valve design itself. Controllers that drive the pneumatic or electrical operation of the valve may be present on or connected to the valve, and may provide operational data of the valve to the input component of the control unit 401, such as the current state of the valve, warnings, or faults within the component or system. Next to the valves 431, 441, 442, 432 connected to respectively segment of the pressure vessel, one or more safety valves (mechanical, pneumatically or electrically operated) for reducing excessive or dangerous overpressure in inner or outer segment may be included in or on the respective wall of the two-segmented pressure vessel. These valves may be present to provide a last-resort safety mechanism; should the pressure build to a level that is not rectifiable by the control valves, or should any number of control valves fail preventing pressure release, these safety valves can open either automatically or driven by the processor, to relieve the system.

[0063] The controller 401 furthermore may be configured for communicating with pumping or compressors systems, e.g. pumps or compressors 421, 422, connected to the different segments in one or more multi-segment pressure vessels for - e.g. in combination with valves - controlling the pressure in multi-segment pressure vessels.

[0064] The controller 401 may furthermore comprise or be connected to other components as required and as understood by the person skilled in the art.

[0065] By way of illustration, embodiments of the present invention not being limited thereto, control of an energy storage and/or handling system comprising at least one multi-segment pressure vessel is described below. An illustration of the general dynamics of/in a multi-segment pressure vessel, e.g. a multi-segment pressure vessel as described in US11181235B2, is given, whereby in this example the general dynamics is described as function of three pressure parameters that have an impact on the design and operation of such vessel. It is to be noted that the specific mathematical formalism used is only illustrative and that embodiments of the present invention are not limited thereto. The example is given of a dual compressed pressure vessel having an inner segment for storing hydrogen gas and an outer segment for storing a secondary gas, such as for example nitrogen gas.

[0066] In the present example, the pressure 302, P_1 of the inner segment 201, where the hydrogen gas is stored, hereafter called P_1. The pressure 301, P_2 of the outer segment 101, where the secondary gas is stored, hereafter called P_2. The separation wall 200 between the inner segment 201 and the outer segment 101 also is indicated in FIG. 2.

[0067] The atmospheric pressure 300 of the ambient where the dCPV vessels are stored is in the present example 1 atmosphere or 1 bar (0,1 MPa). Hereafter called P_{at}.

[0068] The outer segment 101 can be analysed as a single segment pressure vessel because the outer wall 100 is in contact with the atmospheric pressure P_{at} 300 and the inner segment 201 is separated from the outer segment 101 by the inner wall 200. Therefore, the load of the pressure acting on the outer wall 100 is the same as for a single segment pressure vessel.

[0069] The outer wall 100 carries the load of the gas pressure P_2 in the outer segment 101 of the vessel. For example, should the pressure P_2 301 in the outer segment 101 have a pressure of 20 MPa, the pressure forces acting on the outer wall 100 is 20 MPa.

[0070] Depending on the diameter, material and thickness of the outer wall 100, the vessel will show a particular resistance to the internal pressure P_2 301 generated by the secondary gas contained within. This resistance is reflected in the calculations according to European Norms for designing cylindrical pressure vessels for gaseous products. These norms specify the required relationship between pressures, material properties and designs; for cylindrical vessels the design mainly involves the diameter and wall thickness of the vessel.

[0071] The calculation for the required wall thickness for cylindrical shells under internal pressure applying the norm EN13445, part 3: clause 7, is given by the formula:

$$T = \frac{P * ID}{2 * S - P_{2,design}}$$

where

T = required wall thickness (mm)
$P_{2,design}$ = internal design pressure (MPa)
ID = inner diameter of the pressure vessel cilindrical section
S = minimum yield strength (MPa)

[0072] The internal design pressure $P_{2,design}$ is the maximum value for P_2 allowed. For a set of example Cases, these calculations give the following results, summarized in Table 1:

Table 1

Table 1:			
Outer wall 100	Outside Diameter	Internal Design Pressure $P_{2,design}$	Required Wall thickness
Case 1	508mm	20 MPa	7,4mm
Case 2	813mm	20 MPa	11,8mm
Case 3	1219mm	20 MPa	17,7mm

[0073] In the present example, the material properties for the outer wall are assumed to be high-strength steel, such as material standard API 5L grade X100. The minimum yield strength of this material is 690 MPa.

[0074] The pressures, more specifically the differential pressures, acting on the inner wall 200 wall are more complex. There is P1 302 from the hydrogen in the inner segment 201, and P2 301 from the secondary gas in the outer segment 101, both acting on the inner wall 200.

[0075] Because both external and internal pressures act on the wall of the inner vessel, the design pressure is a differential pressure or an overpressure of the inner segment. The overpressure P_o is the difference between P1 302 and P2 301, or

$$P_o = P_1 - P_2$$

[0076] Positive overpressures result in a net internal pressure in the inner segment $P_1 > P_2$, negative overpressures (one might also use the term negative pressures) result in a net external pressure on the inner segment $P_1 < P_2$. If both pressures are assumed to be equal $P_1 = P_2$ the overpressure P_o would be 0 MPa. Contrary to the outer segment, where the internal design pressure $P_{2,design}$ was solely determined by the internal pressure, the inner segment uses the design overpressure $P_{o,design}$ for its calculations.

[0077] As a design overpressure, a value of 0 MPa is not realistic, since differences in pressures during loading, unloading and storage have to be accounted for. Additionally, the inner wall 200 cannot be infinitely thin. Therefore, in our example hereafter we will consider a design overpressure $P_{o,design}$ of +3 MPa as a starting point. This allows for some margin during the loading or unloading process, the inner segment 201 can be pressurized 3 MPa higher than the outer segment 101.

[0078] Table 2 shows the required wall thicknesses for pressure vessels of different sizes under a +3 MPa overpressure, sized to fit as the inner segment in a two-segment pressure vessel design. The inner segment diameter is determined based on the volume ratio between inner and outer segment, in our example cases being 3 to 1. The calculations are performed through norm EN13445, part 3: clause 7 as before, only with $P_{o,design}$

Table 2

Table 2:			
Inner wall 200	Outside Diameter	Design Overpressure $P_{o,design}$	Required Wall thickness
Case 1	421mm	+ 3 MPa	2,63mm
Case 2	686mm	+ 3 MPa	4,29mm
Case 3	1028mm	+ 3 MPa	6,43mm

[0079] The material for the inner segment is assumed to be stainless steel 316L, which has a minimum yield strength of 240 MPa and is a suitable material for storing hydrogen.

[0080] Similar to the outer segment, larger diameter vessels and/or higher design pressures require more wall thickness. It seems a fairly thin wall would be sufficient to withstand a positive overpressure acting on the inner wall 200 of the inner segment 201.

[0081] However, when calculations according to the same EN13445 standard (section 3: clause 8) are performed on the wall thicknesses of the inner wall 200 from the cases in Table 2, thus obtaining negative values for the overpressure, the following results are obtained and shown in Table 3:

Table 3

Table 3:			
Inner wall 200	Outside Diameter	Wall thickness	Allowable Design Overpressure $P_{o,design}$
Case 1	421mm	2,63mm	- 0,345 MPa
Case 2	686mm	4,29mm	- 0,647 MPa
Case 3	1028mm	6,43mm	- 1,125 MPa

[0082] The formula/method for calculating the overpressure when it is negative is given below: Choose *T*,

$$P_y = \frac{T * S}{ID/2}$$

$$P_m = \frac{E * T * \varepsilon}{ID/2}$$

where ε is obtained from figure 8.5-3 based on $\frac{L}{ID}$ and $\frac{ID}{T}$

calculate $\frac{P_m}{P_y}$ and determine $\frac{P_r}{P_y}$ from Figure 8.5-5,
so that $P < P_r$

[0083] With

T = wall thickness
S = minimum yield strength
ID = inner diameter
E = modulus of elasticity
ε = mean elastic circumferential strain at collapse
L = unsupported length of the shell
P_m = theoretical elastic instability pressure for collapse of a perfect cylindrical shell
P_y = pressure at which mean circumferential stress in a cylindrical shell midway between stiffeners reaches yield point
P_r = calculated lower bound collapse pressure
P = external design pressure = $-P_{o,design}$

[0084] These calculations clearly show a flaw in the design. The wall thicknesses that suffice for an overpressure of +3MPa give much more stringent allowed values for negative overpressures.

[0085] To withstand a similar safety margin when the outer segment 101 is pressurized higher P2 301 than the inner segment P1 302, a significantly thicker wall is required in the present example. The thicknesses of the walls required are listed below considering the value L = 1 meter in Table 4:

Table 4

Table 4:			
Inner wall 200	Outside Diameter	Design Overpressure $P_{o,design}$	Required Wall thickness
Case 1	421mm	-3 MPa	6,5mm
Case 2	686mm	- 3 MPa	9mm
Case 3	1028mm	- 3 MPa	11mm

[0086] According to EN13445, the pressure resistance in the case where $P_2 > P_1$ may only be increased by adding wall thickness, or by shortening the unsupported length of the shell. The former adds a significant amount of material as mentioned previously, and is ideally to be avoided. The latter is achieved through adding stiffeners (light and/or heavy) at set points around the vessel. These stiffener rings may be placed externally, internally or partly externally and partly internally. The addition of stiffeners essentially means that each section of the vessel between the stiffeners may be regarded as independent from one another, at least as far as the wall thickness calculation is concerned.

[0087] Under the norm EN13445, should the pressure resistance not be sufficient, additional stiffeners are required, to further shorten the unsupported length of the shell. This is only practical up to a certain point however.

[0088] In the examples shown above, the unsupported length of the shell is assumed to be 1 meter. Further increasing the number of stiffeners, for example to every 0.5 meter, makes the vessel more complex to manufacture, and the material and weight added increase costs as well.

[0089] The factor L, the unsupported length of the shell, is determined based on the length of the cylindrical section of the pressure vessel. Since the stiffeners' width remains independent from their spacing (position on the cylindrical section of the vessel), the unsupported length of the shell is mainly determined by the length of the cylindrical section (for unstiffened cylinders), or the length between two stiffeners (for stiffened cylinders). An accurate option for increasing the pressure resistance for external pressure ($P_2 > P_1$), is adding more stiffeners so that the unsupported length of the shell decreases. This factor L is not present in the calculation formula for internal pressure, so the wall thickness for these calculations ($P_2 > P_1$) is not affected by *L* or the presence of stiffeners.

[0090] In the process where the unsupported length (L) is determined and the wall thickness is calculated and proven to be sufficient to prevent inter-stiffener collapse, the stiffeners themselves have to be evaluated if their mechanical design provides the support to resist collapse. Changing the mechanical stiffener design however, has no impact on the allowable pressure under this norm, it only allows the calculated pressure in the first part of the process to be used.

[0091] Should the design be implemented with the wall thickness as required by the weakest point in the design (the external pressure), the wall of the inner vessel would in itself be able to withstand overpressures as shown below, partly defeating the purpose of the vessel in itself. This required increase in wall thickness adds to the weight and cost of the vessel, and prevents it from being the safe and cheap option for hydrogen storage as desired. Table 5 shows allowed positive overpressures $P_{o,design}$, considering the wall thicknesses from Table 4:

Table 5

Table 5:			
Inner wall 200	Outside Diameter	Wall thickness	Allowable Design Overpressure $P_{o,design}$
Case 1	421mm	6,5mm	+ 7,4 MPa
Case 2	686mm	9mm	+ 6,3 MPa
Case 3	1028mm	11mm	+ 5,1 MPa

[0092] The further reasoning is explained with regard to Case 2, were in Table 6 two options for thickness of the inner wall 200 are considered. The maximum relative overpressure $P_{o,rel,max}$ shows how much the pressure of in the inner segment can be further increased, when both segments are at their design pressures of 20 MPa, $P_{1,design}$ and $P_{2,design}$. Note that when $P_{1,design} = P_{2,design}$, this maximum and minimum relative overpressures are equal to the positive and negative design overpressure $P_{o,design}$ respectively.

Table 6

Table 6:				
Inner wall 200	Outside Diameter	Wall thickness	Max. Relative Overpressure $P_{o,rel,max}$	Min. Relative Overpressure $P_{o,reL,min}$
Case 2 Option A	686mm	4,29mm	3 MPa	-0,647 MPa
Case 2 Option B	686mm	9mm	6,3 MPa	-3 MPa

[0093] If a pressure resistance of at least 3 MPa is desired over the inner wall 200 in both pressure directions, a wall thickness of 9mm is needed. As said, this is not economical, a better solution would be if the wall thickness of 4,29mm could be kept, while still increasing the operational pressure margins for the outer segments.

[0094] It is technically impossible to achieve 3MPa in both directions, but still a much higher value than the 0,647 MPa can be reached. This is possible when not balancing pressures of the inner and the outer segment identically but in fact unbalancing pressure values in the inner and the outer segment.

[0095] For Case 2 this means:

Table 7

Table 7:					
Inner wall 200	Outside Diameter	Wall thickness	Operational overpressure $P_{o,operating}$	Max. Relative Overpressure $P_{o,rel,max}$	Min. Relative Overpressure $P_{o,rel,min}$
Case 2 Option A	686mm	4,29mm	0 MPa	3 MPa	- 0,647 MPa
Case 2 Option C	686mm	4,29mm	+1,1765 MPa	1,8235 MPa	- 1,8235 MPa

[0096] In this table, $P_{o,operating}$ is the operating overpressure; the difference between the operating pressure of the inner segment $P_{1,operating}$, and the operating pressure of the outer segment $P_{2,operating}$, or

$$P_{o,operating} = P_{1,operating} - P_{2,operating}$$

[0097] The introduction of $P_{o,operating}$ (if different from 0) implies that the operating pressures for both segments differ from their design pressures.

[0098] If the pressures values of the inner segment 201 and outer segment 101 are balanced as shown in Table 7 Case 2 Option A, the operational pressure range of the outer segment 101 is much lower than that of the inner segment 201, 3 versus 0,647. As soon as the outer segment's pressure P2 301 has a value higher than 0,647 MPa more than the inner segment pressure P1 302, the inner wall 200 is in danger of collapsing. In the other event where there is an overpressure in the inner segment 201, the differential pressure can go up to 3 MPa.

[0099] Therefore, it is advantageous the pressure in the inner segment P1 302 is controlled so that this pressure is higher than the pressure of the outer segment P2 301.

[0100] In Table 7 Case 2 Option C the pressure of the inner segment is increased with the operating overpressure $P_{o,operating}$ of 1,1765MPa. This means that compared to its operating pressure $P_{1,operating}$, P1 may be increased or decreased by the maximum or minimum relative overpressure, or in this case both 1,8235 MPa.

[0101] Conversely, due to the 1,1765MPa operating overpressure in the inner segment 201, a pressure increase in the outer segment P2 already takes the reduction of this overpressure to reach a balanced pressure in both segments P1 = P2. A further pressure increase in the outer vessel of 0,647 MPa is allowed, so that the maximum overpressure relative to the design pressure for the outer segment 301 increases from 0,647 MPa to 1,1765 MPa + 0,647 MPa = 1,8235 MPa. There is a gain in operational range in the pressure of the outer segment from 0,647 to now 1,8235 MPa. So inner and outer operational pressure ranges are now balanced (1,8235 versus 1,8235 MPa before one of the segments comes into a critical collapse pressure value.

[0102] Changing the operating pressures of the two segments individually *(*$P_{1,operating}$ and $P_{2,operating}$*)* leads to a higher operational margin for the outer segment using the same thinner wall thickness. The inner segment 201 needs to be pressurized higher than the outer segment 101, according to the difference between design overpressures the inner wall 200 can withstand in both directions.

[0103] The operational overpressure is calculated as follows (Equation 1a):

$$P_{o,operating} = P_{o,rel,max} - \frac{P_{o,rel,max} + |P_{o,rel,min}|}{2}$$

[0104] Where

$P_{o,operating}$ = *operational overpressure*
$P_{o,rel,max}$ = *maximum relative overpressure*
$P_{o,rel,min}$ = *minimum relative overpressure*

[0105] With $P_{o,operating}$ calculated, $P_{1,operating}$ may be determined from

$$P_{1,operating} = P_{2,design} + P_{o,operating}$$

[0106] Where

$P_{1,operating}$ = *operating pressure of inner segment*
$P_{2,operating}$ = *operating pressure of outer segment*

[0107] And

$$P_{2,operating} = P_{2,design}$$

[0108] Alternatively, the pressure of the inner vessel may be regarded as a starting point, and the design pressure P2, design in the outer segment 101 of the pressure vessel may be lowered, Equation 1a is then adapted to Equation 1b below.

$$P_{2,operating} = P_{1,operating} - P_{o,operating}$$

[0109] Where

$$P_{1,operating} = P_{2,design}$$

[0110] In case of a collapse of the inner wall 200 the calculated wall thickness of the outer wall 100 should ensure that no dangerous situation will occur. If the inner wall 200 collapses, the hydrogen gas will mix with the secondary gas, nitrogen or carbon dioxide. This mixture of gases does not cause an explosion risk, due to the absence of oxygen. Additionally, the resulting pressure will be lower than $P_{2,design}$.

[0111] This reasoning is why equation 1b is preferred over 1a, as this ensures overall safety.

[0112] Next to the maximum pressures allowed in the system, a set of minimum pressures $P_{1,min}$, $P_{2,min}$ may be determined. In a realistic setting, both segments are not emptied completely, but kept at a minimum pressure level. This keeps the pressure differences at a constant level, and minimizes pressure fluctuations, particularly on the inner wall 200. It is advantageous since it prevents fatigue stress on the inner wall 200 containing the hydrogen gas; hydrogen generally causes more issues in designs prone to fatigue.

[0113] In one example, as illustrated in FIG. 4, a processing unit 401 to control the pressure P1 and P2 and thus achieving a larger operational pressure margin for the outer segment, will consist of an input component, a processing component, a memory/data storage component and an output component.

[0114] The processing unit 401 will, in the example shown, be connected to the input elements, being the pressure sensors 411 for the outer segment and the pressure sensors 412 for the inner segment. 'Pressure sensors' (multiple) is used, since for safety reasons 2 or more pressure sensors could be installed - one of which is redundant- in case one pressure sensor would have a technical defect. The pressure sensors are either directly connected to or in the inner wall 200 or outer wall 100 or are installed in the nozzles or connected pipework for each segment. A temperature transmitter 413 is installed on or in the outer wall 100.

[0115] The controllable operating process equipment, being the valves 431, 441, 442, 432 and the compressors or pumps 421, 422, are also connected to the processing unit 401.

[0116] To increase the pressure P1, and feed hydrogen gas into the inner segment 201, the control unit 401 will send commands through the output component to drive the compressor 422 and to open valve 432 feeding more hydrogen gas in this segment. The pressure is measured by the pressure sensor 412.

[0117] To decrease the pressure P1, and empty hydrogen gas from the inner segment 201, the control unit 401 will send commands through the output component to open valve 442 and release hydrogen gas in the connected piping. The pressure is measured by the pressure sensor 412.

[0118] To increase the pressure P2, and feed the secondary gas into the outer segment 101, the control unit 401 will send commands through the output component to drive the compressor 421 and to open valve 431 feeding more secondary gas in this segment. The pressure is measured by the pressure sensor 411.

[0119] To decrease the pressure P2, and empty the secondary gas from the outer segment 101, the control unit 401 will send commands through the output component to open valve 441 and release secondary gas in the connected piping. The pressure is measured by the pressure sensor 411.

[0120] During storage all valves are in the closed position and the compressors are off. Should the compressor 421 or 422 not be able to deliver the necessary flow or pressure to a respective segment, due to an absence of hydrogen or secondary gas, the pressure cannot be increased in the respective segment. This will likely be the case at some point during operation of the energy-system, due to the variable nature of the renewable energy sources used.

[0121] Further by way of illustration, embodiments of the present invention not being limited thereto, a number of exemplary control processes that could be implemented in an energy storage and/or handling system are discussed below. The flow charts below show how control can be operated. In the exemplary processes shown below, examples are illustrated on what decisions have to be made and what actions need to be taken. Exemplary control processes for 5 operational processes are illustrated.

[0122] A first process that is illustrated shows a possible initialisation process. FIG. 5 illustrates a possible start-up of an energy system comprising at least one multi-segment pressure vessel.

[0123] An exemplary process of filling is shown in flow diagram in FIG. 6. It describes what pressure values are taken to make decisions while filling the inner and outer segment with its respective gas and keeping the system in a balance where the overpressure is P_o is the key variable.

[0124] Similarly, an exemplary process of emptying is shown in flow diagram FIG. 7. It describes how the inner and outer segments are emptied, keeping the system in a balance where the overpressure is P_o is the key variable. $P_{1,min}$ and $P_{2,min}$ are here the parameters to prevent complete emptying of the system.

[0125] An exemplary process for dealing with imbalance is shown in flow diagram FIG. 8. It describes how the overpressure P_o can be brought back to balance, by initially trying to first bring the balance back by increasing the pressure in the inner segment. If this is not possible, it directs to the sub-process of emptying the outer segment to release the secondary gas.

[0126] An exemplary process for storage is shown in flow diagram FIG. 9. It describes the process of storing the gasses, which is mainly a monitoring of the pressure values and if they stay in the desired pressure ranges. In this process commands will lead to other sub-processes.

[0127] In some particular embodiments, based on cyclic or expected temperatures inside the vessel, which are even more present in environments chosen for renewables such as solar energy systems in deserts, temperature differences can account for large pressure changes in a pressure vessel. Therefore, to prevent having to relieve pressure from a system when temperatures rise, a more adequate fill levelling and thus pressure levelling may be calculated, to account for an expected change in pressure at a later time.

[0128] Conversely, in places -mostly located closer to the poles- where wind energy is an efficient energy source, temperatures can drop lower during a day or from season to season, which means the pressure vessel can be filled higher since the density of gas raises when the temperature is lower.

[0129] This will be of crucial importance for on-ground installed pressure vessels, that have direct sunray impact and resulting heat generation. The outer wall material will most likely be a metal alloy, which typically has very good thermal conductive properties, leading to large effects of external temperature and solar radiation on the internal temperature of the vessel.

[0130] Underground installed pressure vessels will have less temperature changes but are harder to maintain and supervise than on-ground installed pressure vessels.

[0131] Temperature changes during a day in the Sahara desert can go from 0°C (273,15K) to +40°C (313,15K)

[0132] For example, a pressure of 20MPa is the desired operational pressure. The temperature at the hottest point during the day is forecasted to be 40°C or 313,15K. At the moment of filling the vessel however, the temperature is only 20°C or 293,15K. The segment in question is only filled to 18.7MPa. When the temperature inside the vessel reaches 40°C, the gas pressure increases to 20MPa.

[0133] This example assumes the internal temperature of the gas in the vessel is exactly equal to the temperature outside the vessel. Other effects that influence the internal temperature in the vessel may also be considered, to make the prediction more accurate.

[0134] The prediction of the internal temperature may be based on data from an external meteorological data system or weather forecast system 800 or temperature data stored in the Memory Data Storage component of the control unit 401 recorded during previous operational period. This data may include temperature, cloud cover, solar irradiation and wind speeds among others. A corresponding system is shown in FIG. 10.

[0135] A leak detection process as shown in flow diagram FIG. 11. It describes the process of detecting possible leaks in the inner wall 200, by monitoring and comparing the pressure values and if they have deviated from previously measured pressure values with a time interval t, stored in the Memory Data Storage component.

[0136] A filling level prediction process is shown in flow diagram FIG. 12. It describes the process of predicting the max pressure level P1 and P2 considering expected temperature changes that following the law of Gay-Lussac will result in a pressure decrease (temperature drops) or pressure increase (temperature raises). This process will improve the filling efficiency, to avoid the need for emptying because of $P_1 > P_{1,design}$ or $P_2 > P_{2,design}$.

[0137] In the second aspect, the present invention relates to an energy handling system for handling energy, the energy handling system comprising at least one multi-segment pressure vessel comprising at least an inner segment and an outer segment, and a controller according to the first aspect for dynamically controlling pressure of a first gas in the inner segment and pressure of a second gas in the outer segment. The energy handling system may be built of several multi-segment pressure vessels, and the multi-segment pressure vessels may be structural elements of the energy handling system. Such energy handling system may be a pipeline, an energy storage construction such as for example a vertical storage construction or a horizontal storage construction, a support construction for solar panels, a support construction for a wind mill, etc. The constructive elements in the energy handling system may mostly or all be multi-segment compressed pressure vessels.

[0138] In a third aspect, the present invention also relates to a method for controlling pressure in at least one multi-segment compressed pressure vessel of an energy handling system, the method comprising

obtaining data related to the pressure in the inner segment and data related to the pressure in the outer segment, and dynamically determining control signals for controlling the pressure in the at least one multi-segment compressed pressure vessel based on the data related to the pressure in the inner segment and the data related to the pressure in the outer segment.

[0139] Further method steps may correspond to the device features expressed for the controller according to the first aspect.

[0140] It is to be understood that although preferred embodiments, specific constructions and configurations, as well as materials, have been discussed herein for devices according to the present invention, various changes or modifications in form and detail may be made without departing from the scope of this invention. Steps may be added or deleted to methods described within the scope of the present invention.

Claims

1. A controller (401) for controlling pressure in at least one multi-segment compressed pressure vessel (100) of an energy handling system, the multi-segment compressed pressure vessel (100) thereby comprises at least an inner segment (201) and an outer segment (101) substantially fully encompassing the inner segment (201), the controller (401) comprising a data input (402) for receiving data related to the pressure (302, P1) in the inner segment (201) and data related to the pressure (301, P2) in the outer segment (101), and a processor (404) being programmed for deriving control signals for controlling the pressure in the multi-segment compressed pressure vessel (100) in imbalance taking into account the data related to the pressure (302, P1) in the inner segment (201) and of the data related to the pressure (301, P2) in the outer segment (101).

2. The controller (401) of claim 1, wherein controlling the pressure in the multi-segment compressed pressure vessel (100) comprises controlling the pressure in the multi-segment compressed pressure vessel (100) as function of a differential pressure between the inner segment (201) and the outer segment (101) of the multi-segment compressed pressure vessel (100).

3. The controller (401) of any of the previous claims, wherein the controller is configured for controlling the pressure in the inner segment to be substantially higher than the pressure in the outer segment.

4. The controller (401) of any of the previous claims, wherein the data input is configured for receiving a pressure in the inner segment (201) and/or a gas pressure in the outer segment (101).

5. The controller (401) according to any of the previous claims,

   wherein the controller (401) is configured for controlling the pressure in one, more or all of the segments of the at least one multi-segment compressed pressure vessel (100), and/or
   wherein the controller (401) is configured for controlling the pressure in one, more or all of the multi-segment compressed pressure vessels (100) of the energy handling system.

6. The controller (401) according to any of the previous claims, the controller being configured for controlling the pressure in the at least one multi-segment compressed pressure vessel, taking into account at least one of a thickness, material and diameter of a separation wall between the inner segment (201) and the outer segment (101) of the at least one multi-segment compressed pressure vessel (100).

7. The controller (401) according to any of the previous claims, the controller (401) being configured for controlling the pressure in the at least one multi-segment compressed pressure vessel, taking into account a temperature of the at least one multi-segment compressed pressure vessel.

8. The controller (401) according to any of the previous claims, the controller (401) furthermore comprising a data output (408) for outputting control signals for controlling pressure in the multi-segment compressed pressure vessel.

9. The controller (401) according to any of the previous claims, wherein the controller (401) is configured for controlling one or more of a start-up process, a filling process, an emptying process, a process for dealing with imbalance, a process for storing of gasses, and a process for leak detection in the at least one multi-segment compressed pressure vessel.

10. The controller (401) according to any of the previous claims, wherein the controller (401) is configured for determining a filling process based on the control signals determined by furthermore taking into account predicted or forecasted internal temperature changes.

11. An energy handling system comprising at least one multi-segment compressed pressure vessel and comprising a controller (401) for controlling gas pressures in the at least one multi-segment compressed pressure vessel according to any of claims 1 to 10.

12. An energy handling system according to claim 11, wherein a wall thickness of a wall between an inner segment and an outer segment of the multi-segment compressed pressure vessel is smaller than 15mm, e.g. less than 12mm, e.g. less than 9mm.

13. A method for controlling pressure in at least one multi-segment compressed pressure vessel of an energy handling system, the method comprising the steps of

- obtaining data related to the pressure in the inner segment and data related to the pressure in the outer segment, and
- determining control signals for dynamically controlling the pressure in the at least one multi-segment compressed pressure vessel based on the data related to the pressure in the inner segment and the data related to the pressure in the outer segment.

14. A method according to claim 13, wherein said control signals are based on a differential pressure between the inner segment (201) and the outer segment (101) of the multi-segment compressed pressure vessel (100).

15. A method according to any of claims 13 to 14, wherein the said controlling comprises one or more of a start-up process, a filling process, an emptying process, a process for dealing with imbalance, a process for storing of gasses, and a process for leak detection in the at least one multi-segment compressed pressure vessel.

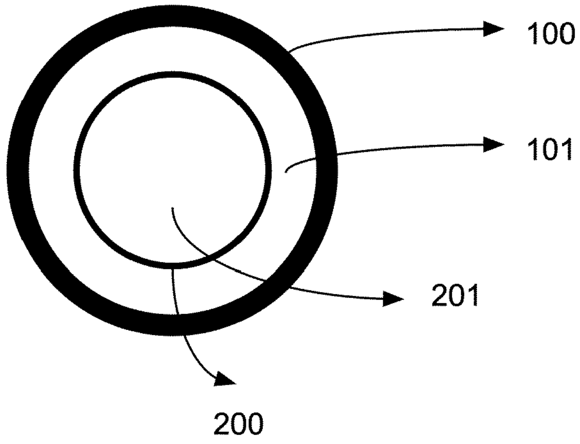

FIG. 1

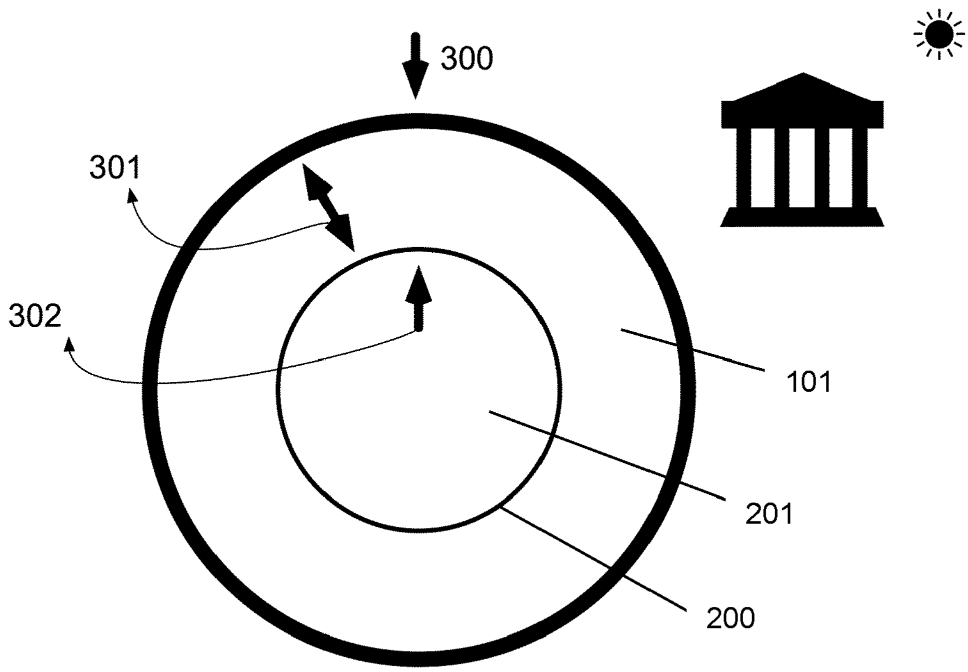

FIG. 2

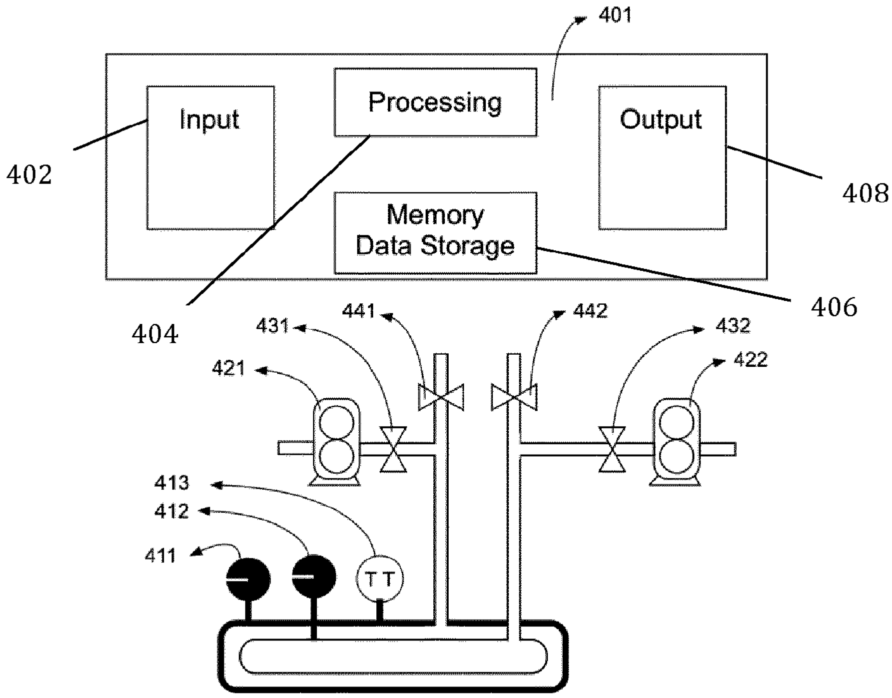
401
Input
Processing
Output
402
408
Memory
Data Storage
406
404
441
442
431
432
421
422
413
412
411
T T

FIG. 3

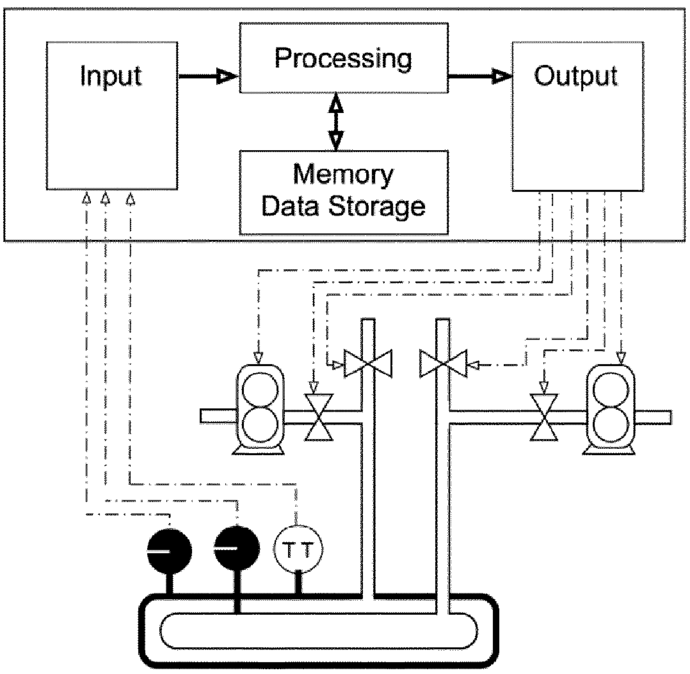
Input
Processing
Output
Memory
Data Storage
T T

FIG. 4

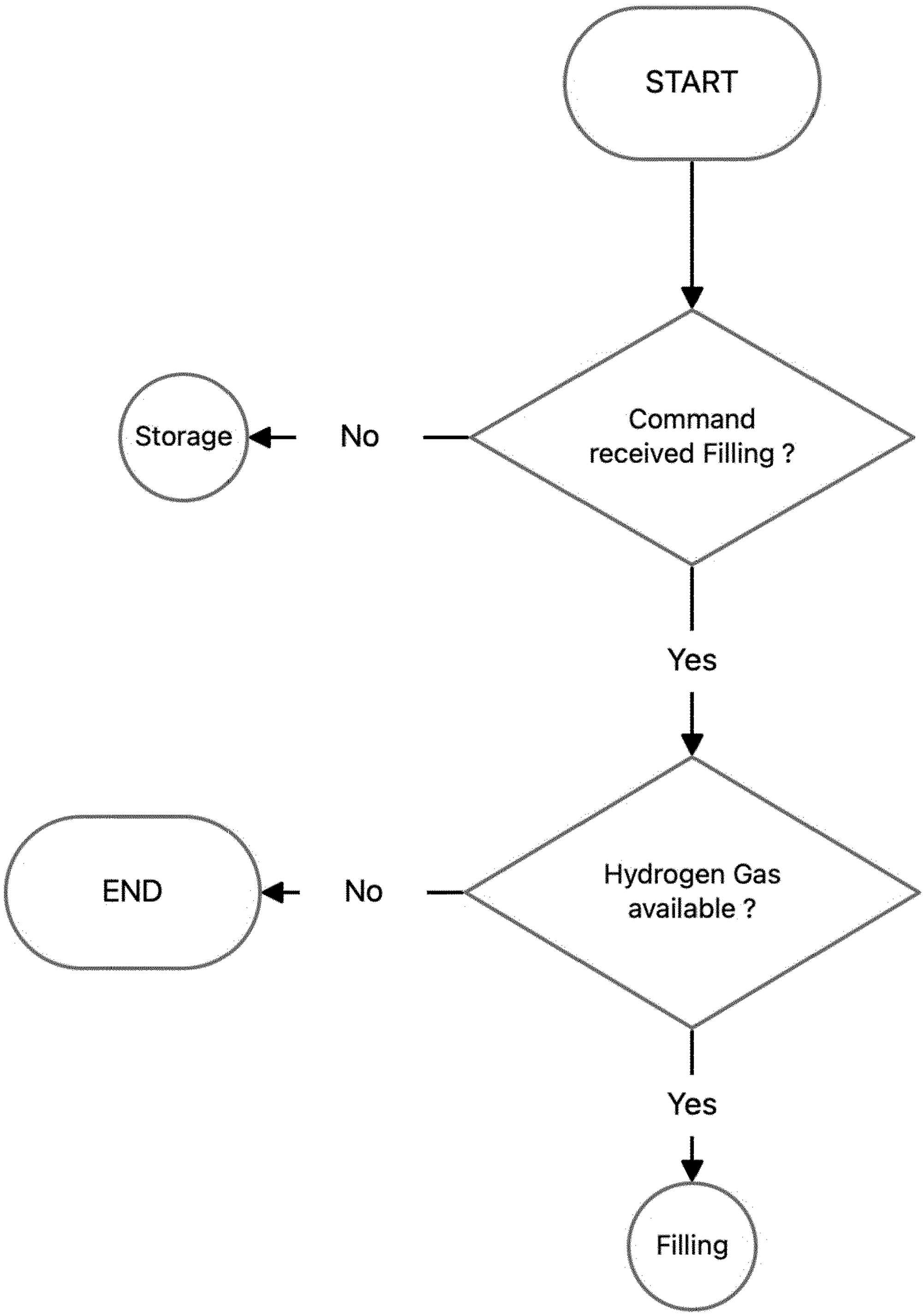
START
Command received Filling ?
No
Storage
Yes
Hydrogen Gas available ?
No
END
Yes
Filling

FIG. 5

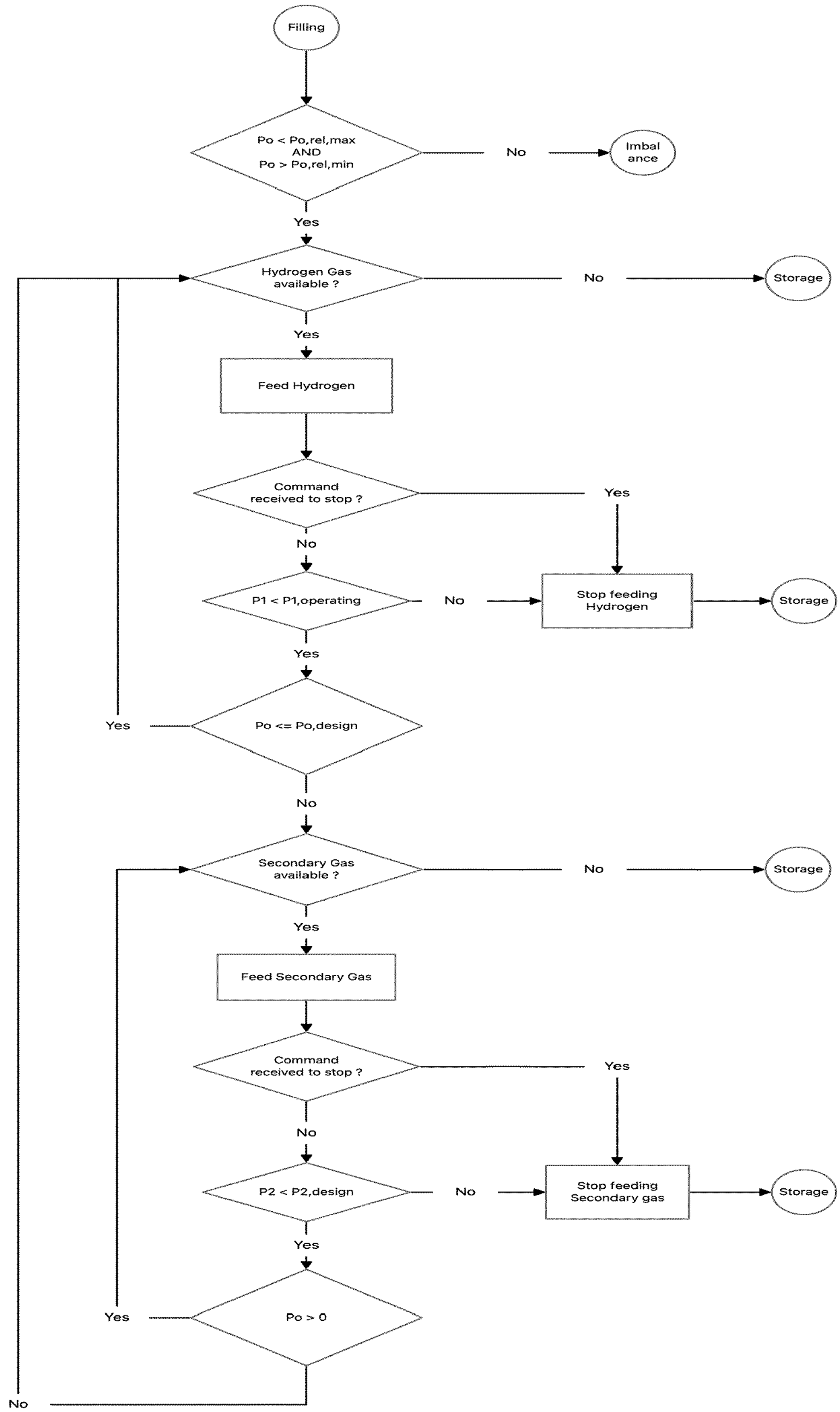
Filling
Po < Po,rel,max
AND
Po > Po,rel,min
No
Imbal
ance
Yes
Hydrogen Gas
available ?
No
Storage
Yes
Feed Hydrogen
Command
received to stop ?
Yes
No
P1 < P1,operating
No
Stop feeding
Hydrogen
Storage
Yes
Po <= Po,design
Yes
No
Secondary Gas
available ?
No
Storage
Yes
Feed Secondary Gas
Command
received to stop ?
Yes
No
P2 < P2,design
No
Stop feeding
Secondary gas
Storage
Yes
Po > 0
Yes
No

FIG. 6

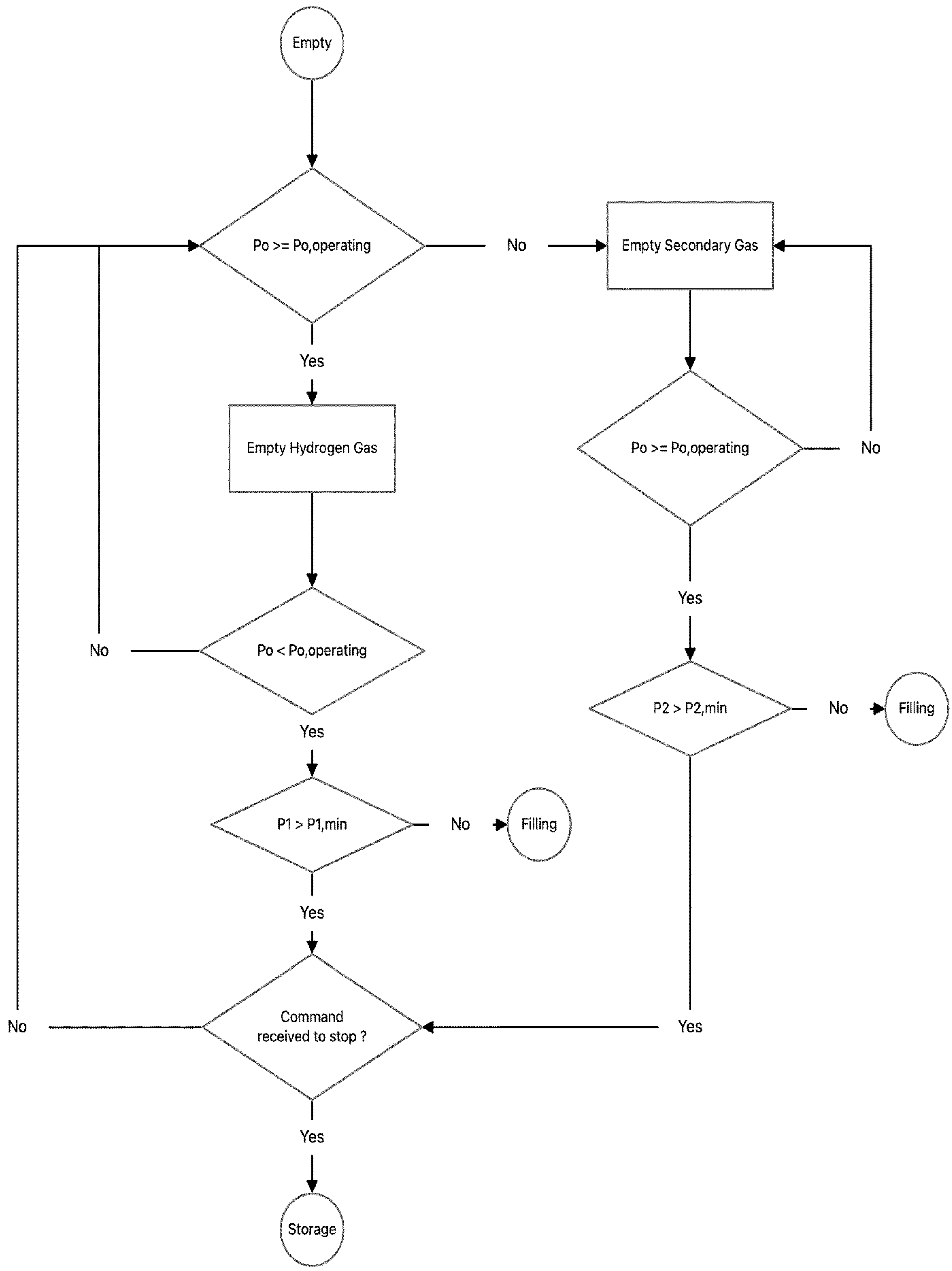
Empty
Po >= Po,operating
No
Empty Secondary Gas
Yes
Empty Hydrogen Gas
Po >= Po,operating
No
Yes
No
Po < Po,operating
P2 > P2,min
No
Filling
Yes
P1 > P1,min
No
Filling
Yes
No
Command received to stop ?
Yes
Yes
Storage

FIG. 7

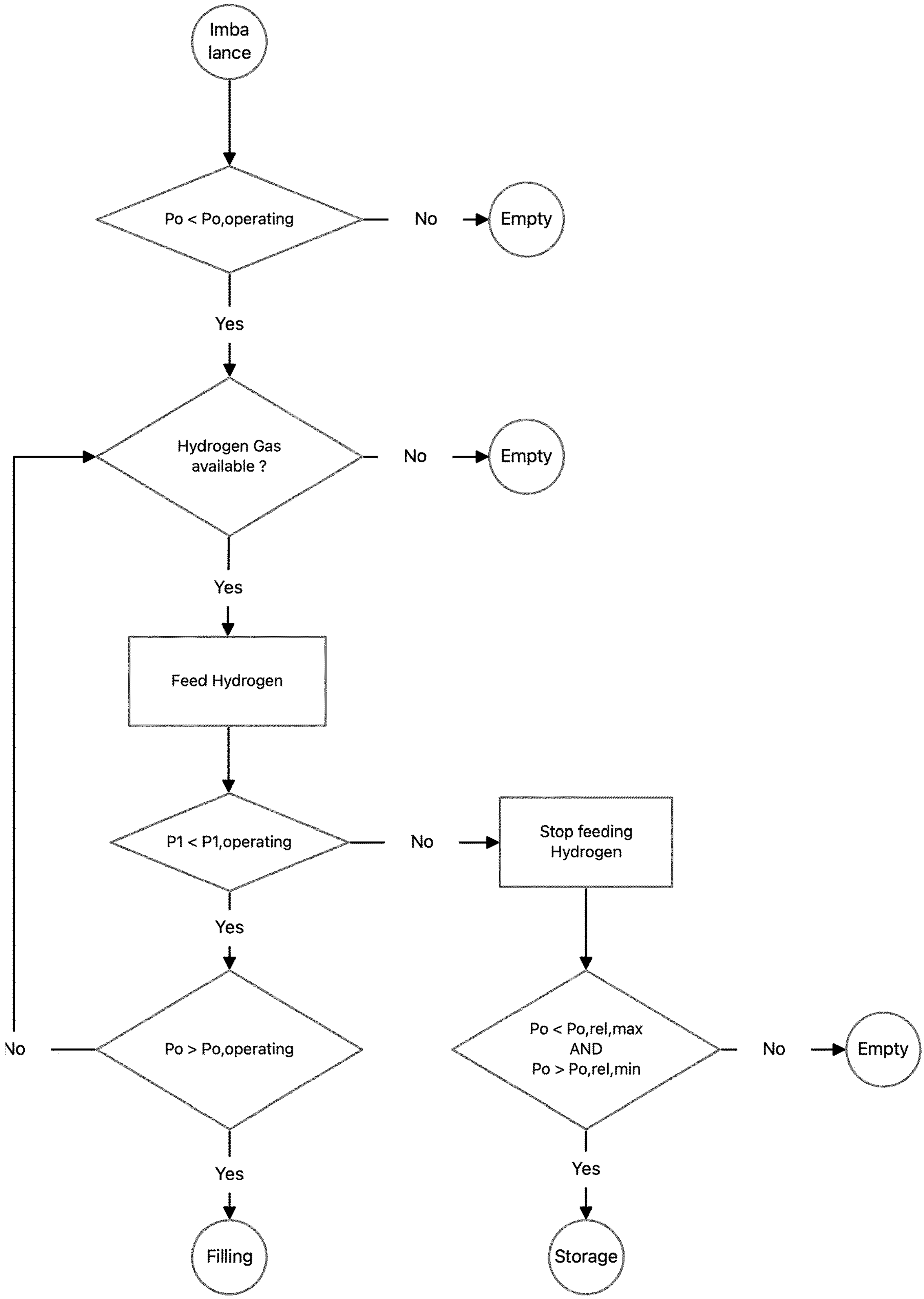
Imba
lance
Po < Po,operating
No
Empty
Yes
Hydrogen Gas
available ?
No
Empty
Yes
Feed Hydrogen
P1 < P1,operating
No
Stop feeding
Hydrogen
Yes
No
Po > Po,operating
Po < Po,rel,max
AND
Po > Po,rel,min
No
Empty
Yes
Yes
Filling
Storage

FIG. 8

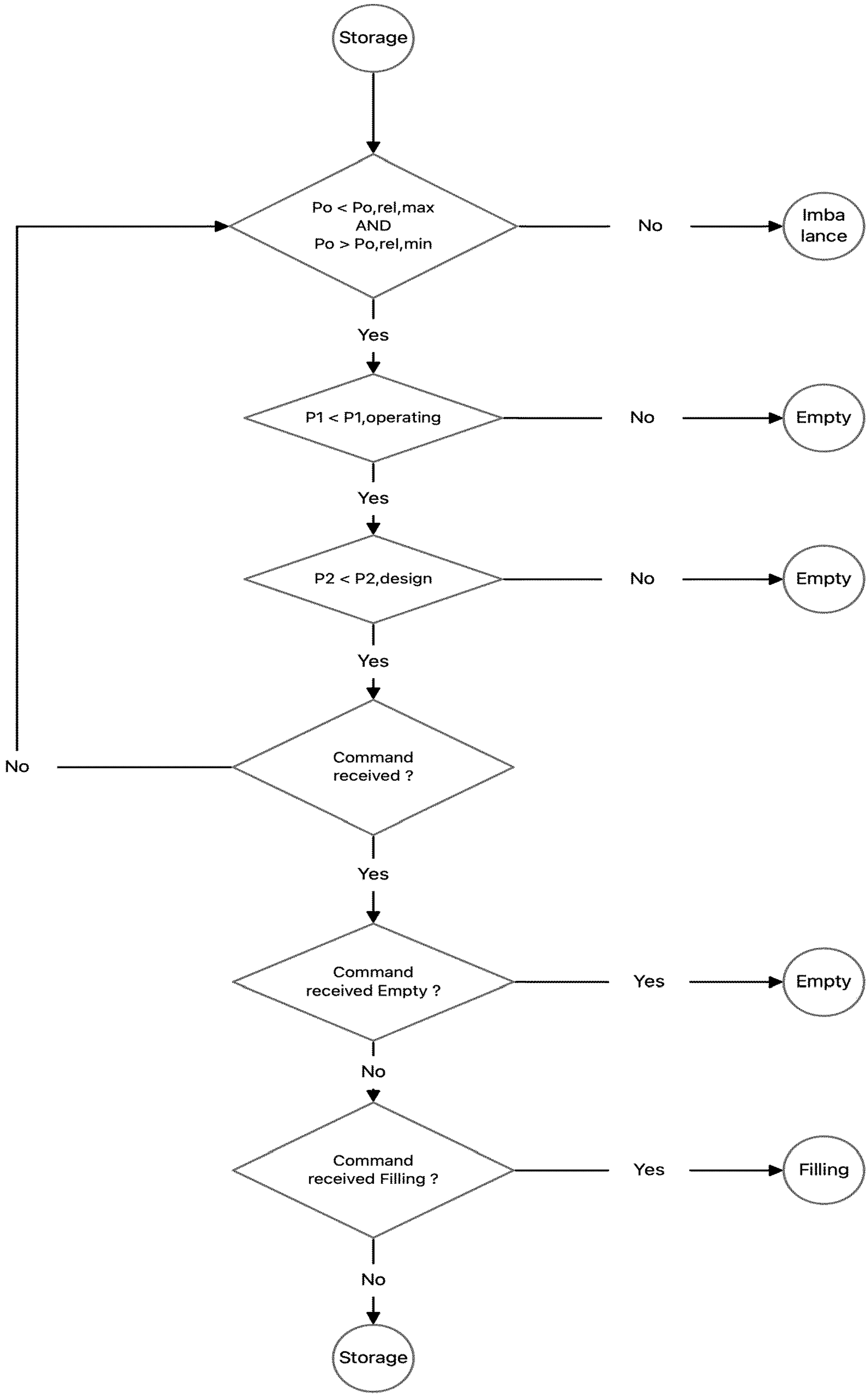
Storage
Po < Po,rel,max
AND
Po > Po,rel,min
No
Imba
lance
Yes
P1 < P1,operating
No
Empty
Yes
P2 < P2,design
No
Empty
Yes
Command
received ?
No
Yes
Command
received Empty ?
Yes
Empty
No
Command
received Filling ?
Yes
Filling
No
Storage

FIG. 9

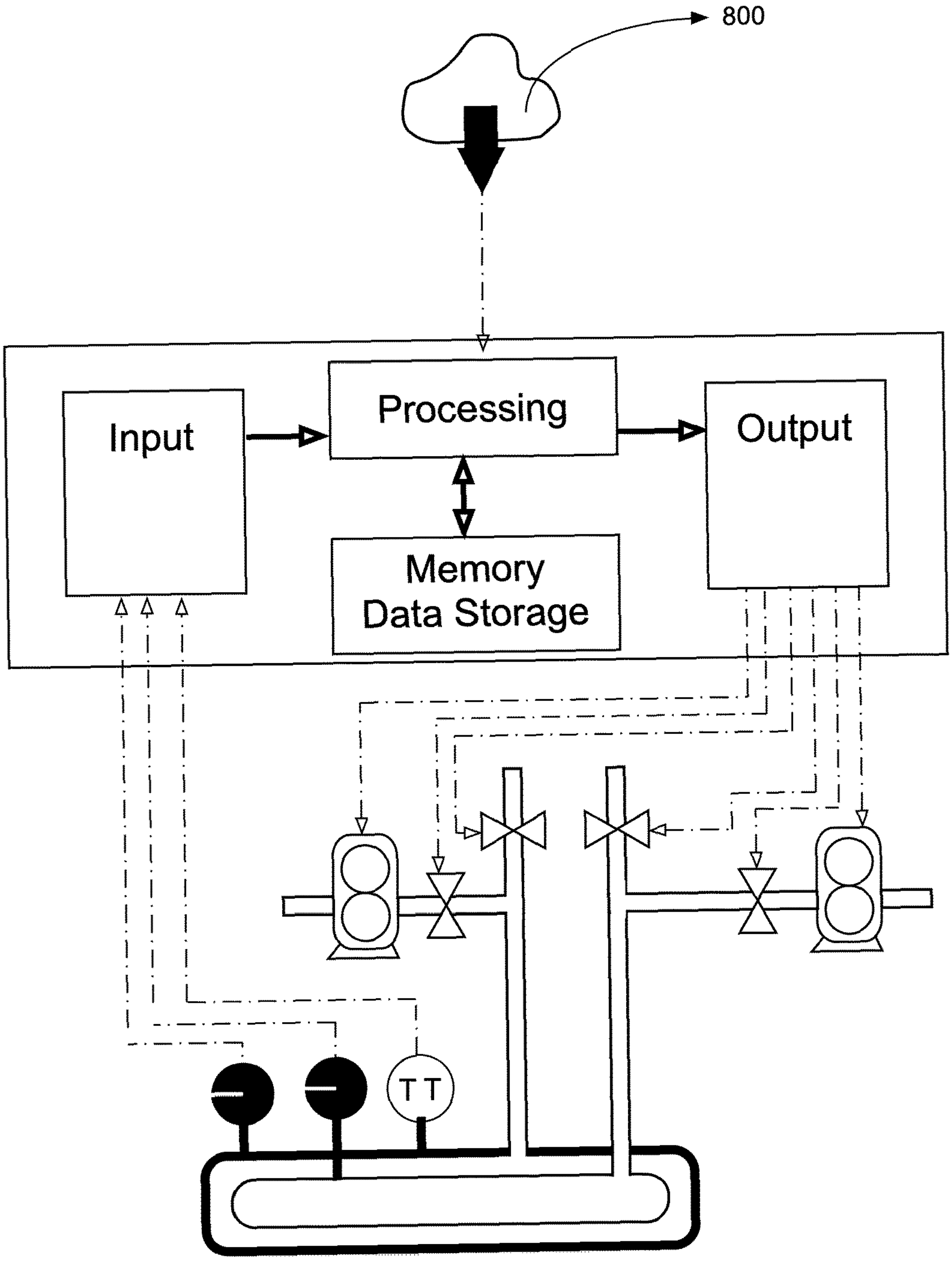

FIG. 10

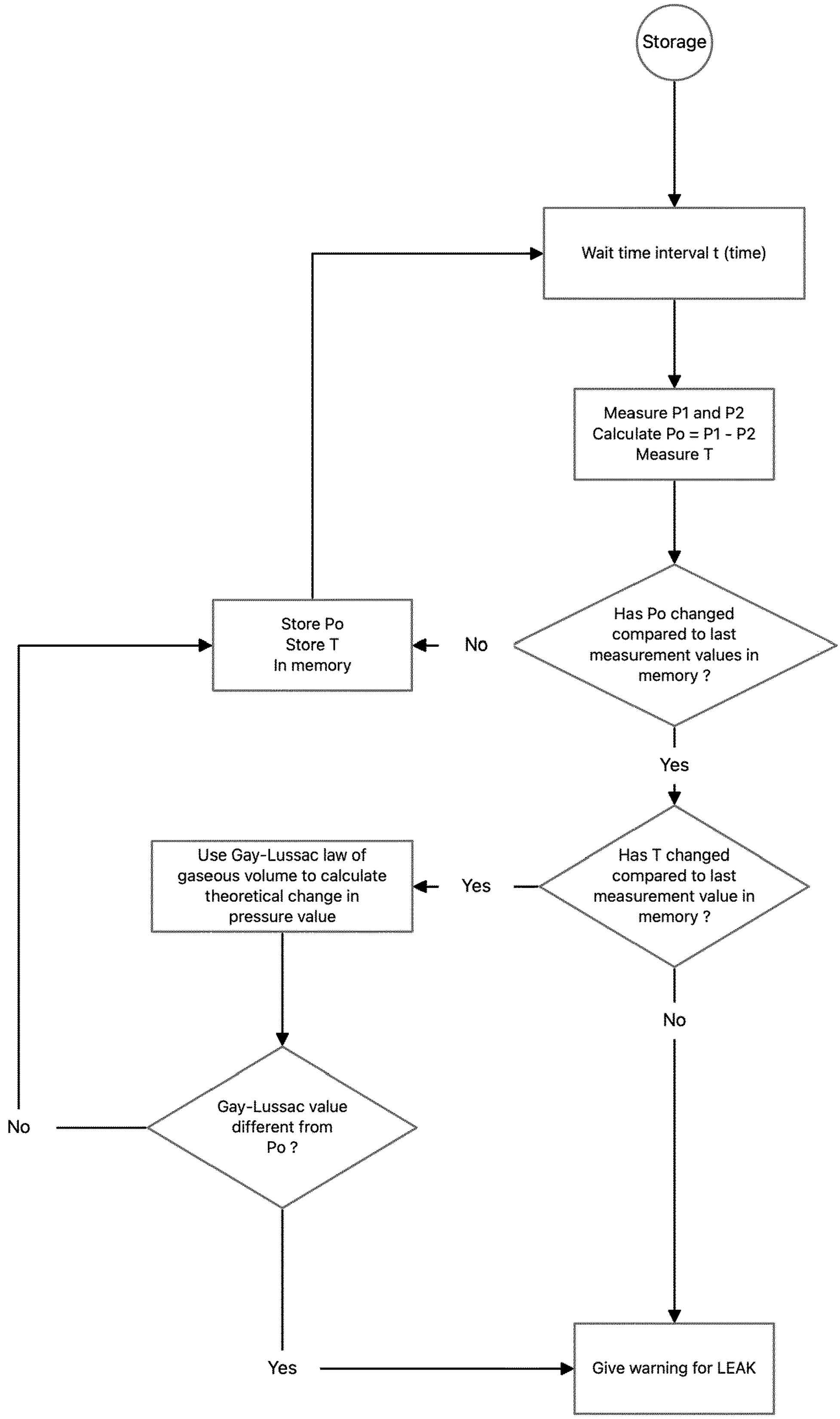
Storage
Wait time interval t (time)
Measure P1 and P2
Calculate Po = P1 - P2
Measure T
Has Po changed
compared to last
measurement values in
memory ?
No
Store Po
Store T
In memory
Yes
Has T changed
compared to last
measurement value in
memory ?
Yes
Use Gay-Lussac law of
gaseous volume to calculate
theoretical change in
pressure value
No
Gay-Lussac value
different from
Po ?
No
Yes
Give warning for LEAK

FIG. 11

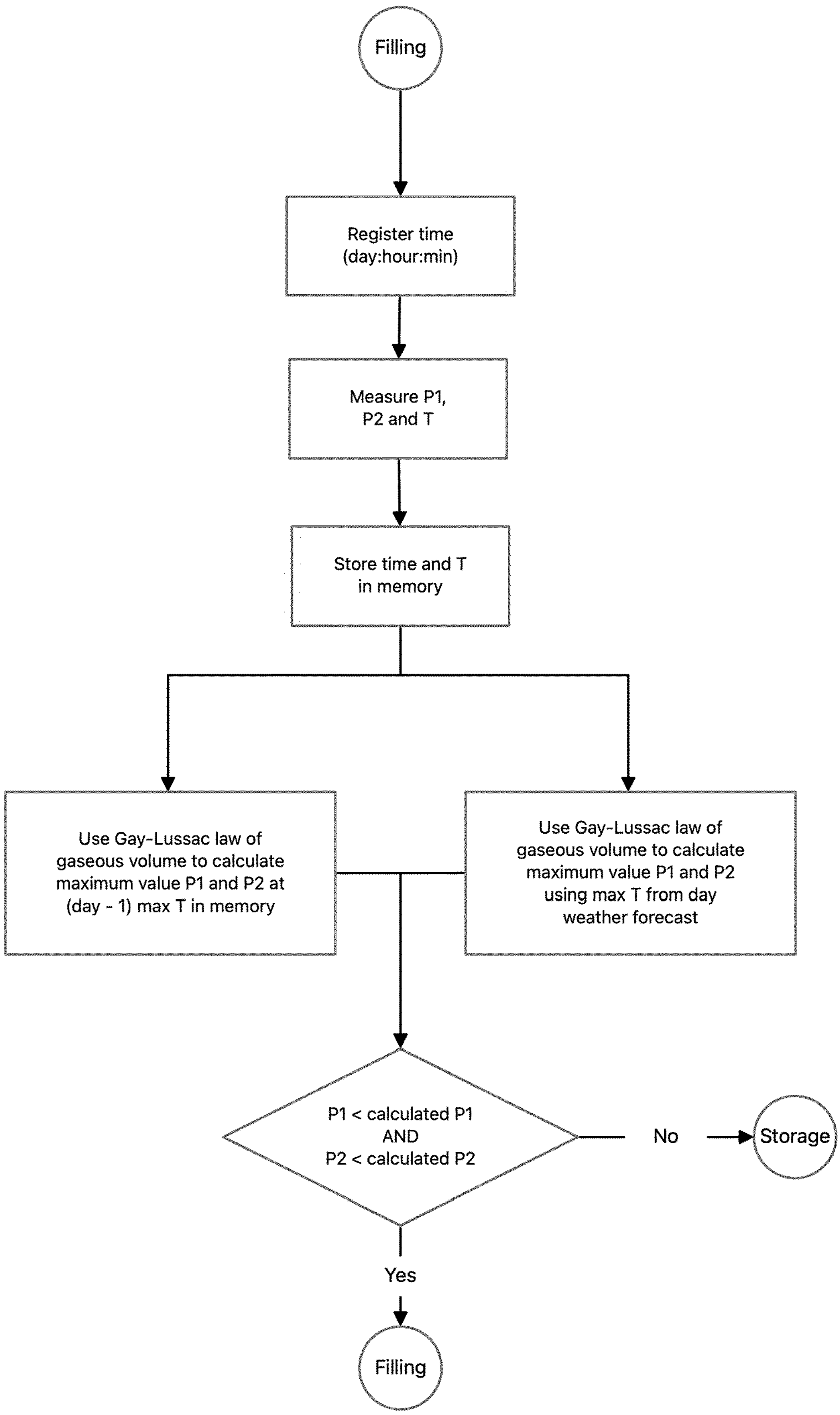
Filling
Register time
(day:hour:min)
Measure P1,
P2 and T
Store time and T
in memory
Use Gay-Lussac law of
gaseous volume to calculate
maximum value P1 and P2 at
(day - 1) max T in memory
Use Gay-Lussac law of
gaseous volume to calculate
maximum value P1 and P2
using max T from day
weather forecast
P1 < calculated P1
AND
P2 < calculated P2
No
Storage
Yes
Filling

FIG. 12

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EUROPEAN SEARCH REPORT

Application Number
EP 23 20 6703

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	15 March 2024	Fritzen, Claas

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