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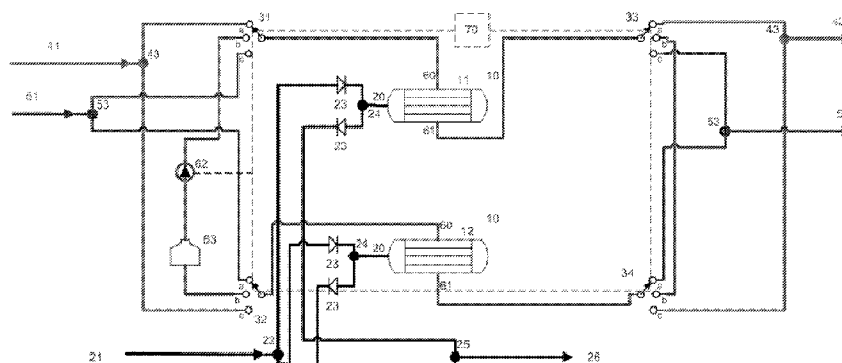
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(54) Title: METAL HYDRIDE HYDROGEN COMPRESSOR

FIGURE 1



(57) Abstract: The invention discloses a metal hydride hydrogen compressor, which is thermally driven and which includes suitably operatively interconnected: at least two compression modules; a gas-distributing system; a heat transfer fluid distributing system including at least four flow switches each of them having one common port which can be alternatively connected to one of three ports, a, b and c; A hot fluid system; a cold fluid system; A heating / cooling conduit; and a control system. The invention also extends to a method of operating a compressor.

METAL HYDRIDE HYDROGEN COMPRESSOR

FIELD OF INVENTION

The present invention relates to a metal hydride hydrogen compressor.

More particularly, the present invention relates to a metal hydride hydrogen
5 compressor which is adapted to be thermally driven.

BACKGROUND TO INVENTION

A promising method of hydrogen compression, which does not require usage of moving parts, is the application of metal hydrides (MH). This method uses a reversible heat-driven interaction of a hydride-forming metal, alloy or inter-
10 metallic compound with hydrogen gas to form a metal hydride. Thereby exothermic formation of the metal hydride is accompanied by absorption of low-pressure hydrogen in the hydride-forming material, during heat removal therefrom at a lower temperature. Alternatively, endothermic decomposition of the MH is accompanied by desorption of high-pressure hydrogen therefrom, during
15 heat supply to the metal hydride at a higher temperature. By such a way, periodic cooling / heating of the MH material results in periodic low-pressure hydrogen absorption / high pressure hydrogen desorption, similarly to suction and discharge processes in a mechanical compressor. Thereby a waste industrial heat having low temperature potential (below 150–200°C), rather than electric
20 power, can be used for hydrogen compression that increases total efficiency of the industrial process and indirectly contributes to a reduction of greenhouse gases and other harmful emissions to be a by-product of generation electricity at thermal power plants utilising fossil fuels.

The engineering solution realising heat-driven hydrogen compression by the
25 usage of MH was at first described by Wiswall and Reilly in US Patent 3,516,263 who disclosed a method of storing hydrogen where hydrogen gas is absorbed by a titanium-iron alloy at the lower temperature, $T_L=10^\circ\text{C}$ and the lower pressure, $P_L\sim 35$ bar, and then desorbed at the higher pressure, up to $P_H=250$ bar, being heated to the higher temperature, up to $T_H\sim 200$ C. This solution provides a

periodically operated hydrogen compression that restricts its applications in continuous technological processes.

A method for providing continuous operation of a metal hydride hydrogen compressor was disclosed in many patents, including ones by Golben and Rosso (US Patent 4,402,187), and Golben (US Patent 4,505,120). According to these inventions, the hydrogen compressor comprises a plurality of hydride containers equipped with hydrogen inlet / outlet pipelines and heat exchange means, an inlet for hydrogen gas fed at a low inlet pressure and an outlet for hydrogen gas supplied at high pressure, as well as heating and cooling means providing a periodic heating / cooling of the heat exchange means associated with the corresponding hydride containers where high-pressure hydrogen desorption / low-pressure hydrogen absorption takes place. The hydrogen inlet / outlet pipelines of the containers are connected through a one-way (check) valve arrangement, and the periodic heating / cooling of the heat exchange means is controlled by timing means.

A similar solution was disclosed by Golben and Rosso (European Patent 0094202 A2) where the heat exchange means comprise a pair of elongated jackets each containing three hydride containers: the first, the second and the third. Each one of the first containers was connected to the hydrogen inlet pipeline, and to the second container located in an opposite jacket; in turn, each second container was connected to the third container located in an opposite jacket, and each third container, at the same time, was connected to the hydrogen outlet pipeline. Every gas connection in this assembly was made through the one-way (check) valve to provide hydrogen flow from the inlet pipeline to the first container and further, to the associated second container, associated third container, and, finally, to the outlet pipeline. The first, second and third containers were filled with different hydride-forming materials in the sequence of the decrease of thermal stability of the hydrogenated material disposed in the next container, as compared to the previous one. The two assemblies of metal hydride containers disposed in the heat exchange jackets (let us call this assembly as a compression module) were heated / cooled in the opposite manner, i.e. when one compression module was heated up the other one was cooled down. By such a way, a three-stage hydrogen compression

process was realised allowing to achieve high compression ratio (more than 10) in a narrow temperature range (cooling and heating by water at the temperatures 20 and 75°C, respectively). The prototype compressor according to the cited invention was characterised by a rather modest output productivity (28 L H₂/min STP), however the productivity could be increased by using several identical containers whose gas pipelines were connected in parallel (let us call this assembly as a compression element). The compressor according to the described invention used flows of hot and cold water for the heating and cooling, respectively. The hot and cold water were supplied to and removed from the compressor via pipelines (separate for both input and output of each heat transfer fluid), and periodic heating and cooling of the compression modules were provided by a system of four three-way servo-valves whose common ports were connected to the inputs and outputs of the hot and cold water, and other ports – to the heat exchange jackets of the compression elements.

The solution described above, if being up-scaled to higher productivities necessary for industrial processes ($\sim 10 \text{ m}^3 \text{ H}_2/\text{h}$ STP and higher), will inevitably meet the following problems:

- Large increase in number of the hydride containers within the external heat transfer jacket will result in the increase of the number of joints in the corresponding gas manifolds and, by such a way, will drastically increase a probability of leaks that will decrease safety and reliability of the compressor. Moreover, making a big number of the pressure containers each of them has a rather complicated layout (pressure-temperature-rated shell, heat exchanger, gas pipelines and filters, etc.), and their assembling will result in very high costs and significant labour resources for making the compressor.
- An attempt to avoid the above-mentioned problem by an increase of the size of a hydride container will result in a drastic worsening of dynamic performances of the compressor because of poor effective thermal conductivity of powdered metal hydride beds. The solution of external heating / cooling of the MH containers in this case becomes inefficient

because of the increase of the effective heat transfer distance and heat losses due to heat exchange of the external surface of the heating / cooling jacket with the environment.

- 5 • The MH containers (especially of the bigger size) must be properly pressure-temperature-rated that results (because of the increase of wall thickness) in the significant increase of their weight and, as a sequence, in a big parasitic thermal mass which has to be alternatively heated and cooled. By such a way, the thermal efficiency of the MH compressor decreases significantly, and special solutions for heat recovery / regeneration are necessary.
- 10 • According to thermodynamic calculations made in V.Z.Mordkovich, Yu.K.Baichtok, M.Kh.Sosna, N.V.Dudakova, N.N.Korostyshevsky *Efficiency analysis for use of intermetallic compounds in hydrogen isolation and compression*, Teoreticheskie Osnovy Khimicheskoi tekhnologii (Foundations of Chemical Technology), 24, No.6 (1990) 769–774), an increase of the
15 number of stages of the MH compressor results in a significant decrease of its efficiency that sets a motivation to reduce the number of stages for large-scale industrial applications. At the same time, the compressor should provide a necessary compression ratio (usually about 20–40, or from 5–10 to 200 bar; the latter value corresponds to the pressure in standard gas
20 cylinders) utilising the available temperature range. The operation between ambient temperatures (cooling) and 150–200°C (heating) is the option available in the industry (including power engineering where steam and super-heated water having similar temperatures are available). As it was shown by Lototsky et. al. (M.Lototsky, H.Halldors, Ye.Klochko, J.Ren, V.Linkov. 7-200 bar / 60 L/h continuously operated metal hydride hydrogen
25 compressor; in: *Hydrogen Materials Science and Chemistry of Carbon Nanomaterials* / ICHMS'2009, XI International Conference Yalta – Crimea – UKRAINE, August 25–31, 2009; Ed. by D.V. Schur, S.Yu. Zaginaichenko, T.N. Veziroglu, V.V. Skorokhod. AHEU, Kiev-2009, pp.298-299), the
30 required hydrogen compression in this temperature range can be achieved by the application of two-stage layout using AB₅-type intermetallic alloy for the first and AB₂-type intermetallic alloy for the second stage. However, the application of a temperature level above the boiling point of water (100°C)

conventionally used as a heat transfer fluid in the industry poses a number of problems when applying technical solutions similar to one suggested in the prototype invention under discussion. In particular, the heat recovery solution proposed in the prototype (time delay in the actuating servo-valves communicating with outputs of the cold and hot water) will result in the contact of cold water circulating at low pressure and steam (or super-heated water) at the higher pressure (about 16 bar at 200°C) that, in turn, will be an origin of a number of objectionable consequences, including gas blocking of the heat exchangers, backflow of the steam or super-heated water into cold water supply line, etc.

- Another problem arising from the operation of a conventional metal hydride compressors in a wider temperature ranges is in high thermal stresses appearing in the metal hydride containers at the beginning of the heating and cooling half-cycles. Taking into account additional stresses originated from the increase of gas pressure in the course of hydrogen desorption (heating) and increase in the volume of the MH material in the course of hydride formation (cooling), it increases the probability of damage (e.g., cracking) of the pressure-loaded external shell of the container thus significantly reducing safety of its operation.

It has also to be noted that any particular realisation of a metal hydride compressor and its main element, metal hydride container, strongly depends on specific application requirements taking into account the following contradictory tendencies:

- The reduction in the size of the container, due to decrease of the effective heat transfer distance within MH bed, results in better hydrogen absorption / desorption dynamic performances, and, in turn, in the shortening the operation cycle time. Correspondingly, the specific productivity per unit of weight of the MH material will be increased. Due to kinetic limitations, this improvement has a maximum limit, and it seems to be problematic to achieve half-cycle time less than 1–2 minutes even for small (several grams) loads of the MH material. Thus, high total output productivity for

smaller containers can be achieved by the increase of their number in the compression element that, as was discussed above, results in appearance of numerous problems with costs, labour efforts, safety and reliability.

- 5 • Although the shortening cycle time is a way to finally increase the productivity of MH compressor, it has a negative influence on the operation lifetime of this apparatus. It is known that the service life of a metal hydride material at specified pressure / temperature conditions is determined by a number of hydrogen absorption /
10 desorption cycles ($\sim 10^4$ when operated on pure hydrogen at $T < 200^\circ\text{C}$ and $P_{\text{H}_2} < 200$ bar), and for the shorter times of the operation cycles the lifetime of the compressor will be shorter.
- 15 • The required total output productivity can be also increased by the increase of weight of MH material in the compression element, particularly, by the increase of the size of the MH container. However, the price for that is the longer operation cycle time and necessity of special solutions providing the efficient operation.

The above listed obstacles and contradictions need to be overcome, in order to develop a safe and reliable industrial-scale metal hydride hydrogen compressor
20 which is relatively simple in manufacturing and operation, and which fits well into specification and main technological processes of an industrial consumer.

It is an object of the invention to suggest a metal hydride hydrogen compressor which will assist in overcoming these problems.

SUMMARY OF INVENTION

25 According to the invention, a metal hydride hydrogen compressor includes:

- (a) At least two compression modules;
- (b) A gas-distributing system;

- (c) A heat transfer fluid distributing system including at least four flow switches each of them having one common port which can be alternatively connected to one of three ports, a, b and c;
- (d) A hot fluid system;
- 5 (e) A cold fluid system;
- (f) A heating / cooling conduit; and
- (g) A control system.

Each compression module may comprise one or more metal hydride compression elements equipped with pipelines for input and output of a heat transfer fluid and a hydrogen input – output pipeline.

The compression element may comprise at least one metal hydride container which may be made as a pressure container filled with a hydride-forming material and equipped with a heat exchanger comprising pipelines for input and output of a heat transfer fluid. The container may also comprise a heat transfer matrix disposed within the metal hydride material to form a metal hydride bed.

15 The container may also comprise a hydrogen input – output pipeline allowing hydrogen gas to flow to / from the metal hydride bed inside the container, through a filter element.

The hydride-forming material disposed in the container may be an AB₅-type hydrogen storage intermetallic alloy where A is Lanthanum which may or may not be partially substituted with Cerium, Mischmetal or Calcium, and B is Nickel which may or may not be partially substituted with at least one component or a plurality of components selected from the group consisting of Cobalt, Aluminium, Manganese, Tin and Copper.

25 The hydride-forming material may also be an AB-type hydrogen storage intermetallic alloy where A is Titanium, and B is Iron which may or may not be partially substituted with at least one component or a plurality of components selected from the group consisting of Titanium, Vanadium and Manganese; the alloy may or may not be additionally doped by Oxygen.

Alternatively, the hydride-forming material may be an AB₂-type hydrogen storage intermetallic alloy where A is Titanium which may or may not be partially substituted with Zirconium, and B includes a plurality of components selected from the group consisting of Iron, Chromium, Manganese, Nickel,
5 Vanadium and Copper.

In the preferred embodiment of the invention the pressure container may be made as a cylinder with spherical end caps.

The pressure container according to the preferred embodiment of the invention may be made of stainless steel, aluminium, or a multilayer composite material.

10 The pressure container may have an internal volume ranging from 2 to 10 litres and length-to-diameter ratio from 5 to 10.

One of the end caps of the pressure container according to the preferred embodiment of the invention may comprise the hydrogen input – output pipeline, and another – the pipelines for input and output of a heat transfer
15 fluid.

According to the preferred embodiment of the invention, the heat exchanger may be located inside the container and may be connected to the pipelines for input and output of a heat transfer fluid. In so doing, the internal heat exchanger may be made as two coaxial pipes. One end of the internal pipe and
20 the space between the pipes may be connected to the pipelines for input and output of a heat transfer fluid which may be located from one side of the coaxial pipe assembly. The external pipe may be plugged from the other end, and the other end of the internal pipe may form a gap with the plugged end of the external pipe to allow the heat transfer fluid to pass from / to the internal pipe
25 to / from the space between the pipes. The heat transfer matrix may be formed by a plurality of heat conductive lamellar fins which may be in a firm thermal contact with outer surface of the external pipe.

The fins may be preferably installed in a transversal position and made of copper, aluminium or lamellar recompressed expanded graphite.

30 The fins may be perforated.

Further, the pressure container according to the preferred embodiment of the invention may comprise one or more gas arteria which may be longitudinally disposed within the metal hydride bed.

5 The gas arteria may or may not be connected to the hydrogen input – output pipeline.

The gas arteria may be made as tubular filter elements. The ends of the tubular filter elements may be plugged.

The filter elements may be made of a porous material.

10 The compression element may also comprise a plurality of the pressure containers whose hydrogen input – output pipelines may be connected to a common hydrogen input – output pipeline, and the pipelines for input and output of the heat transfer fluid may be connected to the common input and output pipelines of the heat transfer fluid.

15 All compression elements within one compression module may have common pipelines for input and output of the heat transfer fluid which may be formed by the connection of the corresponding heat transfer fluid pipelines of the compression elements to input and output heat transfer fluid manifolds.

The compression elements in the compression module may have separate hydrogen input – output pipelines.

20 The gas-distributing system of the compressor according to the invention may comprise low-pressure hydrogen input pipeline, low-pressure manifold, and gas manifolds of the compression elements. The said members of the gas-distributing system may be connected via a system of pipelines and one-way (check) valves which may prevent backflow of hydrogen from the higher
25 pressure to the lower pressure zones of the system.

Further according to the invention, the compressor may comprise two (first and second) compression modules each of which may comprise one compression element to form layout of a one-stage hydrogen compressor.

Alternatively, each of two compression modules may comprise two (first and second) compression elements, to form layout of two-stage hydrogen compressor. In doing so, the first compression element may comprise one hydride-forming material which may provide hydrogen compression from low to medium pressure; and the second compression element may comprise another hydride-forming material which may provide hydrogen compression from medium to high pressure.

For the embodiment of the invention realising the two-stage layout of hydrogen compressor, the hydride-forming material of the first compression element may be characterised by equilibrium hydrogen pressure below the low pressure of hydrogen supplied to the compressor at the temperature close to the temperature of the cold heat transfer fluid, and by the equilibrium hydrogen pressure above the medium pressure of hydrogen discharged to the associated second compression element at the temperature close to the temperature of the hot heat transfer fluid.

The hydride-forming material of the second compression element may be characterised by equilibrium hydrogen pressure below the medium pressure of hydrogen discharged from the associated first compression element, at the temperature close to the temperature of the cold heat transfer fluid, and by the equilibrium hydrogen pressure above the high pressure of hydrogen discharged from the compressor, at the temperature close to the temperature of the hot heat transfer fluid.

Further according to the invention, the heat transfer fluid distributing system may comprise at least four flow switches each of them may have one common port which can be alternatively connected to one of three ports, a, b and c.

The hot fluid system may comprise pipelines for inlet and outlet of a hot fluid which may be connected to hot fluid manifolds.

The hot fluid manifold connected to the inlet pipeline may be connected to the ports a and c of the first and second flow switches.

The hot fluid manifold connected to the outlet pipeline may be connected to the ports a and c of the third and fourth flow switches.

The cold fluid system may comprise pipelines for inlet and outlet of a cold fluid which may be connected to cold fluid manifolds.

- 5 The cold fluid manifold connected to the inlet pipeline may be connected to the ports c and a of the first and second flow switches.

The cold fluid manifold connected to the outlet pipeline may be connected to the ports c and a of the third and fourth flow switches.

- 10 The heating / cooling conduit may comprise pipelines which may connect the common port of the first flow switch to the pipeline for input of the heat transfer fluid to the first compression module, the pipeline for output of the heat transfer fluid from the first compression module to the common port of the third flow switch, the common port of the second flow switch to the pipeline for input of the heat transfer fluid to the second compression module, the pipeline for
15 output of the heat transfer fluid from the second compression module to the common port of the fourth flow switch.

- The heating / cooling conduit may also comprise pipelines which may connect the ports b of any pair of flow switches which are connected to sources and sinks of the hot and cold fluid. These connections may additionally comprise a
20 circulation pump and a buffer tank which may be connected in series with each other and the connecting pipelines.

According to the preferred embodiment of the invention, the input pipeline of the circulation pump is connected to the buffer tank.

- 25 The compressor may also comprise a control system which may provide switching of the flow switches and powering the circulation pump.

The control system may comprise a switching means and a timing means.

Also according to the invention, a method of operating a compressor includes a cyclic sequence of the following steps:

- 5 (a) of generating of higher pressure hydrogen in the first compression module with the simultaneous suction of lower pressure hydrogen in the second compression module;
- (b) of temperature equilibration of the first and second compression modules;
- (c) of generating of higher pressure hydrogen in the second compression module, with the simultaneous suction of lower pressure hydrogen in the first compression module; and
- 10 (d) of temperature equilibration of the first and second compression modules.

Step (a) may be realised by heating the compression elements belonging to the first compression module to a higher temperature, and simultaneous cooling the compression elements which belong to the second compression module to a lower temperature.

- 15 Step (c) may be realised by heating the compression elements belonging to the second compression module to a higher temperature, and simultaneous cooling the compression elements which belong to the first compression module to a lower temperature.

The heating may be provided by the hot heat transfer fluid.

- 20 The cooling may be provided by the cold heat transfer fluid.

Step (b) may provide first module to be cooled down and the second module to be heated up to an intermediate temperature.

Step (d) may provide first module to be heated up and the second module to be cooled down to an intermediate temperature.

- 25 Steps (b) and (d) may be realised by a circulation of the heat transfer fluid in between the first and second compression modules.

Steps (a) to (d) may be realised by switching the flow switches to the positions a, b and c and switching the circulation pump on and off by means of the control block in the following cyclic sequence stages:

- (a) All the flow switches in position a, the circulation pump is off;
- 5 (b) All the flow switches in position b, the circulation pump is on;
- (c) All the flow switches in position c, the circulation pump is off;
- (d) All the flow switches in position b, the circulation pump is on.

The durations of step (a) and step (c) may be equal to a first time set-point of the timing means of the control block.

- 10 The durations of step (b) and step (d) may be equal to a second time set-point of the timing means of the control block.

The cold heat transfer fluid may be water at the temperature 10 to 30°C.

The hot heat transfer fluid may be water at the temperature 60 to 100°C.

- 15 Alternatively, the hot heat transfer fluid may be steam at the temperature 100 to 200°C and the pressure up to 16 bar.

Alternatively, the hot heat transfer fluid may be a superheated water at the temperature 100 to 200°C and the pressure up to 16 bar.

BRIEF DESCRIPTION OF DRAWINGS

- 20 The invention will now be described by way of example with reference to the accompanying schematic drawings.

In the drawings there is shown in:

Figure 1: Piping diagram of a one-stage thermally driven metal hydride hydrogen compressor;

- 25 Figure 2: Piping diagram of a two-stage thermally driven metal hydride hydrogen compressor; and

Figure 3: Layout of a metal hydride container according to the preferred embodiment of the invention.

DETAILED DESCRIPTION OF DRAWINGS

Referring to the drawings, there is shown a metal hydride compressor in accordance with the invention.

The one-stage thermally driven metal hydride hydrogen compressor representing one embodiment of the invention includes the following components, as indicated by the corresponding reference numerals shown in Figure 1:

- 10 10 – Compression modules
 - 11 – Compression element / first compression module
 - 12 – Compression element / second compression module
 - 20 – Hydrogen input / output pipelines of the compression elements
 - 21 – Low-pressure hydrogen input
- 15 22 – Low-pressure manifold
 - 23 – Check valves
 - 24 – Gas manifolds of the compression elements
 - 25 – High-pressure manifold
 - 26 – High-pressure hydrogen output
- 20 31–34 Flow switches:
 - a – Heating first / cooling second compression module
 - b – Transient / thermal equilibration mode
 - c – Heating second / cooling first compression module

41 – Input of the hot fluid

42 – Output of the hot fluid

43 – Hot fluid manifolds

51 – Input of the cold fluid

5 52 – Output of the cold fluid

53 – Cold fluid manifolds

60 – Input of the heat transfer fluid to the compression element

61 – Output of the heat transfer fluid from the compression element

62 – Circulation pump

10 63 – Buffer tank

70 – Control system

The two-stage thermally driven metal hydride hydrogen compressor representing another embodiment of the invention includes the following components, as indicated by the corresponding reference numerals shown in

15 Figure 2:

10 – Compression modules

11 – First compression element / first module

12 – First compression element / second module

13 – Second compression element / first module

20 14 – Second compression element / second module

20 – Hydrogen input / output pipelines of the compression elements

21 – Low-pressure hydrogen input

22 – Low-pressure manifold

- 23 – Check valves
- 24 – Gas manifolds of the compression elements
- 25 – High-pressure manifold
- 26 – High-pressure hydrogen output
- 5 31–34 – Flow switches:
 - a – Heating first / cooling second compression module
 - b – Transient / thermal equilibration mode
 - c – Heating second / cooling first compression module
- 41 – Input of the hot fluid
- 10 42 – Output of the hot fluid
- 43 – Hot fluid manifolds
- 51 – Input of the cold fluid
- 52 – Output of the cold fluid
- 53 – Cold fluid manifolds
- 15 60 – Input of the heat transfer fluid to the compression element
- 61 – Output of the heat transfer fluid from the compression element
- 62 – Circulation pump
- 63 – Buffer tank
- 64 – Input manifold of the heat transfer fluid
- 20 65 – Output manifold of the heat transfer fluid
- 70 – Control system

The key component of any embodiment of this invention is the compression element (11-14) comprising one or more metal hydride containers. In the preferred embodiment of the invention the hydride container includes the following components, as indicated by the corresponding reference numerals shown in Figure 3:

11 – Pressure container

15 – Metal hydride material

16 – Gas pipeline / in-line filter

17 – Gas arterium / tubular filter

10 18 – Valve

20 – Hydrogen input / output pipeline of the pressure container

60 – Input of the heat transfer fluid

61 – Output of the heat transfer fluid

66 – Internal pipe of heat exchanger

15 67 – External pipe of heat exchanger

68 – Fins of heat exchanger

According to the invention, a compressor comprises at least two compression modules (10) schematically shown in Figures 1 and 2. The compression module comprises one (Figure 1: 11 and 12), two (Figure 2: 11 and 13, 12 and 14) or more compression elements each of them is connected to the gas-distributing system of the compressor by means of hydrogen input / output pipeline (20) and to the heating / cooling conduit of the compressor by means of the input (60) and output (61) pipelines for the heat transfer fluid. In the embodiment when the compression module comprises more than one compression elements (see Figure 2 as an example), their input pipelines (60) are connected to the input manifold of the heat transfer fluid (64) and the output ones (61) – to the output manifold of the heat transfer fluid (65).

Hydrogen input / output pipelines (20) of the associated compression elements (11–14) are connected to the associated gas manifolds (24).

The gas-distributing system of the compressor comprises low-pressure hydrogen input port (21) connected through low-pressure manifold (22) and
5 one-way (check) valves (23) to gas manifolds (24) of the compression elements (11, 12) forming the first stage of the compressor. When one-stage operation layout of the compressor is realised (Figure 1), the gas manifolds (24) of the compression elements (11, 12) are also connected, through one-way (check) valves (23) to the high-pressure manifold (25) connected to the high-pressure
10 hydrogen output port (26).

Alternatively, in the embodiment realising two-stage operation (Figure 2), the gas manifolds (24) of the first stage compression elements (11, 12) are connected, through one-way (check) valves (23), to the gas manifolds (24) of the second stage compression elements (14, 13) located in the opposite
15 compression module (10). Further, the gas manifolds (24) of the second stage compression elements (13, 14) are connected, through one-way (check) valves (23), to the high-pressure manifold (25) connected to the high-pressure hydrogen output port (26).

A similar arrangement when the gas manifold of a compression element of n^{th}
20 stage of the compressor is connected through one-way valve to the gas manifold of a compression element of $(n+1)^{\text{th}}$ stage belonging to the opposite compression module can be realised in other embodiments of the invention realising a multi-stage compression layout. In this case the gas systems of the first and last stages are arranged in a similar manner as it is shown in Figure 2,
25 i.e. the low-pressure manifold of the compressor is connected, through one-way valves (23), to gas manifolds (24) of the compression elements of the first stage, and gas manifolds (24) of the compression elements of the last stage are connected, through one-way valves (23), to the high-pressure manifold (25) of the compressor. However, as is was noted above, the increase in the number of
30 stages in the compressor is not efficient from the thermodynamic point of view, and one- and two-stage layouts (Figure 1 and Figure 2, respectively) are the preferred embodiments of the invention.

The heat transfer fluid pipelines (Figure 1: 60, 61), or manifolds (Figure 2: 64, 65), together with the heat exchangers of metal hydride containers in the compression elements (shown as example in Figure 3: 66, 67, 68), form a working part of the heating / cooling conduit providing periodic heating and cooling of the compression elements in the associated compression modules. In so doing, the pipelines for input and output of the heat transfer fluid belonging to the associated compression modules can be alternatively connected to the hot and cold fluid systems through the heat transfer fluid distribution system comprising four flow switches (31–34). The flow switches can also provide the connection of the pipelines for input and output of the heat transfer fluid of both compression modules to the auxiliary part of the heating / cooling conduit by connecting the ports (b) of the flow switches (31 and 32) and (33 and 34). The said connections should also accommodate in series circulation pump (62) and buffer tank (63). In Figure 1 and Figure 2, as an example, the circulation pump (62) and buffer tank (63) are shown to be connected in between ports (b) of the flow switches (31 and 32), but alternative connection in between ports (b) of the flow switches (33 and 34) is also possible within invention. However, it is preferred that the input line of the circulation pump (62) was directly connected to the buffer tank (63) or even was immersed therein, like in the known solutions of bath circulators.

The flow switches (31–34) can be made by different ways, in particular, as manifolds of three shut-off valves having common port on one side and separate ports on the other side, as 4-way switching valves, or specially designed gas distribution devices having a common port(s) which can be alternatively connected to one of three associated ports. Independently of the particular realisation, each flow switch (31–34) should be able to provide alternative connections of its common port to one of three associated ports, a, b and c.

Preferably, the flow switches (31–34) have to be remotely actuated using solenoids, electric motors, or pneumatic / electro-pneumatic actuators.

The compressor also comprises hot fluid system formed by the hot fluid input pipeline (41), hot fluid manifolds (43) and hot fluid output pipeline (42). The

distribution of the hot fluid to the compression modules (10) is provided by the heat transfer fluid distribution system, through flow switches (31–34), where the hot fluid manifold (43) connected to the input pipeline (41) is connected to the ports a and c of the first (31) and the second (32) flow switches, respectively. By the similar manner, the hot fluid manifold (43) connected to the output pipeline (42) is connected to the ports a and c of the third (33) and the fourth (34) flow switches, respectively.

Similarly, the cold fluid system of the compressor comprises the cold fluid input (51) and output (52) pipelines each connected to its own cold fluid manifold (53). The manifold (53) connected to the input pipeline (51) is connected to the ports c and a of the first (31) and the second (32) flow switches, respectively. By the similar manner, the cold fluid manifold (53) connected to the output pipeline (52) is connected to the ports c and a of the third (33) and the fourth (34) flow switches, respectively.

Hydrogen compression is provided by the periodic heating and cooling of the metal hydride material(s) disposed in metal hydride containers. One metal hydride container, or an assembly of several containers whose gas and heat transfer fluid pipelines are connected in parallel form the compression elements located in the associated compression modules. All compression elements within one compression module have common pipelines for input (60) and output (61) of the heat transfer fluid formed by the connection of the corresponding heat transfer fluid pipelines of the compression elements to input (64) and output (65) heat transfer fluid manifolds. The compression elements in the compression module have separate hydrogen input – output pipelines (20) connected to the associated gas manifolds (24).

The metal hydride containers, generally, may have any layout comprising the necessary components, viz. gas-proof pressure container (shell), hydride-forming material, heat exchanger, pipelines for input and output of heat transfer fluid, heat transfer matrix, and hydrogen input – output pipeline with filter element.

An optimal (for large-scale industrial hydrogen compressor applications) layout of a metal hydride container (Figure 3) is suggested as a preferred embodiment of the present invention.

5 The metal hydride container comprises a pressure cylinder with spherical end caps (11) preferably made of stainless steel, but aluminium or multilayer composite material (if fit into specified pressure / temperature ratings) can be used as well. The container can have internal volume from 2 to 10 litres, and length-to-diameter aspect ratio from 5 to 10. The specified upper limit of the internal volume and lower limit of the aspect ratio are determined by the fact
10 that the overrunning these limits will result in too long characteristic heat transfer distances in the metal hydride bed and, correspondingly, too slow hydrogen absorption / desorption processes. The containers with lower internal volume and higher aspect ratio can be made in a more efficient layout providing shorter cycle time, but their application generates a number of problems
15 discussed above.

The cylinder (11) is filled with a hydride-forming material (15) in the form of powder, granules or composite structures. The usage of powder is preferable since it facilitates the procedure of filling the metal hydride container having a complicated internal geometry with the material (15) and, from the other hand,
20 increases the hydrogen storage capacity of the container due to absence of inert binder necessary for making the granules or composite structures.

The kind and specific composition of the hydride-forming material (15) depends on a number of factors, including hydrogen pressure / temperature operating conditions, purity of feeding hydrogen, required productivity, and compressor
25 layout (one- or multi-stage). In the latter case the proper selection of the material is the most important factor, since thermodynamic and other performances of two materials applied in a previous and a next stage should be carefully aligned to each other. Preferably, the following kinds of the hydride-forming material can be applied taking into account the possibility of variation of
30 their performances by the variation in the component composition:

- AB₅-type hydrogen storage intermetallic alloys where A is Lanthanum which can be partially substituted with Cerium,

Mischmetal or Calcium (to decrease thermal stability of the hydride), and B is Nickel which can be partially substituted with at least one component or a plurality of components selected from the group consisting of Cobalt, Aluminium, Manganese, Tin and Copper (to increase thermal stability of the hydride and, in some cases, to add poisoning tolerance and to prolong operating cycle life of the material). The AB₅-type materials are the most flexible in possibility of variation of their thermodynamic characteristics by the component substitution, easy activated and relatively tolerant to the poisoning with impurities, so it is preferable to use them for the first stage of hydrogen compression.

- AB-type hydrogen storage intermetallic alloys where A is Titanium, and B is Iron which can be partially substituted with at least one component or a plurality of components selected from the group consisting of Titanium, Vanadium and Manganese. This kind of materials is less expensive and is characterised by higher hydrogen capacity than AB₅-type alloys, but it is less flexible as to variation of its thermodynamic performances by the component substitution, has unfavourable thermodynamic features (two plateaux or significant plateau slope of pressure-composition isotherms) and is extremely sensitive to poisoning with gas impurities (the poisoning tolerance, however, can be increased in some extent by additional doping of the AB-type material by Oxygen). The best use of this kind of materials is one for the second stage of hydrogen compressor in multi-stage layout.

- AB₂-type hydrogen storage intermetallic alloy where A is Titanium which may or may not be partially substituted with Zirconium, and B includes a plurality of components selected from the group consisting of Iron, Chromium, Manganese, Nickel, Vanadium and Copper. These alloys are characterised by higher hydrogen absorption capacity, flexibility in adjusting their thermodynamic properties by variation in component composition, possibility to achieve high equilibrium hydrogen pressures at moderate heating

temperatures. They are, however, more expensive than AB₅ and AB and are easily deactivated by impurities (though to a lesser extent than AB). Their best use is in the second (and further, if necessary) stages of hydrogen compressor in multi-stage layout.

5 The cylinder (11) also comprises an internal heat exchanger made as two pipes (66, 67) of different diameter placed coaxially to each other and to the axis of the cylinder (11). The internal (66) and external (67) pipes of the heat exchanger are coming through one of the end caps of the container through a tee-union assembly one end of which is leak-proof-connected to the cap, and
10 the others (60, 61) form the input and output pipelines for the heat transfer fluid. In the Figure 3 the input pipeline communicates with the internal pipe of the heat exchanger, and the output one with the space between the internal and external pipes. According to the embodiment under consideration, this feature is insignificant, and the opposite connection of the input and output
15 pipes of the heat transfer fluid can also be applied.

The opposite sides of the pipes (66, 67) are ended close to the opposite end cap. The external pipe (67) is plugged at the end, and the corresponding end of the internal pipe (66) ends at the shorter distance to form a gap with the plugged end. By such a way the heat transfer fluid is allowed to pass from / to
20 the internal pipe (66) to / from the space between the pipes forming a core tube of the heat exchanger where heat transfer fluid flows from / to the pipeline (60) to / from pipeline (61). The heat exchanger is held only from the side of the corresponding end cap of the container where pipelines (60, 61) are located. The other end of the heat exchanger (corresponding to the plugged end of the
25 pipe 67) is not fastened. Such a layout significantly reduces thermal loads in the container during its periodic heating and cooling. The outer pipe (67) of the heat exchanger is equipped by a plurality of heat conductive lamellar fins (68) which are in a firm thermal contact with outer surface of the pipe (67).

The fins (68) are preferably installed in a transversal position and made of heat-conductive material, such as copper, aluminium or lamellar recompressed
30 expanded graphite. The fins are also perforated to allow the hydride-forming

material (15) to be easy loaded into the container and to be uniformly distributed in its inner space.

Gas fittings connecting the internal space of the container comprising the metal hydride bed (hydride forming material 15 and heat transfer matrix formed by fins 68) and hydrogen input / output pipeline (20) are installed in the end cap opposite to one carrying the pipelines (60, 61) for input and output of heat transfer fluid. The fittings can include gas-proof connection equipped with in-line filter (16) and shut-off valve (18).

To allow quick and uniform passing of hydrogen gas through whole length of the metal hydride bed formed by a fine powder of hydride-forming material, one or more gas arteria (17; preferably made as porous tubular filters) are introduced in the container. The arteria are located longitudinally passing through the metal hydride bed. Although at least one gas arterium can be connected to the inner side of gas fitting penetrating through the corresponding end cap of the container, it is not compulsory, and the gas arteria (plugged from both ends) can be just placed within the container in the proper position (as shown in Figure 3 for one arterium 17). The contamination of gas flow by a fine hydride powder is prevented by the in-line filter (16).

Typical example of realisation of the described layout is a stainless steel container having internal volume of about 4 litres and length-to-diameter aspect ratio about 7. The container rated for $P_{\max}=200$ bar and $T_{\max}=200^{\circ}\text{C}$ weights about 20 kg and comprises 12 or 14 kg of the AB_2 - or AB_5 -type alloy, respectively. Hydrogen storage capacity of the metal hydride container was found to be about $2 \text{ m}^3 \text{ H}_2$ STP. 90% charge / discharge time of the container mainly depends on pressure / temperature conditions and flow rate of the heat transfer fluid, and was estimated to be approximately 1 to 2 hours. Therefore, if metal hydride container of this type is incorporated in a compression element of the metal hydride compressor according to the present invention, the productivity from 0.9 to $1.8 \text{ m}^3/\text{h}$ will be achieved using a single container in the compression element (in total 2 containers for one-stage and 4 for two-stage layout). Correspondingly, using compression elements comprising ten

containers (in total 20 for one-stage and 40 for two-stage layout) will result in the productivity 9 to 18 m³/h.

The operation of the compressor is referenced by Figure 1 and Figure 2 and includes the following steps:

- 5 (a) of generating of higher pressure hydrogen in the first compression module with the simultaneous suction of lower pressure hydrogen in the second compression module;
- (b) of temperature equilibration of the first and second compression modules;
- 10 (c) of generating of higher pressure hydrogen in the second compression module, with the simultaneous suction of lower pressure hydrogen in the first compression module; and
- (d) of temperature equilibration of the first and second compression modules.
- 15 The listed steps (a) to (d) are committed sequentially in the cyclic mode, so as step (d) is followed by step (a).

Steps (a) to (d) are realised by switching the flow switches (31) to the positions a, b and c and switching the circulation pump on and off by means of the control system (70) in the following cyclic sequence:

- 20 (a) All the flow switches in position a, the circulation pump is off;
- (b) All the flow switches in position b, the circulation pump is on;
- (c) All the flow switches in position c, the circulation pump is off;
- (d) All the flow switches in position b, the circulation pump is on.

During step (a), the hot fluid, from the input pipeline (41), manifold (43) and
25 port a of first flow switch (31) flows through the first compression module (10), via corresponding input (60) and output (61) pipelines. The metal hydride containers in the compression elements (11, 13) associated with this module

are heated up, and the hot fluid is removed through port a of the third flow switch (33), manifold (43) and output pipeline (42). Simultaneously and by a similar manner, the cold fluid, from the input pipeline (51), manifold (53) and port c of second flow switch (32) flows through the second compression module.

- 5 The metal hydride containers in the compression elements (12, 14) associated with this module are cooled down, and the cold fluid is removed through port a of the fourth flow switch (34), manifold (53) and output pipeline (52). The step (a) continues for the specified period of time (approximately 0.5 to 3 hours, depending of size of the metal hydride containers and their geometric features, pressure / temperature conditions and flow rates of both cold and hot fluids)
- 10 necessary for the desorption of high-pressure hydrogen from compression elements (11) of the first compression module and low-pressure hydrogen absorption in compression elements (12) of the second compression module. In the case of the multi-stage operation (Figure 2) the last also concerns the
- 15 compression modules of the second stage, viz., (13, hydrogen desorption) and (14, hydrogen absorption).

It is preferred that the compressor would use hot and cold fluids available in the consumer's technological infrastructure. The preferred cold fluid is water at the temperature $T_l=10-30^{\circ}\text{C}$ circulating in industrial cooling systems. The hot fluid

20 can be hot water ($T_h=60-100^{\circ}\text{C}$) or, preferably, steam or superheated water ($T_h=100-200^{\circ}\text{C}$, pressure up to 16 bar), for example, waste steam vented from a turbine.

The duration of the step (a), to be equal to the duration of the step (c) is pre-determined by a first time set-point to be set by timing means of the control

25 system (70).

By completing the step (a), the compression elements (11, 13) in the first compression module are heated to a higher temperature, T_h that can be above the boiling point of water, if steam or superheated water is used as a hot fluid. At the same time, the compression elements (12, 14) in the second

30 compression module are cooled to a lower temperature, $T_l=10-30^{\circ}\text{C}$.

After completion of the step (a), the control system (70) switches flow switches (31-34) into position b and the circulation pump (62) on. The heat transfer fluid

(preferably water) to be in the buffer tank at a medium temperature ($T_m \sim 50-70^\circ\text{C}$) begins to circulate along the heating / cooling conduit, now connecting the buffer (63), pump (62), and heat exchangers in the metal hydride containers of the hot (11, 13) and cold (12, 14) compression modules. In doing so, the hot containers are cooled down and cold ones heated up to the temperature approaching T_m from above and below, respectively. By such a way the heat accumulated in the hot containers is used to pre-heat the cold containers, and partial heat recovery takes place. Since $T_l < T_m < T_h$, the temperature stresses in the cooled and heated containers are lower than in the case if the cold and hot fluids would directly used for temperature equilibration by an immediate switching from step (a) to step (c).

The duration of the step (b), to be equal to the duration of the step (d) (to mainly depend on the higher and lower temperatures, total mass of the containers, capacity of the buffer tank, productivity of the circulation pump, and to be approximately 5 to 30 minutes) is pre-determined by a second time set-point to be set by timing means of the control system (70).

Step (c) is similar to the step (a), providing cooling down the metal hydride containers (11, 13) of the first module resulting in lower-pressure hydrogen absorption therein, and heating up the metal hydride containers (12, 14) of the second module providing higher-pressure hydrogen desorption there-from.

The present invention allows to build reasonably efficient industrial-scale metal hydride hydrogen compressors driven by waste industrial heat which are simpler, less costly and labour-consuming, and more safe and reliable in the operation than the known prototypes.

Due to high selectivity of the processes of reversible hydrogen absorption / desorption in metal hydrides, the operation of the compressor will result in a useful side effect of additional hydrogen purification during its compression. As a result, the output high pressure hydrogen will be delivered at high purity (better than 99.999%) and, therefore, will have a high commercial value.

The invention can be used in power engineering (for example, to provide cooling of turbo-generators at thermal or nuclear power plants), integrated hydrogen

energy-technological systems for industrial and domestic applications, as well as chemical engineering, gas service, etc., for filling gas cylinders with high-pressure high-purity hydrogen gas.

PATENT CLAIMS

1. A metal hydride hydrogen compressor, which is thermally driven and which includes suitably operatively interconnected:

(a) At least two compression modules;

5 (b) A gas-distributing system;

(c) A heat transfer fluid distributing system including at least four flow switches each of them having one common port which can be alternatively connected to one of three ports, a, b and c;

(d) A hot fluid system;

10 (e) A cold fluid system;

(f) A heating / cooling conduit; and

(g) A control system.

2. A compressor as claimed in claim 1, in which:

15 (a) Each of the compression modules includes one or more metal hydride compression elements equipped with pipelines for input and output of a heat transfer fluid and a hydrogen input – output pipeline, all compression elements within one compression module have common pipelines for input and output of the heat transfer fluid formed by the connection of the corresponding heat transfer fluid pipelines of the compression elements to input and
20 output heat transfer fluid manifolds, and separate hydrogen input – output pipelines;

25 (b) The gas-distributing system includes low-pressure hydrogen input and high-pressure hydrogen output pipelines, low- and high-pressure manifolds, and gas manifolds of the compression elements connected to the said hydrogen input – output pipelines, low- and high-pressure manifolds via a system of

pipelines and one-way (check) valves preventing backflow of hydrogen from the higher pressure to the lower pressure zones of the system;

- 5 (c) The heat transfer fluid distributing system including at least four flow switches each of them having one common port which can be alternatively connected to one of three ports, a, b and c;
- 10 (d) The hot fluid system includes pipelines for inlet and outlet of a hot fluid connected to hot fluid manifolds, wherein the hot fluid manifold connected to the inlet pipeline is connected to the ports a and c of the said first and second flow switches, and the hot fluid manifold connected to the outlet pipeline is connected to the ports a and c of the said third and fourth flow switches;
- 15 (e) The cold fluid system includes pipelines for inlet and outlet of a cold fluid connected to cold fluid manifolds, wherein the cold fluid manifold connected to the inlet pipeline is connected to the ports c and a of the said first and second flow switches, and the cold fluid manifold connected to the outlet pipeline is connected to the ports c and a of the said third and fourth flow switches;
- 20 (f) The heating / cooling conduit includes pipelines connecting the common port of the said first flow switch to the said pipeline for input of the heat transfer fluid to the first compression module, the said pipeline for output of the heat transfer fluid from the first compression module to the common port of the said third flow switch, the common port of the said second flow switch to the said pipeline for input of the heat transfer fluid to the second compression module, the said pipeline for output of the heat transfer fluid from the second compression module to the common port of the said fourth flow switch, and the ports b of
- 25 any pair of the flow switches which are connected to sources and sinks of the hot and cold fluid; the heating / cooling conduit additionally comprises a circulation pump and a buffer tank
- 30

connected in series to the pipelines connecting ports b of the said flow switches; and

(g) The control system is adapted to provide switching of the said flow switches and powering the said circulation pump, the control system comprises a switching means and a timing means.

3. A compressor as claimed in claim 2, in which the compression element includes at least one metal hydride container provided as a pressure container filled with a hydride-forming material and equipped with a heat exchanger comprising pipelines for input and output of a heat transfer fluid; a heat transfer matrix disposed within the metal hydride material to form a metal hydride bed; the container also includes a hydrogen input – output pipeline allowing hydrogen gas to flow to / from the metal hydride bed inside the container, through a filter element.

4. A compressor as claimed in claim 3, in which the hydride-forming material is an AB₅-type hydrogen storage intermetallic alloy where A is Lanthanum which may or may not be partially substituted with Cerium, Mischmetal or Calcium, and B is Nickel which may or may not be partially substituted with at least one component or a plurality of components selected from the group consisting of Cobalt, Aluminium, Manganese, Tin and Copper.

5. A compressor as claimed in claim 3, in which the hydride-forming material is an AB-type hydrogen storage intermetallic alloy where A is Titanium, and B is Iron which may or may not be partially substituted with at least one component or a plurality of components selected from the group consisting of Titanium, Vanadium and Manganese; the alloy may or may not be additionally doped by Oxygen.

6. A compressor as claimed in claim 3, in which the hydride-forming material is an AB₂-type hydrogen storage intermetallic alloy where A is Titanium which may or may not be partially substituted with Zirconium, and B includes a plurality of components selected from the group consisting of Iron, Chromium, Manganese, Nickel, Vanadium and Copper.

7. A compressor as claimed in any one of claims 3 to 6, in which the compression element includes a plurality of pressure containers whose hydrogen input – output pipelines are connected to a common hydrogen input – output pipeline of the compression element, and the pipelines for input and output of the heat transfer fluid are connected to the common input and output pipelines of the heat transfer fluid.
8. A compressor as claimed in claim 7, in which the pressure container is made as a cylinder with spherical end caps one of which includes the hydrogen input – output pipeline and another comprises the pipelines for input and output of a heat transfer fluid connected to the heat exchanger which is located inside the container.
9. A compressor as claimed in claim 7 or claim 8, in which the pressure container is made of stainless steel, aluminium, and/or a multilayer composite material.
10. A compressor as claimed in any one of claims 7 to 9, in which the pressure container has an internal volume from 2 to 10 litres and length-to-diameter ratio from 5 to 10.
11. A compressor as claimed in any one of claims 3 to 10, in which the internal heat exchanger is made as two coaxial pipes where one end of the internal pipe and the space between the pipes are connected to the pipelines for input and output of a heat transfer fluid located from one side of the coaxial pipe assembly, the external pipe is plugged from the other end, the other end of the internal pipe forms a gap with the plugged end of the external pipe to allow the heat transfer fluid to pass from / to the internal pipe to / from the space between the pipes, and the heat transfer matrix, is formed by a plurality of heat conductive lamellar fins to be in a firm thermal contact with outer surface of the external pipe.
12. A compressor as claimed in claim 11, in which the fins are installed in a transversal position and made of copper, aluminium and/or lamellar recompressed expanded graphite.

13. A compressor as claimed in claim 11 or claim 12, in which the fins are perforated.
14. A compressor as claimed in any one of claim 7 to 13, in which the pressure container includes at least one gas arteria longitudinally disposed within the metal hydride bed.
15. A compressor as claimed in claim 14, in which the gas arteria may or may not be connected to the hydrogen input – output pipeline.
16. A compressor as claimed in claim 13 or claim 14, in which the gas arteria are made as tubular filter elements made of a porous material.
17. A compressor as claimed in claim 16, in which the ends of the tubular filter elements are plugged.
18. A compressor as claimed in any one of the preceding claims, which includes two compression modules each of which includes one compression element to form a layout of one-stage hydrogen compressor.
19. A compressor as claimed in any one of the preceding claims, which includes two compression modules each of which includes two (first and second) compression elements, to form a layout of two-stage hydrogen compressor where the first compression element includes one hydride-forming material and provides hydrogen compression from low to medium pressure, and the second compression element comprising another hydride-forming material and provides hydrogen compression from medium to high pressure.
20. A compressor as claimed in claim 19, in which the hydride-forming material of the first compression element is characterised by equilibrium hydrogen pressure below the low pressure of hydrogen supplied to the compressor at the temperature close to the temperature of the cold heat transfer fluid, and by the equilibrium hydrogen pressure above the medium pressure of hydrogen discharged to the associated second

compression element at the temperature close to the temperature of the hot heat transfer fluid.

21. A compressor as claimed in claim 18 or claim 19, in which the hydride-forming material of the second compression element is characterised by equilibrium hydrogen pressure below the medium pressure of hydrogen discharged from the associated first compression element at the temperature close to the temperature of the cold heat transfer fluid, and by the equilibrium hydrogen pressure above the high pressure of hydrogen discharged from the compressor at the temperature close to the temperature of the hot heat transfer fluid.
22. A compressor as claimed in any one of claims 2 to 21, in which the input pipeline of the said circulation pump is connected to the buffer tank.
23. A method of operating a compressor, which includes a cyclic sequence of the following steps:
- (a) of generating higher pressure hydrogen in the first compression module by heating the associated compression elements to a higher temperature provided by the hot heat transfer fluid, with the simultaneous suction of lower pressure hydrogen in the second compression module by cooling the associated compression elements to a lower temperature provided by a cold heat transfer fluid;
 - (b) of temperature equilibration of the first and second compression modules, where the first module is cooled down and the second module is heated up to an intermediate temperature, by a circulation of the heat transfer fluid in between the first and second compression modules;
 - (c) of generating higher pressure hydrogen in the second compression module by heating the associated compression elements to a higher temperature provided by the hot heat transfer fluid, with the simultaneous suction of lower pressure

hydrogen in the first compression module by cooling the associated compression elements to a lower temperature provided by a cold heat transfer fluid; and

5 (d) of temperature equilibration of the first and second compression modules, where the first module is heated up and the second module is cooled down to an intermediate temperature, by a circulation of the heat transfer fluid in between the first and second compression modules.

10 24. A method as claimed in claim 23, in which the steps (a) to (d) are realised by switching flow switches to positions a, b and c and switching the circulation pump on and off by means of a control block in the following cyclic sequence:

(a) All the flow switches in position a, the circulation pump is off;

(b) All the flow switches in position b, the circulation pump is on;

15 (c) All the flow switches in position c, the circulation pump is off;

(d) All the flow switches in position b, the circulation pump is on.

20 25. A method as claimed in claim 23 or claim 24, in which duration of step (a) and the duration of step (c) are equal to a first time set-point of the timing means of the control block and the durations of steps (b) and (d) are equal to a second time set-point of the timing means of the control block.

26. A method as claimed in any one of claims 23 to 25, in which the cold heat transfer fluid is water at the temperature 10 to 30°C.

25 27. A method as claimed in any one of claims 23 to 26, in which the hot heat transfer fluid is water at the temperature 60 to 100°C.

28. A method as claimed in any one of claims 23 to 27, in which the hot heat transfer fluid is steam at the temperature 100 to 200°C and the pressure up to 16 bar

29. A method as claimed in any one of claims 23 to 28, in which the hot heat transfer fluid is a superheated water at the temperature 100 to 200°C and the pressure up to 16 bar
30. A metal hydride compressor substantially as hereinbefore described with
5 reference to the accompanying drawings.
31. A method of operating a metal hydride compressor substantially as hereinbefore described with reference to the accompanying drawings.

FIG. 1

FIGURE 1

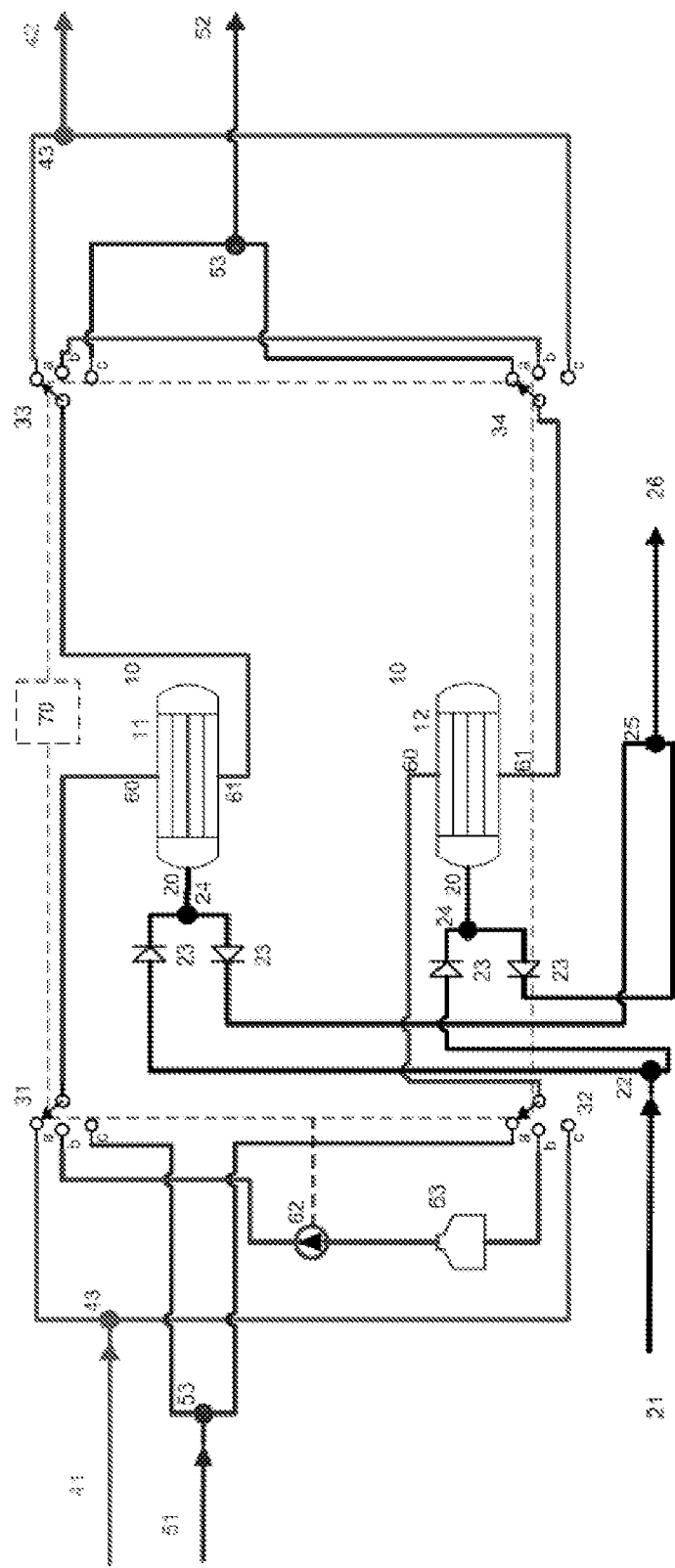


FIG. 2

FIGURE 2

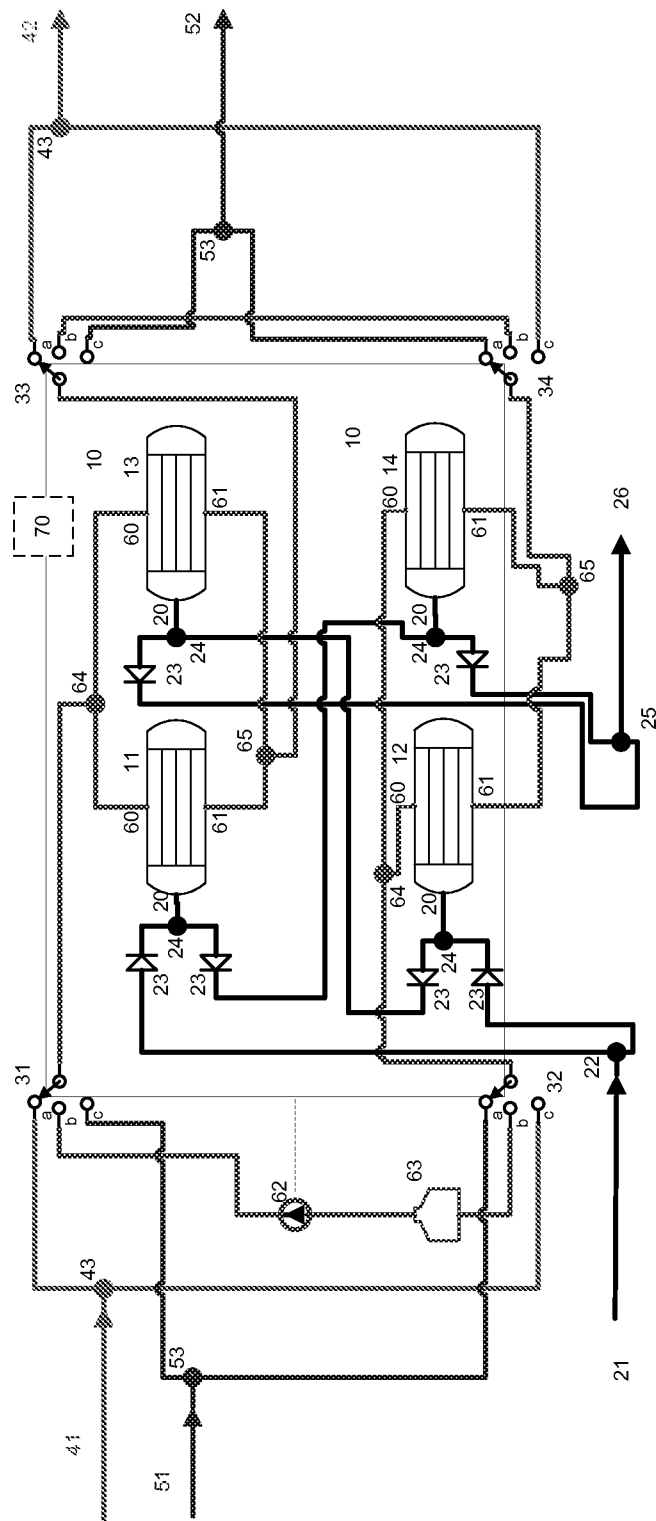


FIG. 3

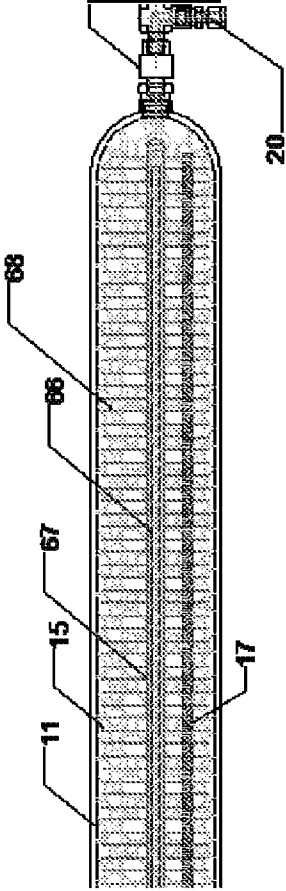


FIGURE 3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB2012/050686

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

F04B 37/02 (2006.01)**C01B 3/00** (2006.01)**F17C 11/00** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI, EPODOC: (1) keywords: hydrogen, compress, heat, cold, high, low, temperature; (1.1) hydride; (1.2) absorb and similar terms; (1.3) IPC, ECLA: F04B37, C01B3, Y02E60/low; (2) hydrogen, compress, hydride and similar terms; (3) IPC: F17C 11/00, ECLA: F17C11/00D, C01B3/00D/LOW and compress

Google Patents : search terms: hydride, compressor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4402187 A (GOLBEN et al.) 06 September 1983	1-28
A	WO 2010/087723 A1 (INSTITUTT FOR ENERGITEKNIKK) 05 August 2010	1-28
A	US 2004/0042957 A1 (MARTIN) 04 March 2004	1-28
A	US 4085590 A (POWELL et al.) 25 April 1978	1-28



Further documents are listed in the continuation of Box C



See patent family annex

* Special categories of cited documents:	
"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

23 April 2012

Date of mailing of the international search report

30 April 2012

Name and mailing address of the ISA/AU

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB2012/050686

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See the Supplemental Box

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

Supplemental Box

(To be used when the space in any of Boxes I to IV is not sufficient)

Continuation of Box No: III

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

- **Claims 1-22** are directed a metal hydride hydrogen compressor having at least two compression modules. The feature of a heat transfer fluid distributing system including at least four switches each of them having one common port which can be alternatively connected to one of three ports a, b and c is specific to this group of claims.
- **Claims 23- 28** are directed to a method of operating a compressor. The steps of: generating high pressure hydrogen in a first compression module by heating associated compression elements to a higher temperature provided by a hot heat transfer fluid, with simultaneous suction of lower pressure hydrogen in a second compression module by cooling associated compression elements to lower temperature provided by a cold heat transfer fluid (step (a)); temperature equilibration of the first and the second compression modules where the first module is cooled down and the second module is heated up to an intermediate temperature by a circulation of a heat transfer fluid in between the first and second compression modules (step (b)); generating high pressure hydrogen in a second compression module by heating associated compression elements to a higher temperature provided by a hot heat transfer fluid, with simultaneous suction of lower pressure hydrogen in a first compression module by cooling associated compression elements to lower temperature provided by a cold heat transfer fluid (step (c)); temperature equilibration of a first and a second compression modules where first module is heated up and the second module is cooled down to an intermediate temperature by a circulation of a heat transfer fluid in between the first and second compression modules (step (d)) are specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the claimed inventions and therefore cannot provide the required technical relationship. The only feature common to all of the claimed inventions and which provides a technical relationship among them is a hydrogen compressor using alternative heating and cooling having two compression modules. However this feature does not make a contribution over the prior art because it is individually disclosed in:

US 4402187 A (GOLBEN et al.) 06 September 1983 - This document discloses a hydrogen compressor using alternative heating and cooling having two compression modules in form of hydride containers 47 and 48 in figure 2.

WO 2010/087723 A1 (INSTITUTT FOR ENERGITEKNIKK) 05 August 2010- This document discloses a hydrogen compressor using alternative heating and cooling having two compression modules in form of hydride containers in Abstract and accompanying figure.

Therefore in the light of this document this common feature cannot be a special technical feature. Therefore there is no special technical feature common to all the claimed inventions and the requirements for unity of invention are consequently not satisfied *a posteriori*.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/IB2012/050686

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report				Patent Family Member			
US	4402187	CA	1182985	EP	0094202	JP	58217782
WO	2010087723	EP	2391846	NO	20090497		
US	2004042957	AU	42164/01	CA	2300770	CA	2402510
		WO	0169144				
US	4085590	NONE					

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX