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(54) **SYSTEMS AND METHODS FOR HYDROGEN LIQUEFACTION**

(57) A hydrogen liquefaction system that utilizes two separate compression services, one controlled via pressure and the other via capacitance, to maintain the rotating equipment at its design point. The system also employs an intermediate flash drum to capture boil off gas and a catalyst bed to convert para-hydrogen into ortho-hydrogen. Changing pressure levels within the turbo expander loop are used to transfer hydrogen from the expander loop into the "condensate" or "feed" streams, while maintaining the "condensate" stream at a constant pressure. The system is capable of efficiently producing high-purity liquid hydrogen at a low cost, making it a valuable tool in industries such as fuel cells, energy storage, and aerospace.

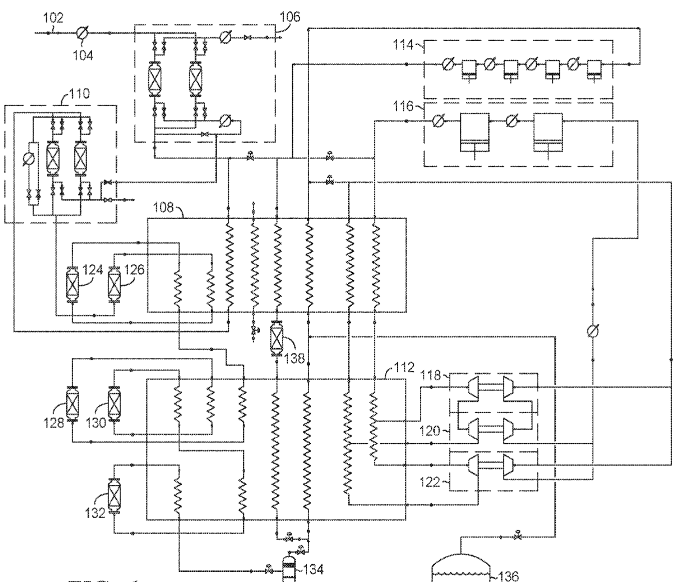


*FIG. 1.*

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## Description

TECHNICAL FIELD

**[0001]** The present invention relates generally to the field of hydrogen liquefaction systems, and in particular, to a hydrogen liquefaction system.

BACKGROUND

**[0002]** Hydrogen is an essential element in various industrial processes, and its demand continues to increase due to its use as a fuel in the transportation sector. Hydrogen is stored and transported in various forms, including liquid hydrogen.

SUMMARY

**[0003]** The present invention provides a hydrogen liquefaction system with dual compression services and turbo expanders that reduces energy consumption and increases efficiency. The system separates two compression services, where one service is connected to turbo expanders, which is controlled via pressure, while a separate compression service is also capacitive controlled at the same time. Both compression services are controlled using separate means but done in unison. The system uses changing pressure levels within the turbo expander loop to keep the rotating equipment at its design point. This is accomplished by actively transferring hydrogen from the expander loop into the condensate loop and then into the feed stream. While the pressure level of the expander stream is changed, the "condensate" stream will be maintained at a constant pressure. The system also uses an intermediate flash drum to capture boil off gas at an intermediate pressure within the liquefier process. Additionally, a section of catalyst is added to convert para-hydrogen into ortho-hydrogen, thereby increasing the efficiency of the system.

BRIEF DESCRIPTION OF THE DRAWINGS

**[0004]** Illustrative aspects are described in detail below with reference to the attached drawing figures, which are incorporated by reference herein and wherein:

FIG. 1 depicts one example system for liquefying hydrogen gas, in accordance with aspects hereof;
FIG. 2 depicts one example sub-system for liquefying hydrogen gas, in accordance with aspects hereof;;
FIG. 3 depicts one example sub-system for liquefying hydrogen gas, in accordance with aspects hereof;;
FIG. 4 depicts one example sub-system for liquefying hydrogen gas, in accordance with aspects hereof;
FIG. 5 one example sub-system for liquefying hydrogen gas, in accordance with aspects hereof; and
FIG. 6 depicts a method liquefying hydrogen gas, in accordance with aspects hereof

DESCRIPTION

**[0005]** Aspects herein relate to systems and processes for liquefying hydrogen gas. In certain aspects, systems described herein can be utilized for hydrogen gas liquefaction.

**[0006]** Certain conventional hydrogen gas liquefaction processes can include compressing hydrogen gas. However as noted above, compressing hydrogen gas in such processes is resource-intensive and inefficient. Further, in the same or other conventional processes, a refrigerant may be utilized to aid in liquefying the hydrogen gas. Yet, such processes may be slow to react to total heat load requirements in the liquefaction system, which can introduce inefficiencies into the system. Therefore, there is a need for new systems and processes for cooling hydrogen gas that are less resource-intensive and/or more efficient.

**[0007]** The high cost of producing and storing hydrogen gas presents significant issues. Hydrogen is a highly flammable and explosive gas, and it requires specialized equipment and infrastructure to produce and store it safely. The hydrogen liquefaction system described herein is designed to be energy-efficient and cost-effective, making it an attractive option for industrial processes that require the use of hydrogen gas.

**[0008]** Another issue that the present hydrogen liquefaction system solves is the low energy density of hydrogen gas. Hydrogen gas has a very low energy density compared to other fuels, which makes it difficult to store and transport. The hydrogen liquefaction system described in the claims addresses this issue by compressing and liquefying the gas, which increases its energy density and makes it easier to store and transport. This makes hydrogen gas a more practical and viable option for industrial processes that require a high energy fuel source.

**[0009]** Finally, the hydrogen liquefaction system described herein also addresses the issue of impurities and moisture in hydrogen gas. Impurities and moisture can affect the quality of the hydrogen gas and reduce its performance in industrial processes and the liquefier itself. The cryogenic adsorption system and intermediate flash drum described in the claims are designed to recover hydrogen molecules from the gas, ensuring that it is of high quality and performs optimally in the industrial process. This increases the efficiency and reliability of the industrial process, reducing costs and improving performance.

**[0010]** The systems and processes described herein can alleviate one or more of the issues described above. For instance, in aspects the system uses a combination of turbo expanders and capacitive controlled compression services. These components work together to provide an energy-efficient and cost-effective way to produce and store hydrogen gas. The system also uses changing pressure levels within the turbo-expander loop to keep the rotating equipment at its design point, which further reduces energy consumption and cost.

**[0011]** In additional aspects, the system includes a cold expander and a warm expander. The warm and cold expanders are used to recover energy from the gas and cool it to cryogenic temperatures, which increases its energy density and makes it easier to store and transport. Both Warm and Cold Expanders reduce the pressure of the process gas and heat exchange with the product gas to cool the product gas. System can entail a single expander, two expanders in series, three expanders (2 warm in series, 1 in cold) or four expanders (2 warm in series, 2 cold in series). The system also includes a hydrogen tank to store the liquefied gas, which makes it easier to transport and use in industrial processes.

**[0012]** In further aspects, the system includes a cryogenic adsorption system. The cryogenic adsorption system is designed to remove impurities and moisture from the gas. This component works to ensure that the hydrogen gas produced by the system is of high quality and performs optimally in industrial processes.

**[0013]** Additionally, the system includes an intermediate flash drum and a section of catalyst. The intermediate flash drum captures boil off gas at an intermediate pressure as the pressure of the feed liquid hydrogen is reduced at cryogenic temperatures. A section of catalyst is added to the gas stream to reverse the conversion of para-hydrogen back into ortho-hydrogen, which increases the efficiency of the process.

**[0014]** Additionally, the system described herein provides a comprehensive solution to the issues related to the production and storage of hydrogen gas. By using a combination of turbo expanders, compressors, and adsorption systems, the system provides an energy-efficient and cost-effective way to produce and store hydrogen gas. The system also addresses the issues of low energy density and impurities in the gas, ensuring that it is of high quality and performs optimally in industrial processes.

**[0015]** The systems and methods described herein relate to a hydrogen liquefaction system that separates two compression services, where one service is connected to turbo expanders that are controlled via pressure while a separate compression service is capacitive controlled. The two compression services are controlled using separate means but done in unison. This allows changing pressure levels within the turbo-expander loop to keep the rotating equipment at its design point, actively transferring hydrogen from the expander loop into the condensate loop and then into the feed stream. While the pressure level of the turbo-expander stream is changed, the "condensate" stream will be maintained at a constant pressure. The systems and method provide for the separation of the two compression services, which allows for efficient and effective control of pressure levels within the turbo-expander loop.

**[0016]** The system and methods described herein provides for the use of an intermediate flash drum to capture boil-off gas at an intermediate pressure. This allows the system to capture and reuse hydrogen and the cooling imparted therein would otherwise be lost, increasing efficiency and reducing waste. The intermediate flash drum also allows for better control of pressure levels within the system.

**[0017]** Additionally the system and methods described herein use a section of catalyst to convert para-hydrogen into ortho-hydrogen. This allows the system to operate more efficiently and effectively by reversing the heat intensive process of converting ortho-hydrogen into para-hydrogen. This allows the system to produce more liquefied hydrogen with less waste, increasing overall efficiency. For hydrogen which ends up in the tank, it must be converted to para-hydrogen for effective storage. The current description adds catalyst on the gas leaving the flash drum as that gas would have already been converted to para hydrogen but because it flashed it will not go to the tank and thus can be converted back to ortho-hydrogen, improving energy efficiency.

**[0018]** FIG. 1 schematically depicts one example system 100 for cooling hydrogen gas. It should be understood that the system 100 depicted in FIG. 1 is provided schematically to highlight the connections between various components of the system 100. It should also be understood that the system 100 depicted in FIG. 1 is but one example system and that other systems for cooling hydrogen gas are also contemplated by the disclosure herein. In the aspect depicted in FIG. 1, the system 100 can include a hydrogen gas source 102, a cooler 104, an adsorption system 106, a heat exchanger 108, a cryogenic adsorption system 110, heat exchanger 112, a condensate compressor 114, recycle compressor 116, warm expander 118, warm expander 120, cold expander 122, catalyst beds 124 -132, flash tank 134, a storage tank 136, and adsorbent bed 138.

**[0019]** In aspects, the hydrogen gas sources 102 can include any convenient source of hydrogen gas that is desirable to expose to a cooling process. In one aspect, the hydrogen gas sources 102 can include any hydrogen gas source is the origin of the hydrogen that is used as the feedstock for the liquefaction system. The hydrogen gas source 102 can be any facility or process that produces hydrogen gas, such as a chemical plant or a hydrogen production plant. Hydrogen can be produced from a variety of sources, including natural gas, coal, biomass, and electrolysis of water. The purity of the hydrogen gas source can vary depending on the production process and the intended use. In various aspects, the hydrogen gas source 102 can be at a pressure of between atmospheric pressure and 50 bar.

**[0020]** In certain aspects as discussed above, the adsorption system 200 can remove the impurities of at least a portion of the hydrogen gas source 102. The initial hydrogen gas source 102 and every portion prior to the flash drum 134 may be called the feed stream.

**[0021]** In certain aspects as discussed above, the hydrogen gas liquefier can include an adsorption system 106 as depicted in FIG. 1 and FIG. 2. Adsorption system 106 is a type of gas separation system that uses adsorption technology to selectively remove or retain specific components of a gas stream. The system works by exposing the gas stream to a solid material, known as an adsorbent, which has a high surface area and affinity for certain components of the gas mixture.

**[0022]** As the hydrogen source 102 passes through the adsorption system 106, the targeted components are selectively adsorbed onto the surface of the adsorbent material. This results in a separation of the gas mixture into two or more streams, each with a different composition. The adsorption process can be controlled by adjusting the temperature, pressure, and flow rate of the gas streams.

**[0023]** The performance of an adsorption system depends on the specific adsorbent material used, as well as the operating conditions of the system. Adsorbent materials can vary widely in their chemical and physical properties, such as surface area, pore size distribution, and selectivity for certain components. The choice of adsorbent material depends on the specific application and the desired separation performance.

**[0024]** Turning now to FIG. 2 which depicts a schematic diagram of an exemplary adsorption system 200 according to aspect herein. The adsorption system 200 provides an example schematic of the adsorption system 106. A hydrogen feedstock gas enters the adsorption system 200 and initially pass through one or more valves 202 or 206. Upon passing through one or more valves, the hydrogen feedstock pass through an adsorption bed 204. Adsorption bed 204 is a vessel or container designed to hold an adsorbent material, which is a substance capable of adsorbing (collecting) other substances on its surface. In the case of an adsorption system 200 for hydrogen gas, the adsorbent material may be activated carbon or a zeolite material, which can selectively adsorb non-hydrogen gases from a mixed gas stream.

**[0025]** The adsorption bed 204 consists of a cylindrical vessel filled with the adsorbent material, which is typically in the form of small beads or pellets. The adsorbent material is packed tightly into the vessel, with spaces between the beads to allow for the flow of gas. The vessel may be insulated to maintain a low temperature, as adsorption of some molecules occurs more readily at lower temperatures.

**[0026]** In operation, the hydrogen gas source 102 is passed through the adsorption bed 204, and the adsorbent material collects the impurities while allowing hydrogen gas to pass through. The adsorption process is reversible, so the adsorbent material can be regenerated by passing a separate gas stream through the bed that desorbs the other gasses. This regeneration process typically involves heating the adsorbent material to a higher temperature and/or lower pressure to release the collected gas. This can be done using valves 202 and 206 in such a way as to allow the hydrogen gas to pass down from the adsorption system 200 and any impurity gas to be removed through valve 210 and cooler 208.

**[0027]** Returning now to FIG. 1, the gas feedstock, which now is primarily hydrogen gas, passes from the adsorption system 106 to the heat exchanger 108. The heat exchanger 108 can be any convenient type of heat exchanger as long as such a heat exchanger is compatible with hydrogen gas liquefying. In operation, in certain aspects, the heat exchanger 108 is adapted to transfer heat from the hydrogen gas to an external heat sink such as liquid nitrogen, thereby cooling the hydrogen gas while also warming up the liquid nitrogen and, in aspects, forming gaseous nitrogen. In aspects, the heat exchanger 108 can be in fluid communication with the one or more hydrogen gas sources via the hydrogen gas conduit or line 302, 303, 312, 316, or 314. In various aspects, the heat exchanger 108 can be in fluid communication with one or more liquid nitrogen output conduits, e.g., the liquid nitrogen output conduit 310, which may ultimately supply liquid nitrogen to the heat exchanger 108. In other aspects, the external heat sink may be other cryogenic gases, liquids, or mixtures thereof.

**[0028]** As depicted in FIG. 3 the heat exchanger 108 provides cooling to hydrogen gas coming from the adsorption system 200 or 106 through line 302. As the gas passes from line 302 through the heat exchanger 108 the gas is cooled. From there, the gas moves on to line 306 to be further purified by the cryogenic adsorption system 110 as described in FIG. 5. The line 306 feeds into line 502 of FIG. 5. From there the hydrogen gas is fed into the cryogenic adsorption system 500.

**[0029]** Cryogenic adsorption system 500 is a type of gas separation system that uses cryogenic temperatures and adsorption technology to separate gas mixtures. The system is often used in industrial applications to separate and purify gases such as nitrogen, oxygen, argon, and hydrogen. The cryogenic adsorption system 500 consists of a number of adsorption beds 508, which are filled with a porous material, such as activated carbon, zeolite, or molecular sieves. The gas mixture is passed through the adsorption bed 508, where the different components of the hydrogen gas are selectively adsorbed onto the surface of the porous material. The adsorption process is typically controlled by adjusting the temperature and pressure within the system using valves 504 and 506. In operation, the hydrogen gas source 102 is passed through the adsorption bed 508, and the adsorbent material collects the hydrogen gas or the impurities while allowing other gases or hydrogen gas to pass through. The adsorption process is reversible, so the adsorbent material can be regenerated by passing a separate gas stream through the bed that desorbs the impurities . This regeneration process typically involves heating the adsorbent material to a higher temperature and/or lower pressure to release the collected gas. This can be done using valves 504 and 506 in such a way as to allow the hydrogen gas to pass down from the adsorption system 500 and any impurity gas to be removed through valve 510. In this process, the subject hydrogen gas is exposed or processed at cryogenic temperatures but remains in the gas phase.

**[0030]** Turning back to FIG. 1, the hydrogen gas that leaves the cryogenic adsorption system 110 moves into catalyst beds 124 and 126. Catalyst bed 124 and 126 are chambers or vessels containing a solid material called a catalyst, which is used to promote a chemical reaction by reducing the activation energy required for the reaction to occur. Catalyst beds 124 and 126 may be a fixed bed reactor filled with a solid catalyst material. The catalyst beds 124 and 126 are designed to facilitate the chemical reaction that converts ortho-hydrogen into para-hydrogen. This reaction involves flipping the quantum spin state of the hydrogen atoms from an ortho configuration to a para configuration. The catalyst beds 126 and 126 may comprise a variety of materials such as ferric oxide. In another aspect, the catalyst may be contained within the heat exchanger 108.

**[0031]** Turning now to FIG. 3, the hydrogen feed line 308 allow the hydrogen gases to pass through the catalyst beds 124 and 126 and the heat exchanger 108. This promotes the conversion of any ortho-hydrogen existing in the feedstock into para-hydrogen. All while being cooled such as to increase the amount of liquid hydrogen in the line 318. After passing through the heat exchanger 108, the feedstock passes through a series of lines such as line 304, which passes through heat exchanger 112. The lines are allowed to pass through catalyst beds 128, 130, and 132 which operate and are structured similarly to catalyst beds 124 and 126 described above. The feedstock makes one additional pass through the heat exchanger 112 before exiting to valve 318. The feedstock at this point has a high ratio of liquid hydrogen to gaseous hydrogen.

**[0032]** The feedstock that is now primarily hydrogen in the liquid form is passed through valve 318 into flash drum 134. Flash drum 134 is a type of separator used in chemical processes to separate liquid from gas. Flash drum 134 operates under a lower pressure than the upstream system. Flash drum 134 is used to capture boil off gas at an intermediate pressure. This stream is blended with the condensate stream, warmed, compressed, then a slipstream is fed back to the feedgas to be liquefied. This process helps to reduce the amount of hydrogen gas lost during the liquefaction process, which is important in terms of cost and efficiency. The gaseous hydrogen captured by the flash drum 134 is passed through valve 320 and back into the heat exchanger 112 in line 304 and on to heat exchanger 108 through line 312. In some aspects, the gaseous hydrogen may be passed through catalyst to convert para-hydrogen back to ortho-hydrogen while in heat exchanger 108 to increase the efficiency of the system.

**[0033]** Turning back to FIG. 1, the hydrogen boil off gas that was captured by flash drum 134 is now passed through heat exchanger 112 and 108 and then into condensate compressor 114. Condensate compressor 114 is a type of compressor used in gas processing systems to increase the pressure of a gas. The condensate compressor 114 may be a reciprocating compressor, screw compressor, or a centrifugal compressor.

**[0034]** Turning now to FIG. 4, the boil off gas captured by the flash drum 134 is carried using line 312 and 402 into the condensate compressor 114. The condensate compressor 114 is responsible for compressing the condensate hydrogen back to a desired pressure. This is achieved using a series of compressors 404 and a series of coolers 406.

**[0035]** Initially, the hydrogen from the flash drum 134 enters a compressor 404 where the hydrogen is compressed to a higher pressure. The line is then fed into a cooler 406 where it is cooled further to a lower temperature. The cooled hydrogen then enters another compressor 404 where it is compressed to a higher pressure. The compressed hydrogen then exits the first compressor and enters another cooler 406 where it is cooled further again. This process is repeated with a series of compressors 404 and coolers 406 until the hydrogen is compressed to the desired pressure. The series of compressors 404 and coolers 406 allow for efficient compression of the hydrogen while minimizing the energy required for the process. Additionally, the use of multiple compressors 404 and coolers 406 allows for better control over the compression process and ensures that the hydrogen is compressed to the desired pressure with high accuracy as well as mechanical and thermal limitations of the equipment. The hydrogen stream exits the condensate compressor 114 through lines 302, 303, or 314.

**[0036]** Turing now to FIG. 1, the stream exits the condensate compressor and a slipstream of hydrogen is allowed to enter back into the upstream system and mixed in line 302 to be processed again. The gaseous hydrogen is passed through the heat exchanger 108 and 112 and into the condensate valve 320. As shown in FIG. 3, the hydrogen feed comes from the condensate compressor 114 and enters the heat exchanger 108 by means of lines 304 or 303. A series of valves upstream of this process determines where the feed goes making it either proceed through line 303 and onto the adsorbent bed 138 or line 312 and onto the condensate valve 320. The adsorbent bed 138 removes any impurities and then sends the stream through heat exchanger 112 and through valve 320 to be processed again by the condensate compressor 114.

**[0037]** A control system for regulating the pressure of the compressed hydrogen in the system involves multiple components, such as pressure sensors, valves, and controllers such as valves 318, 320, 322, and 324. Components 318, 320, 322, and 324 may be pressure sensors, valves, controllers, pressure regulators, or any other component that is designed to regulate or control the pressure of the system. The system is designed to ensure that the pressure and volumetric flow within the turbo-expander loop remains within a specified range to keep the rotating equipment operating at its design point.

**[0038]** The control system may use feedback from pressure sensors located at various points in the system to monitor the pressure levels. Based on the readings, the system can adjust the flow of hydrogen into or out of the turbo-expander loop using control valves. In this way, the system can actively transfer hydrogen from the expander loop into the "condensate" or "feed" streams to maintain the pressure level within the specified range.

**[0039]** The control system may also include controllers that are programmed to adjust the valves based on the feedback from the pressure sensors. The controllers may use algorithms to ensure that the valves are adjusted in the most efficient manner to maintain the desired pressure levels.

**[0040]** In addition to regulating the pressure, the control system may also monitor other parameters such as temperature, flow rate, and composition of the hydrogen stream. By continuously monitoring and adjusting the system parameters, the control system can maintain the hydrogen liquefaction system in an optimal operating condition, ensuring maximum efficiency and reliability.

**[0041]** Turbo-expanders 118-122 are used to convert the energy of a high-pressure gas from the condensate compressor into mechanical work. In this system, the turbo expanders 118-122 cool the hydrogen gas as it expands through a series of turbines or expanders. As the hydrogen gas expands, it loses energy and its temperature drops, which causes it to cool down.

**[0042]** The cooled hydrogen gas is then fed into heat exchanger 112 and is warmed in 112 and 108 to cool the feed hydrogen. Once it has passed through 108 it will be near ambient temperature and be recompressed in 116. Low pressure gaseous hydrogen is passed through a recycle compressor 116 that, as shown if FIG. 4 has a series of coolers 406 and compressors 412 to re-pressurize the gaseous hydrogen and is fed back into the turbo-expanders 118-122. If the hydrogen is allowed to go into line 314 the hydrogen proceeds through heat exchanger 108 and 112 and into one or more turbo-expander 118 or 122. In one example, the hydrogen is passed into a single turbo-expander such as turbo expander 122. In other examples such as shown in FIG. 3, there is a series of turbo-expanders that process the hydrogen.

**[0043]** One or more of the turbo-expanders 118-122 may also be a cryogenic expander which is a type of expansion turbine commonly used in industrial processes for the purpose of removing mechanical energy from the expansion of low-temperature gas streams to reduce the temperature of the stream further. The mechanical energy is dissipated through a shaft driven compressor, oil brake, generator, or other means. The one or more turbo-expanders 118-122 may operate in series, parallel or independently.

**[0044]** In aspects related to FIG. 1, liquid hydrogen is directed to storage tank 136 to be stored for later use. Storage tank 136 may be a specialized storage vessel used to store liquid. Low-temperature hydrogen tanks, also known as cryogenic tanks, are used to store hydrogen liquid at temperatures, typically below -253°C, which is the boiling point of hydrogen. These tanks are commonly used in the storage and transportation of liquefied hydrogen, which is a more compact and energy-dense form of hydrogen that can be used in certain industrial applications, such as rocket propulsion or as a fuel for hydrogen-powered vehicles. Storage tank 136 may include various safety features to prevent leaks or ruptures, including pressure relief valves, rupture disks, and other safety devices. Additional boil-off gas from within the storage tank 136 may be directed back into the processing system if the pressure of the storage tank 136 exceeds a pre-determined threshold.

**[0045]** In the disclosed hydrogen liquefaction system described in relation to FIGs. 1-4, two compression services are utilized, each controlled by separate means, but working in unison. The first compression service is controlled through pressure, while the second is capacitive controlled.

**[0046]** The pressure control works by actively transferring hydrogen from the expander loop to the condensate loop then to the feed streams to maintain a constant pressure in the condensate stream. This allows the rotating equipment, such as the turbo expanders, to maintain their design point such as volumetric flow as the pressure level in the expander stream changes. The turboexpanders 118-122 and recycle compressor 116 have varying pressures but their inlets/outlets are kept at a constant pressure ratio from one another.

**[0047]** On the other hand, the capacitive control works by monitoring the temperature throughout the system or the pressure of the expander loop and adjusting the capacitive control system accordingly. The capacitive control system maintains a constant suction and discharge pressure on the condensate compressor 114. This ensures that the hydrogen liquid content concentration in the condensate valve 322 stays within the required range for efficient operation of the liquefaction system.

**[0048]** The pressure control in the system regulates the flow of hydrogen through the turbo-expanders 118-122, which are critical components in the liquefaction process. The pressure control system ensures that the turbo-expanders operate at their design points by maintaining a constant pressure ratio across the turbo-expanders 118-122. This is accomplished by actively transferring hydrogen from the expander loop into the condensate loop then to the feed streams.

**[0049]** The capacitive control system works in tandem with the pressure control system to ensure optimal operating conditions. The capacitive control system maintains the condensate stream at a constant pressure to keep the condensate above its critical pressure. This ensures that the condensate remains in its liquid state prior to 322, which is essential for the liquefaction process.

**[0050]** The two control systems work together to ensure the optimal performance of the hydrogen liquefaction system. The capacitive control system helps to maintain the proper hydrogen pressure above critical pressures but at varying flows, while the pressure control system keeps the rotating equipment operating at its optimal conditions. The use of separate control systems for each compression service ensures that the system can adjust to changes in operating conditions quickly and efficiently, providing for a highly effective and reliable hydrogen liquefaction system. The changing pressure levels within the turbo-expander loop may be achieved through the use of a pressure regulator.

**[0051]** FIG. 6 depicts one example method 600 for cooling hydrogen gas. The method 600 can include the step 610 of receiving a first volume of hydrogen gas at a feedstock pressure. In aspects, the hydrogen gas can include any or all of the properties and parameters discussed above with respect to the one or more hydrogen gas sources of FIG. 1. In certain aspects, the hydrogen gas can be received via one or more of the boil-off gas input conduits such as collected by the flash drum 134 discussed above.

**[0052]** The method 600 can also include a step 620 of directing the feedstock into an adsorption system that includes an adsorption bed and a catalyst bed. The adsorption system is configured to separate the hydrogen gas from other gases and may include catalyst beds to convert ortho-hydrogen into para-hydrogen. The method 600 can include a step 630 of transferring the purified hydrogen gas into a hydrogen liquefaction system that includes at least two compression services. One of the compression services is connected to turbo expanders that are controlled via pressure. The other compression service is capacitive controlled. Both compression services are controlled separately but in unison.

**[0053]** Further, the capacitive control of the second compression service is achieved through a variable frequency drive. In another aspect, the capacitive control of the second compression service is achieved through variable clearance pockets. In another aspect, the capacitive control of the second compression service is achieved through controlled compressor suction valves.

**[0054]** The method 600 can also include step 640 which can use the changing pressure levels within the turbo-expander loop such as turbo-expanders 118-122 to keep the rotating equipment at its design point. This is accomplished by actively transferring hydrogen from the expander loop into the "condensate" or "feed" streams. While the pressure level of the expander stream is changed, the "condensate" stream will be maintained at a constant pressure.

**[0055]** Further in aspects, a flash drum is used to capture intermediate pressure boil off gas at step 650. After the intermediate flash drum, in several steps as described herein, at step 660 catalyst beds are used to convert para-hydrogen into ortho-hydrogen. Additionally, a series of compressors 404 and a series of coolers 406 are provided to compress and condense the hydrogen gas. The compressors and coolers may be arranged in any suitable configuration, such as a series or parallel arrangement, to provide the desired level of compression and cooling. Finally, the liquefied hydrogen is stored in a hydrogen tank for later use.

**[0056]** The method 600 further comprises the section of catalyst for converting para-hydrogen into ortho-hydrogen wherein the first and second compression services are controlled using separate means but done in unison; wherein the apparatus is configured to operate within a temperature range of -150°C to -253°C and a pressure range of 1 bar to 50 bar. Additionally, the flash drum operates at a pressure range of 1-3 bar or 0.5-4 bar.

**[0057]** From the foregoing, it will be seen that this disclosure is one well adapted to attain all the ends and objects hereinabove set forth together with other advantages which are obvious and which are inherent to the structure.

**[0058]** It will be understood that certain features and subcombinations are of utility and may be employed without reference to other features and subcombinations. This is contemplated by and is within the scope of the claims.

**[0059]** While specific elements and steps are discussed in connection to one another, it is understood that any element and/or steps provided herein is contemplated as being combinable with any other elements and/or steps regardless of explicit provision of the same while still being within the scope provided herein. Since many possible embodiments may be made of the disclosure without departing from the scope thereof, it is to be understood that all matter herein set forth or shown in the accompanying drawings is to be interpreted as illustrative and not in a limiting sense.

**[0060]** Example embodiments are mentioned below.

**[0061]** [Embodiment 1]: A system for hydrogen gas liquefaction, the system comprising:

a first compression service connected fluidically to a turbo expander, wherein a first pressure within the turbo expander is controlled to maintain a constant pressure ratio;

a second compression service controlled via capacitive control;

means for actively transferring hydrogen from the expander loop into the feed streams via a condensate loop, thereby changing pressure levels within the turbo expander loop;

an intermediate flash drum for capturing boil off gas at an intermediate pressure; and

wherein the first and second compression services are controlled using separate means but done in unison.

**[0062]** [Embodiment 2] The system according to embodiment 1, wherein the first compression service comprises a reciprocating compressor.

**[0063]** [Embodiment 3] The system according to embodiment 2, wherein the second compression service comprises a reciprocating compressor.

**[0064]** [Embodiment 4] The system according to embodiment 3, wherein the system further comprises one or more turbo expanders that are arranged in a series configuration.

**[0065]** [Embodiment 5] The system according to embodiment 4, wherein the system further comprises a cooling system that cools the compressed hydrogen to a temperature below its boiling point.

**[0066]** [Embodiment 6] The system according to embodiment 1, wherein the system further comprises a control system that regulates the pressure of the compressed hydrogen.

**[0067]** [Embodiment 7] The system according to embodiment 6, wherein the system further comprises a section of catalyst for converting para-hydrogen into ortho-hydrogen.

**[0068]** [Embodiment 8] The system according to embodiment 7, wherein the system further comprises a recycle compressor that compresses the hydrogen that has not been liquefied.

**[0069]** [Embodiment 9] A method for liquefying hydrogen gas, the method comprising:

providing a first compression service connected to a turbo expander loop, wherein the turbo expander is controlled via pressure;
providing a second compression service controlled via capacitive control;
actively transferring hydrogen from the turbo expander loop into a feed stream, thereby changing pressure levels within the turbo expander loop;
maintaining the condensate stream at a constant pressure while the pressure level of the expander stream is changed;
capturing boil off gas at an intermediate pressure in an intermediate flash drum; and
wherein the first and second compression services are controlled using separate means but done in unison.

**[0070]** [Embodiment 10] The method according to embodiment 9, wherein the capacitive control of the second compression service is achieved through a variable frequency drive.

**[0071]** [Embodiment 11] The method according to embodiment 9, wherein the capacitive control of the second compression service is achieved through variable clearance pockets.

**[0072]** [Embodiment 12] The method according to embodiment 9, wherein the second compression service is achieved through controlled compressor suction valves.

**[0073]** [Embodiment 13] The method according to embodiment 9, wherein the method further comprises a heat exchanger that exchanges heat between the compressed hydrogen and a coolant fluid. [Embodiment 14] The method according to embodiment 9, wherein the system further comprises a control system that regulates the pressure of the compressed hydrogen.

**[0074]** [Embodiment 15] The method according to embodiment 9, wherein the system further comprises a recycle compressor that compresses the hydrogen that has not been liquefied.

**[0075]** [Embodiment 16] The method according to embodiment 9, wherein the intermediate flash drum operates at a pressure of between about 1 and 3 bar.

**[0076]** [Embodiment 17] An apparatus for liquefying hydrogen comprising:

a first compression service connected to a turbo expander, wherein the turbo expander is controlled via pressure;
a second compression service controlled via capacitive control; means for actively transferring hydrogen from the expander loop into a feed stream, thereby changing pressure levels within the turbo-expander loop;
an intermediate flash drum for capturing boil off gas at an intermediate pressure;
and a section of catalyst for converting para-hydrogen into ortho-hydrogen; wherein the first and second compression services are controlled using separate means but done in unison; wherein the apparatus is configured to operate within a temperature range of -150°C to -253°C and a pressure range of 1 bar to 50 bar.

**[0077]** [Embodiment 18] The apparatus of embodiment 17, wherein the changing pressure levels within the turbo-expander loop are achieved through the use of a pressure regulator.

**[0078]** [Embodiment 19] The apparatus of embodiment 17, wherein the first compression service comprises a reciprocating compressor.

**[0079]** [Embodiment 20] The apparatus of embodiment 17, wherein the second compression service comprises a reciprocating compressor.

## Claims

**1.** A system for hydrogen gas liquefaction, the system comprising:

a first compression service connected fluidically to a turbo expander, wherein a first pressure within the turbo expander is controlled to maintain a constant pressure ratio;
a second compression service controlled via capacitive control;
means for actively transferring hydrogen from the expander loop into the feed streams via a condensate loop, thereby changing pressure levels within the turbo expander loop;
an intermediate flash drum for capturing boil off

gas at an intermediate pressure; and
wherein the first and second compression services are controlled using separate means but done in unison.

**2.** The system according to claim 1, wherein the first compression service comprises a reciprocating compressor.

**3.** The system according to claim 2, wherein the second compression service comprises a reciprocating compressor.

**4.** The system according to claim 3, wherein the system further comprises one or more turbo expanders that are arranged in a series configuration.

**5.** The system according to claim 4, wherein the system further comprises a cooling system that cools the compressed hydrogen to a temperature below its boiling point.

**6.** A method for liquefying hydrogen gas, the method comprising:

providing a first compression service connected to a turbo expander loop, wherein the turbo expander is controlled via pressure;
providing a second compression service controlled via capacitive control;
actively transferring hydrogen from the turbo expander loop into a feed stream, thereby changing pressure levels within the turbo expander loop;
maintaining the condensate stream at a constant pressure while the pressure level of the expander stream is changed;
capturing boil off gas at an intermediate pressure in an intermediate flash drum; and
wherein the first and second compression services are controlled using separate means but done in unison.

**7.** The method according to claim 6, wherein the capacitive control of the second compression service is achieved through a variable frequency drive.

**8.** The method according to claim 6, wherein the capacitive control of the second compression service is achieved through variable clearance pockets.

**9.** The method according to claim 6, wherein the second compression service is achieved through controlled compressor suction valves.

**10.** The method according to claim 6, wherein the method further comprises a heat exchanger that exchanges heat between the compressed hydrogen and a coolant fluid.

**11.** The method according to claim 6, wherein the system further comprises a control system that regulates the pressure of the compressed hydrogen.

**12.** An apparatus for liquefying hydrogen comprising:

a first compression service connected to a turbo expander, wherein the turbo expander is controlled via pressure;
a second compression service controlled via capacitive control; means for actively transferring hydrogen from the expander loop into a feed stream, thereby changing pressure levels within the turbo-expander loop;
an intermediate flash drum for capturing boil off gas at an intermediate pressure;
and a section of catalyst for converting para-hydrogen into ortho-hydrogen; wherein the first and second compression services are controlled using separate means but done in unison;
wherein the apparatus is configured to operate within a temperature range of -150°C to -253°C and a pressure range of 1 bar to 50 bar.

**13.** The apparatus of claim 12, wherein the changing pressure levels within the turbo-expander loop are achieved through the use of a pressure regulator.

**14.** The apparatus of claim 12, wherein the first compression service comprises a reciprocating compressor.

**15.** The apparatus of claim 12, wherein the second compression service comprises a reciprocating compressor.

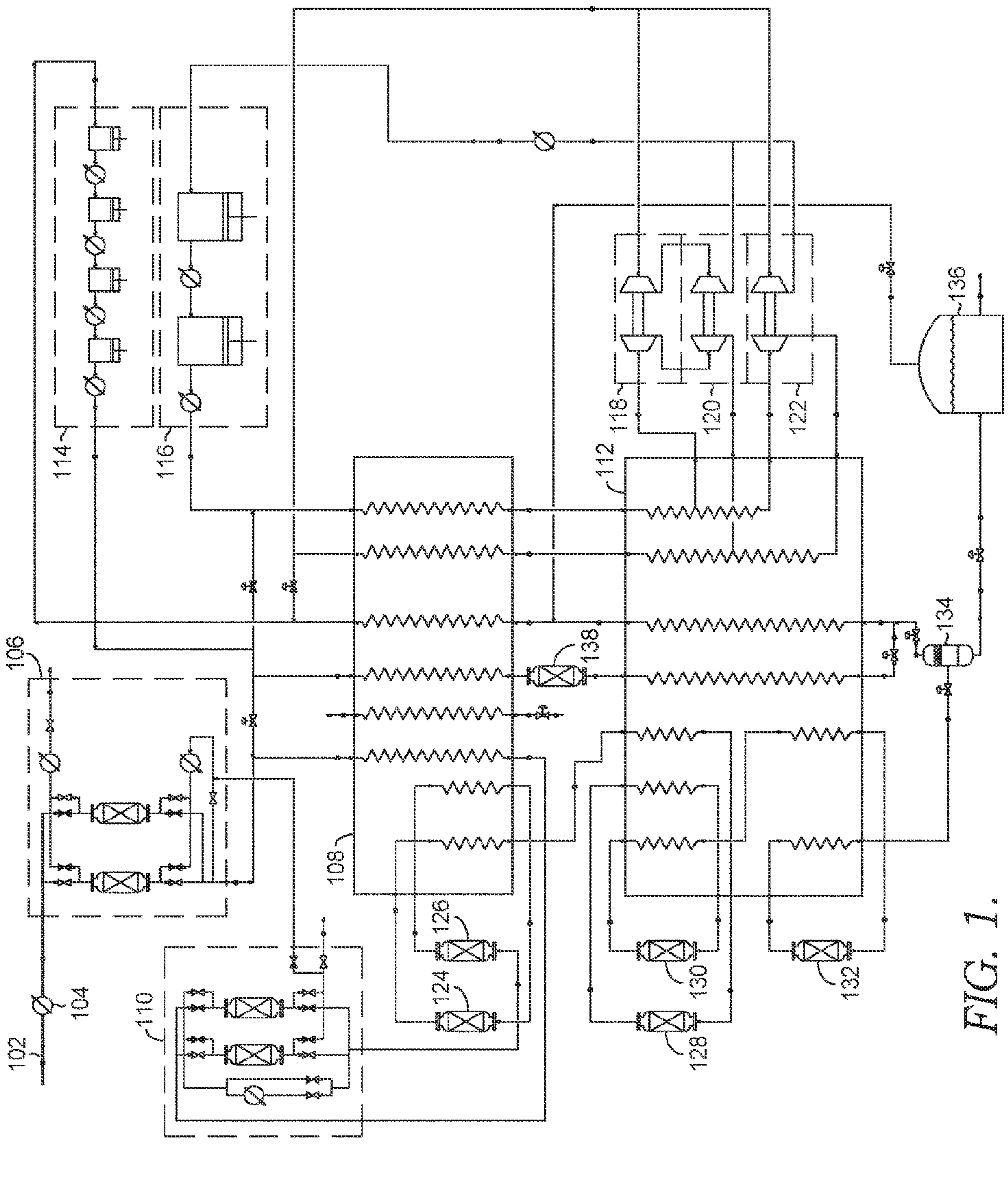
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FIG. 1.

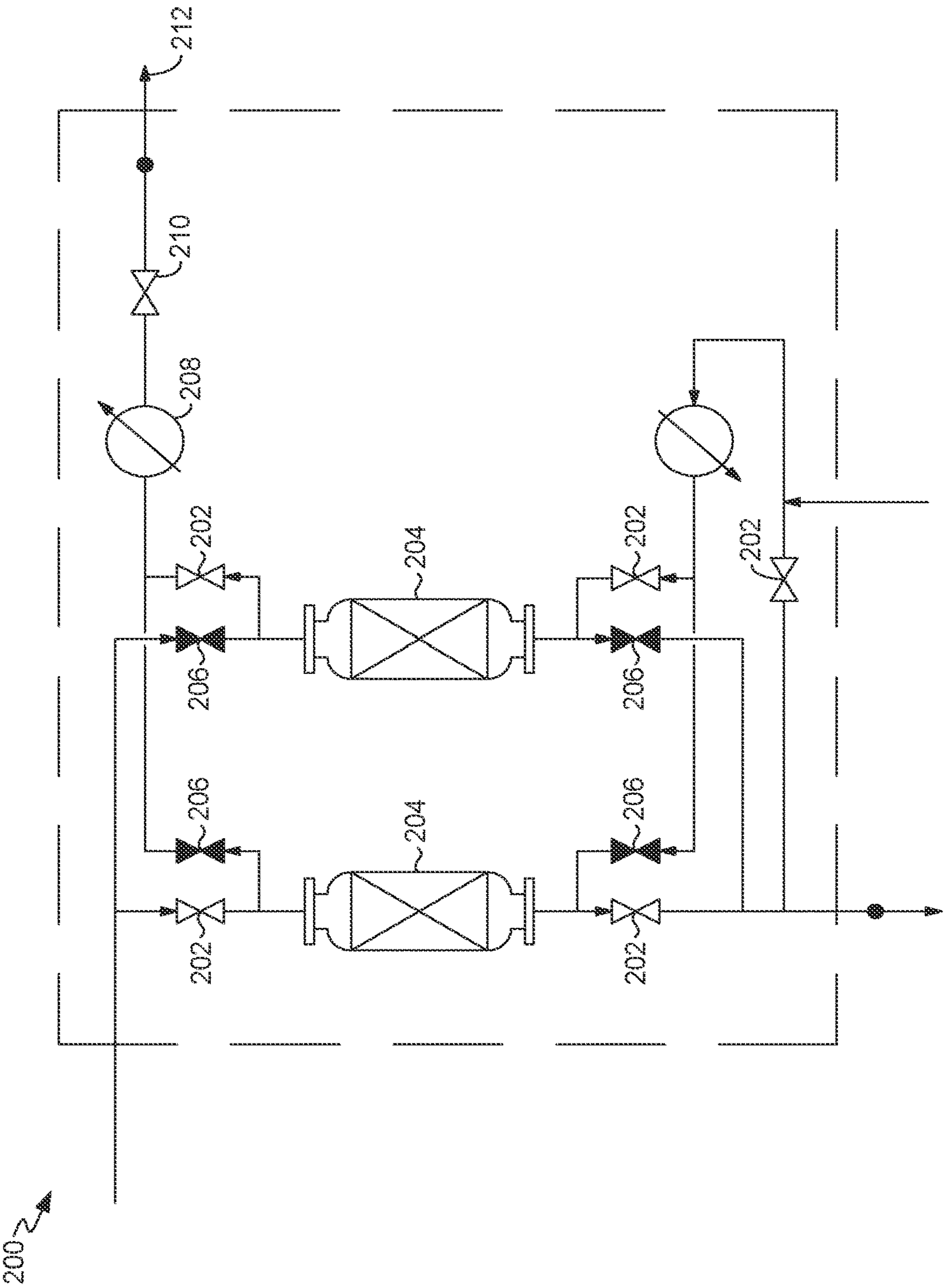


FIG. 2.

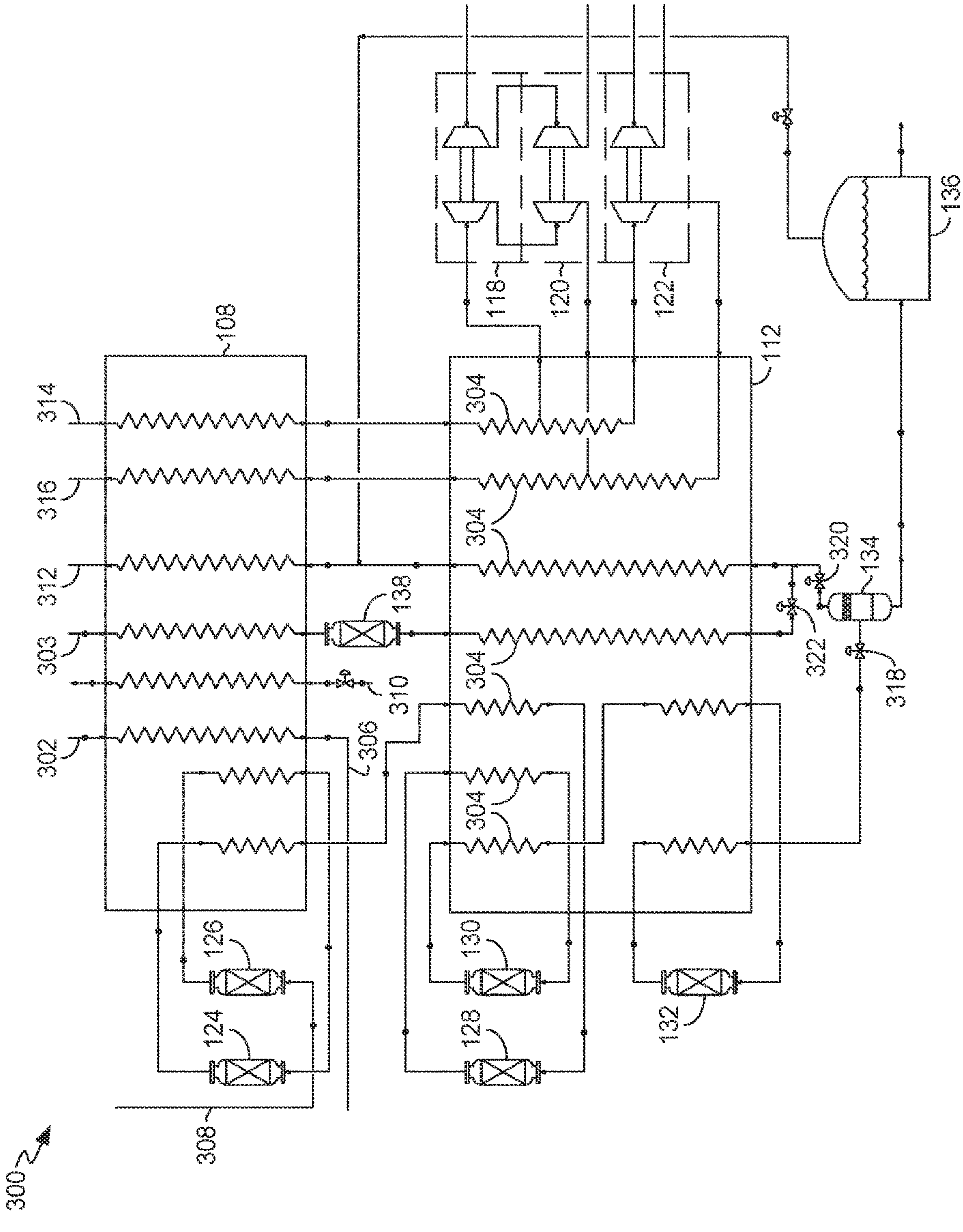
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FIG. 3.

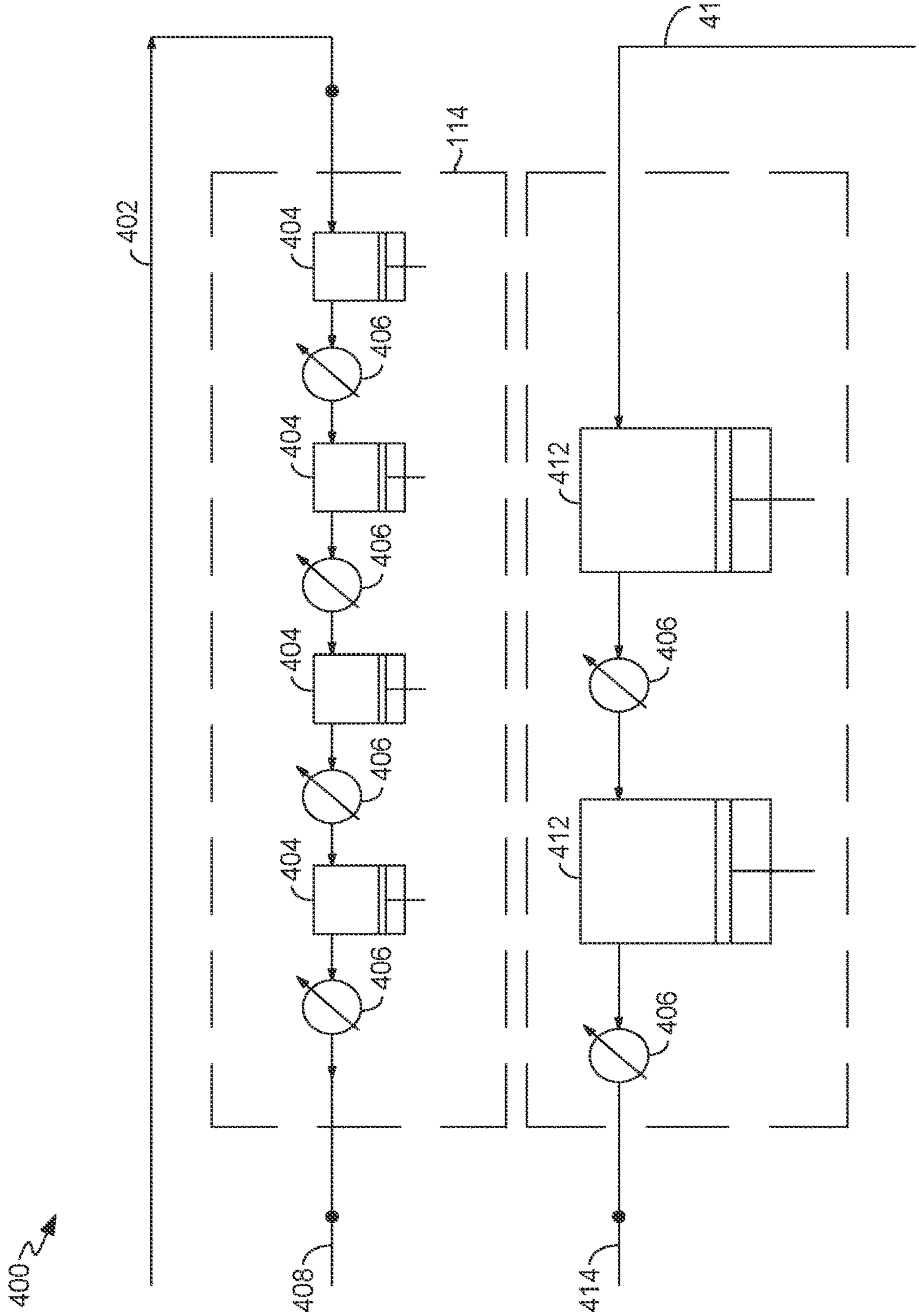
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FIG. 4.

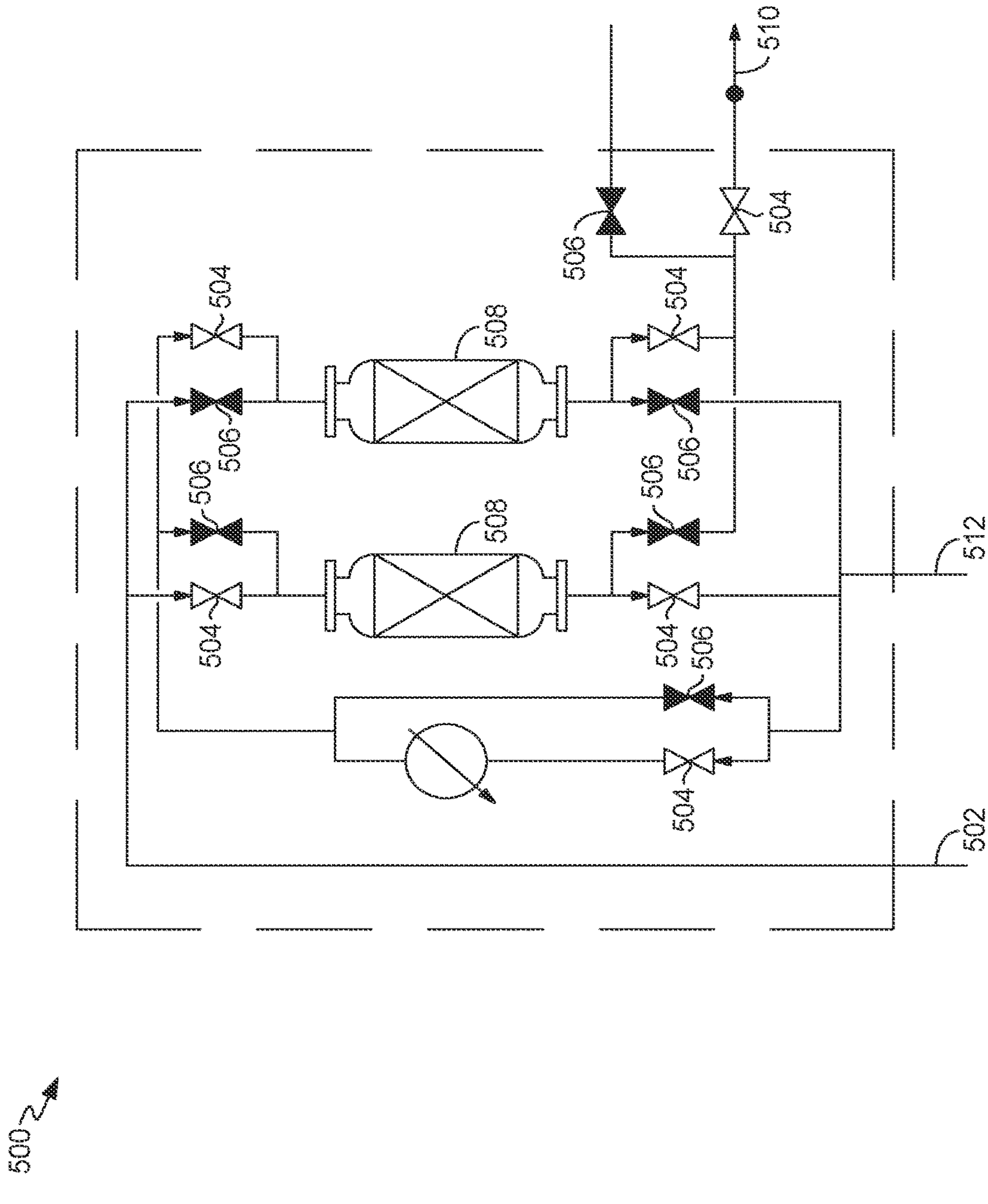
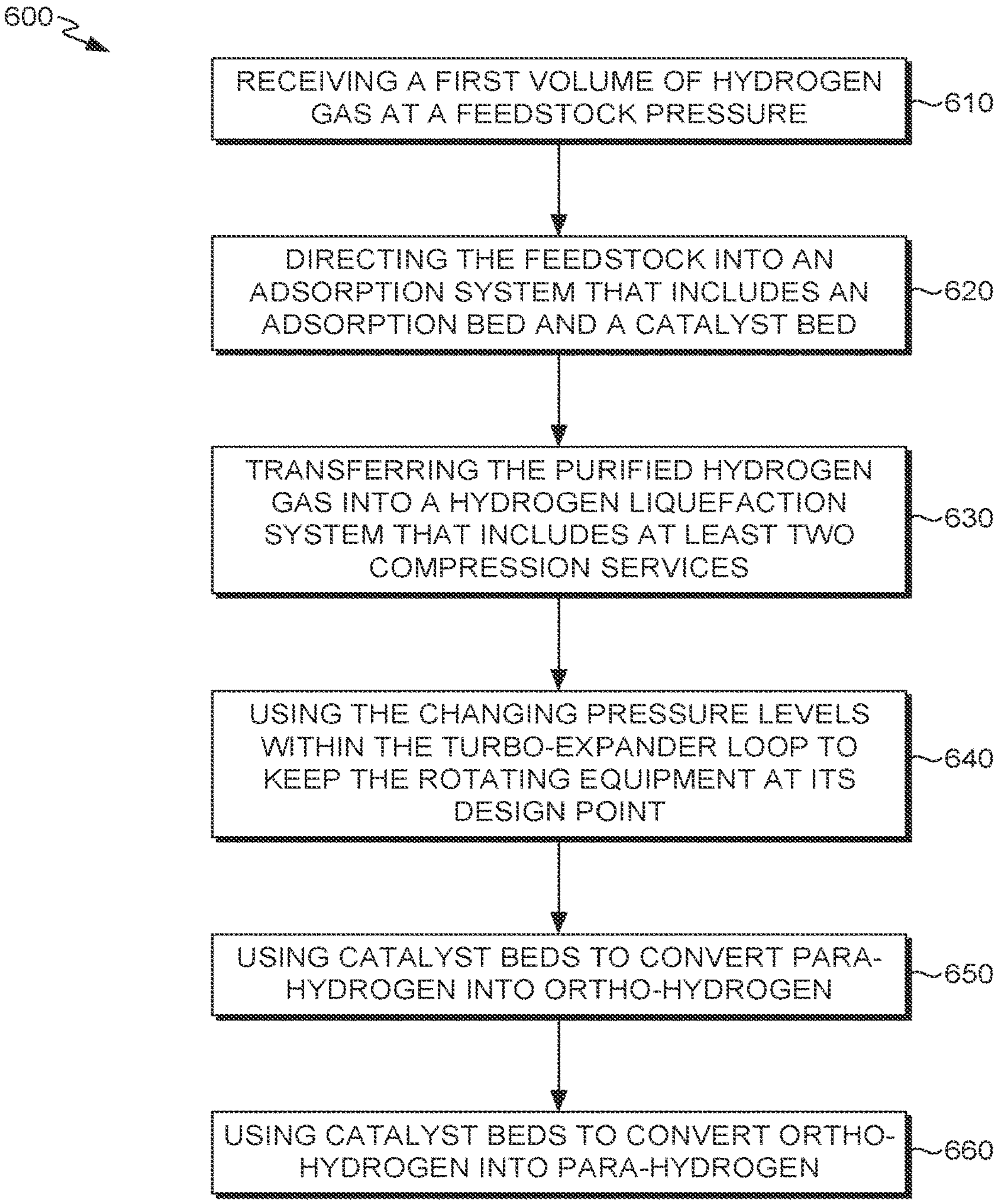



FIG. 5.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RECEIVING A FIRST VOLUME OF HYDROGEN GAS AT A FEEDSTOCK PRESSURE
610
DIRECTING THE FEEDSTOCK INTO AN ADSORPTION SYSTEM THAT INCLUDES AN ADSORPTION BED AND A CATALYST BED
620
TRANSFERRING THE PURIFIED HYDROGEN GAS INTO A HYDROGEN LIQUEFACTION SYSTEM THAT INCLUDES AT LEAST TWO COMPRESSION SERVICES
630
USING THE CHANGING PRESSURE LEVELS WITHIN THE TURBO-EXPANDER LOOP TO KEEP THE ROTATING EQUIPMENT AT ITS DESIGN POINT
640
USING CATALYST BEDS TO CONVERT PARA-HYDROGEN INTO ORTHO-HYDROGEN
650
USING CATALYST BEDS TO CONVERT ORTHO-HYDROGEN INTO PARA-HYDROGEN
660

*FIG. 6.*