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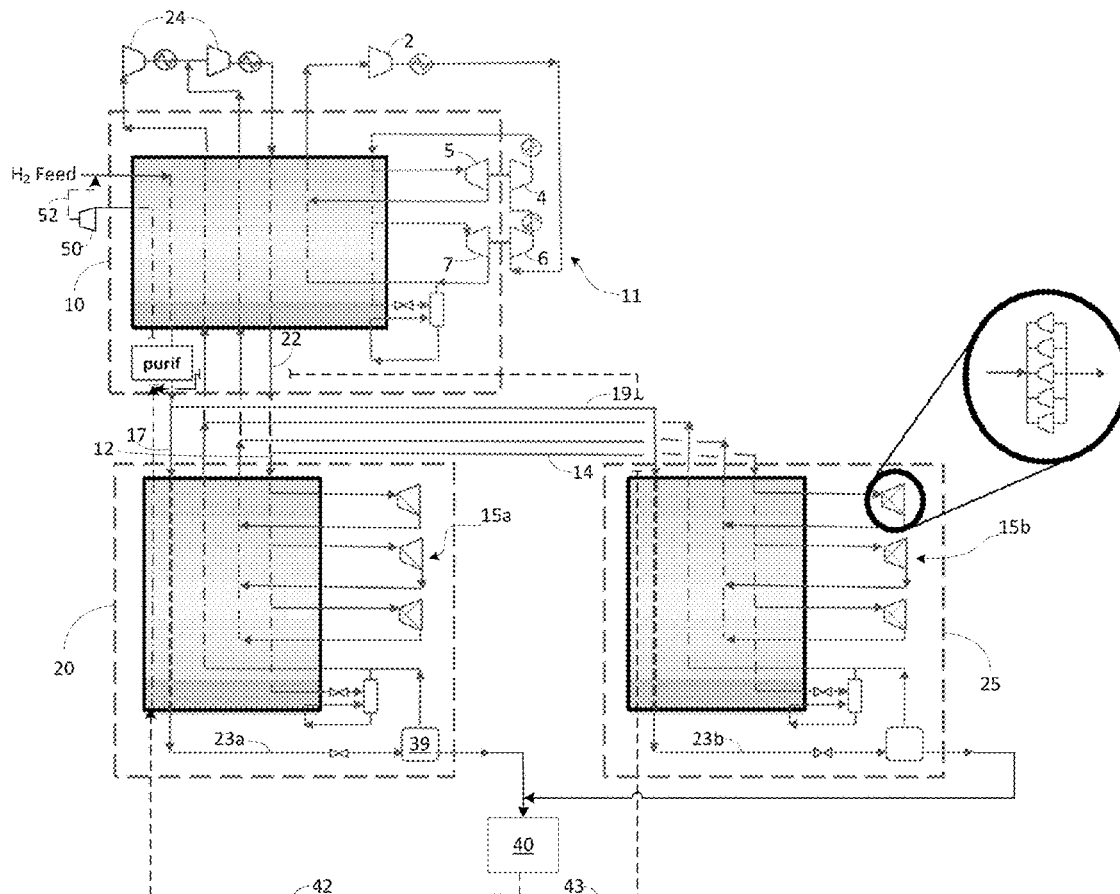
(19) **United States**(12) **Patent Application Publication**
TURNEY et al.(10) **Pub. No.: US 2023/0009727 A1**(43) **Pub. Date: Jan. 12, 2023**(54) **METHOD FOR LARGE HYDROGEN
LIQUEFACTION SYSTEM****Publication Classification**

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Georges Claude, Paris (FR)**(21) Appl. No.: **17/896,036**(22) Filed: **Aug. 25, 2022****Related U.S. Application Data**(60) Provisional application No. 63/104,806, filed on Oct.
23, 2020, provisional application No. 63/293,080,
filed on Dec. 22, 2021.(57) **ABSTRACT**

A method for the liquefaction of hydrogen is provided. The can include the steps of: precooling a hydrogen feed stream in a precooling cold box having a heat exchanger disposed therein to form a cooled hydrogen stream, wherein the heat exchanger is configured to cool down the feed stream within the precooling cold box by indirect heat exchange between the hydrogen feed stream and a precooling refrigerant; and withdrawing the cooled hydrogen stream from the precooling cold box; introducing the cooled hydrogen stream to a plurality of liquefaction cold boxes, wherein the cooled hydrogen stream liquefies within the plurality of liquefaction cold boxes by indirect heat exchange against a liquefaction refrigerant to form a product hydrogen stream in each of the plurality of liquefaction cold boxes, wherein the product hydrogen stream is in liquid form or pseudo-liquid form wherein there are M total precooling cold boxes and N total liquefaction cold boxes, wherein M is less than N.



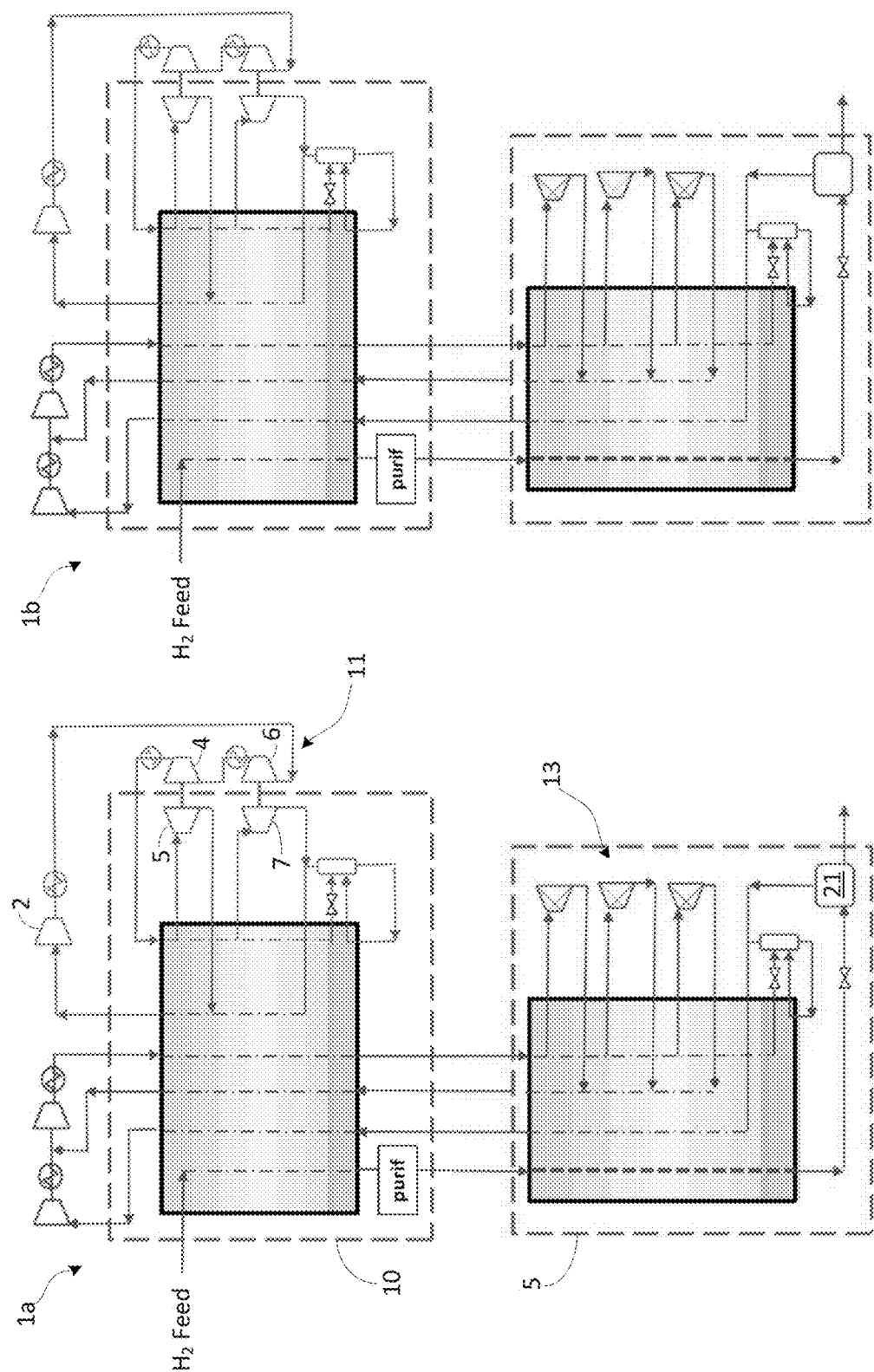


FIG. 1
(Prior Art)

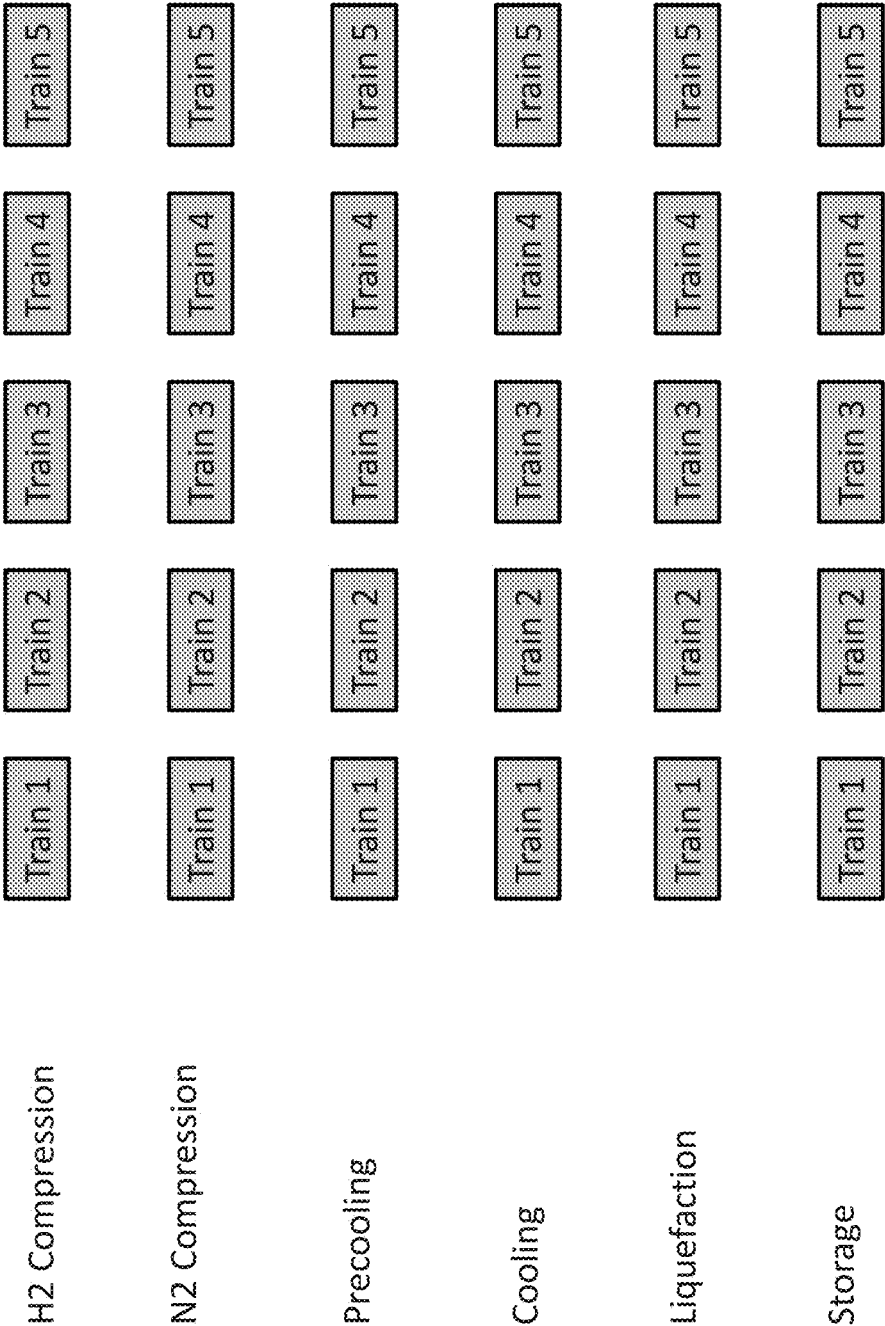


FIG. 2
(Prior Art)

FIG. 3

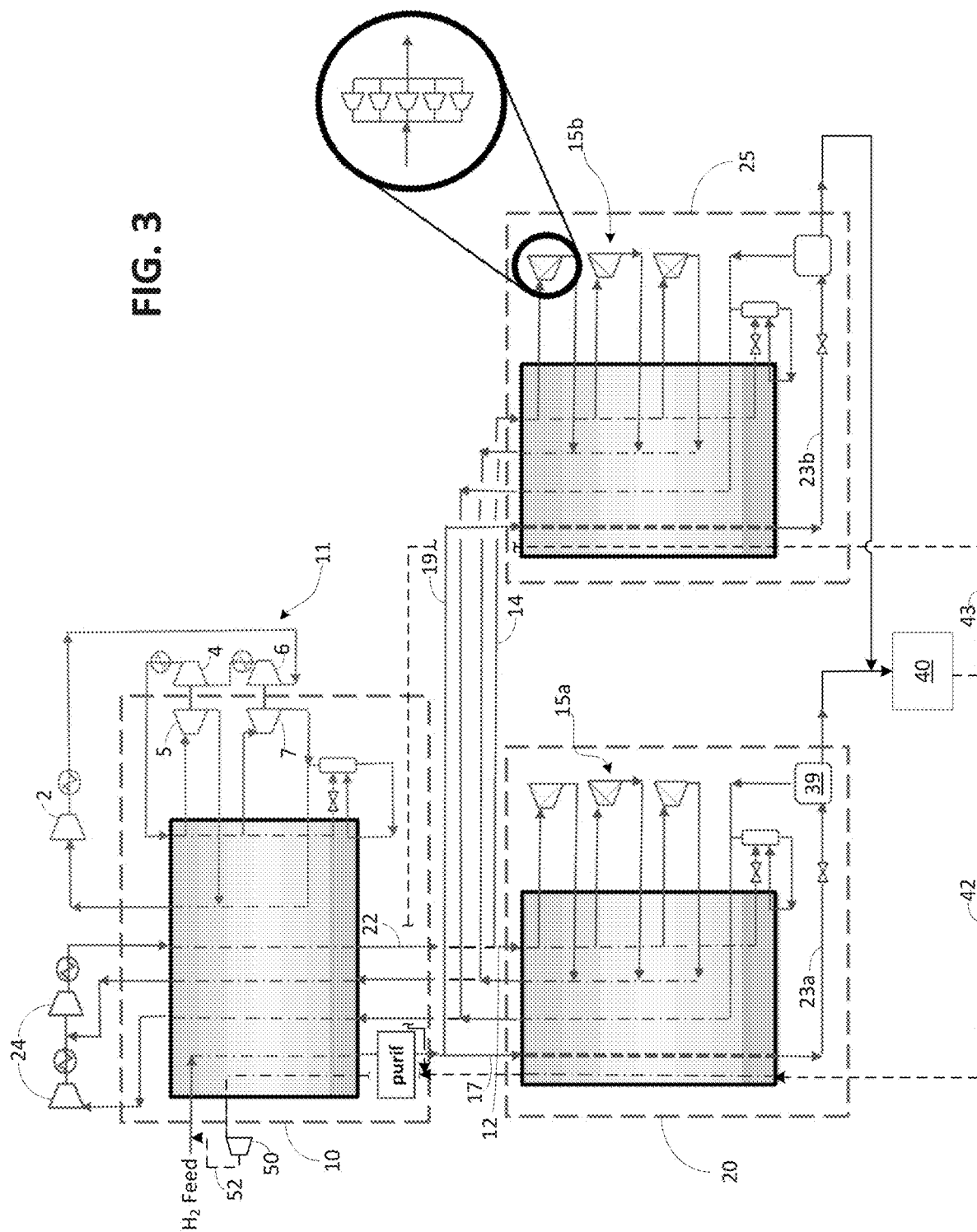
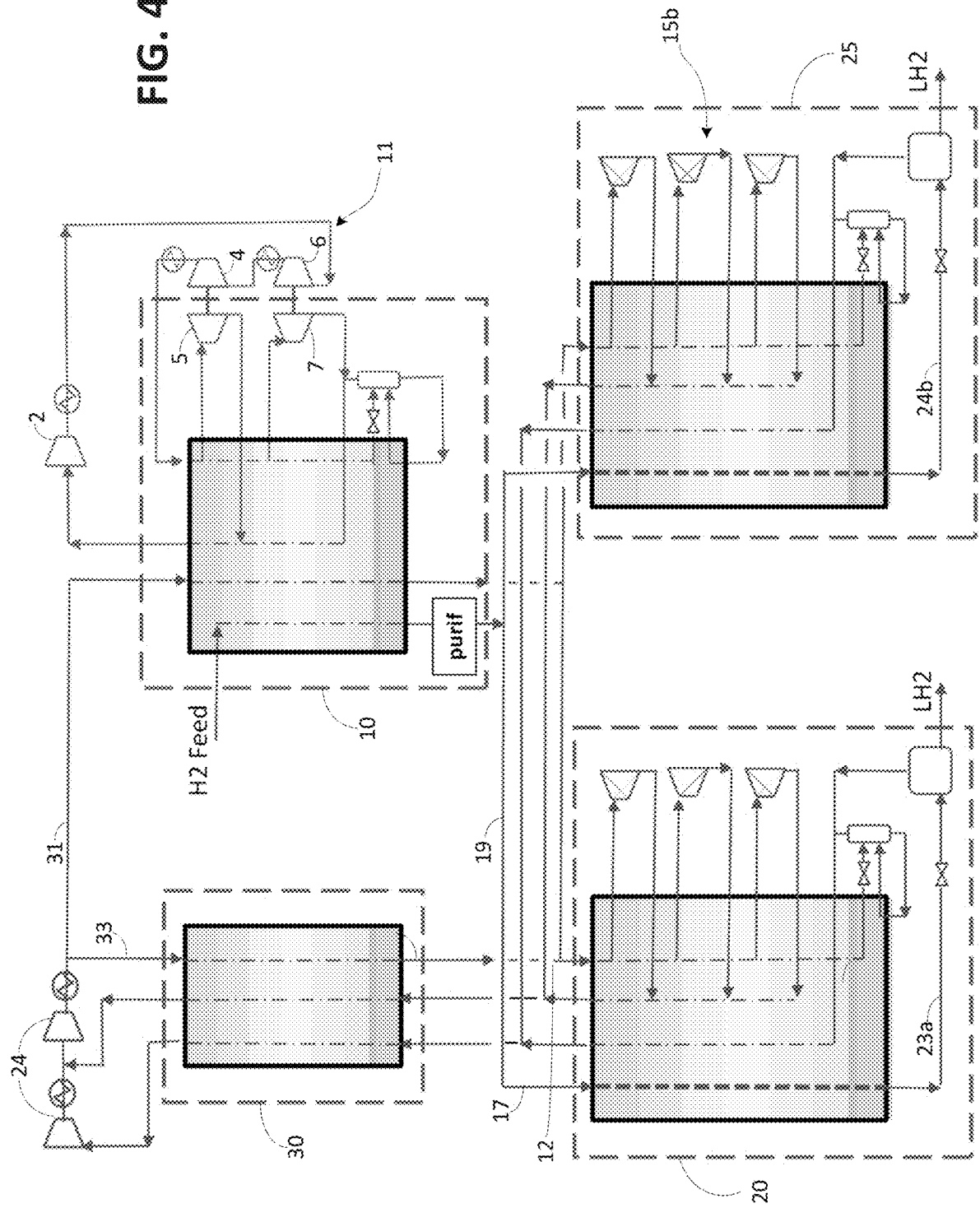


FIG. 4



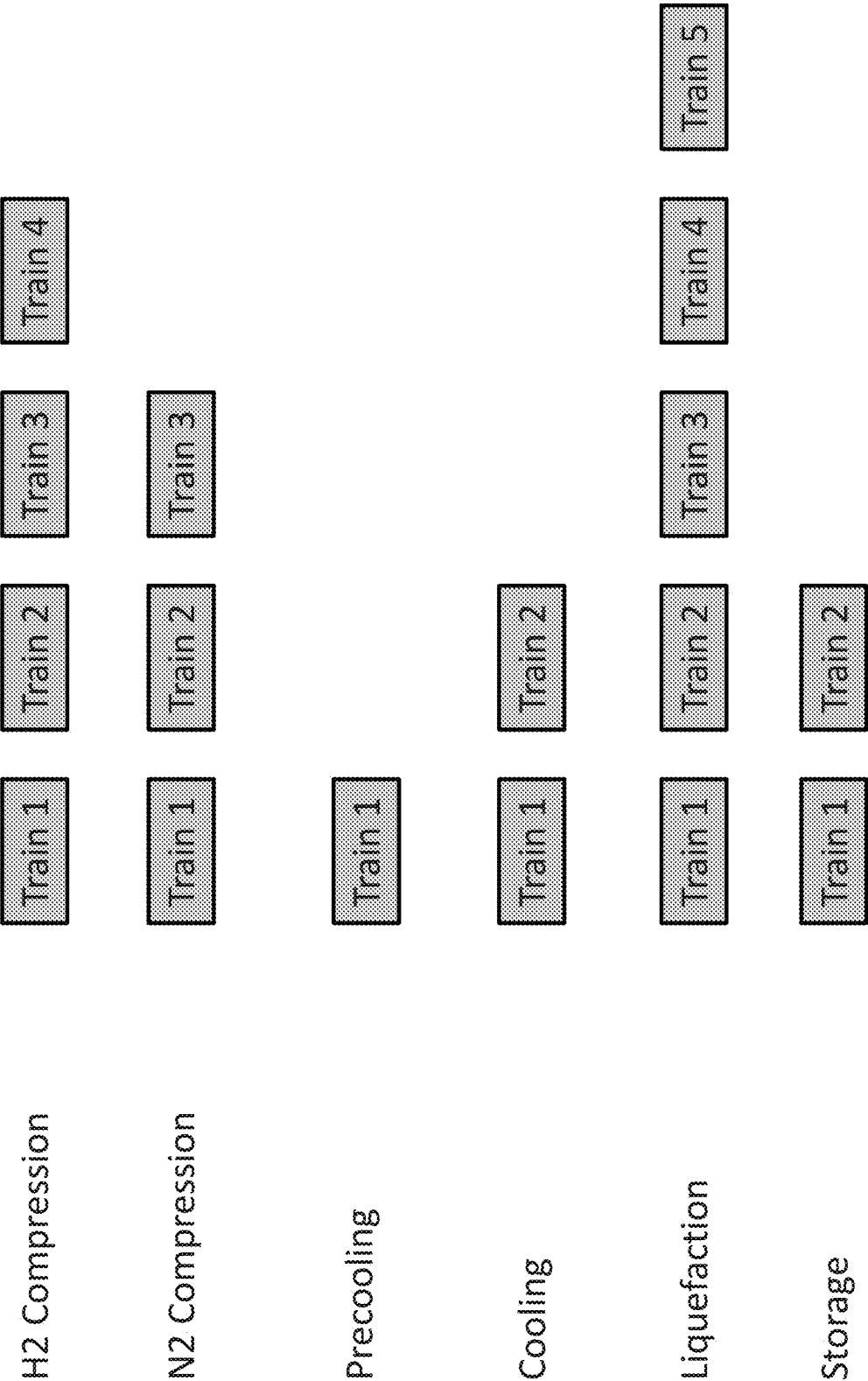


FIG. 5

METHOD FOR LARGE HYDROGEN LIQUEFACTION SYSTEM

CROSS REFERENCE OF RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application Ser. No. 63/104,806 filed on Oct. 23, 2021, and U.S. Provisional Application Ser. No. 63,293,080 filed on Dec. 22, 2021, both of which are hereby incorporated by reference in their entireties.

TECHNICAL FIELD

[0002] The present invention generally relates to a method and apparatus for producing liquid hydrogen, particularly in large quantities.

BACKGROUND OF THE INVENTION

[0003] Hydrogen is a key molecule as a sustainable energy carrier. Liquefaction of hydrogen is key for its transportation and distribution to local markets.

[0004] Hydrogen liquefaction processes require refrigeration over a very wide temperature range (20K to 300K). It is common to have separate dedicated refrigeration systems for the warm end (80K to 300K) and the cold end (20K to 80K) since the specific refrigeration demands and cost vary significantly with temperature. Regarding the warm temperature range (80K to 300K): referenced art exists using a) closed loop N₂ cycle, b) vaporization of LIN from an ASU, c) mixed hydrocarbon refrigerant, and d) optionally pre-cooling to a first temperature (250K to 300K) using NH₃ and/or water. Regarding the cold temperature range (20K to 80K): referenced art exists using closed loop H₂ cycle, He cycle, and/or Ne/He cycles.

[0005] It is known in the art that the largest equipment within the cold boxes are the heat exchangers (typically brazed aluminum). As shown in Table I, the required heat exchanger surface area (which is directly related to UA i.e., heat transfer coefficient x area) significantly decreases at colder temperatures. As a result, typical good engineering practice would be to design multiple modules split by temperature level (and different insulation types) and for each level of temperature to design multiple parallel trains according to heat exchange surface areas. Therefore, normal engineering work will consist of M precooling cold boxes and N liquefaction cold boxes with M>N. In the Table below, MR is mixed refrigerant, N₂ is nitrogen, He is helium, Ne is neon, and H₂ is hydrogen.

TABLE I

Heat Exchanger Surface Area as a Function of Refrigerant Type

	deg C.	deg K.	% of ex-change area						
	25	298							
	0	273			4.4		2.2		167
			68%						
MR	-155	118		MR		MR		MR	
			13%						
N ₂	-185	88	18%	N ₂		N ₂	1	N ₂	
75% He/	-243	30		He/Ne	1	He/Ne		He/Ne	
25% Ne									
H ₂	-251	22	1%	H ₂		H ₂		H ₂	1

[0006] Cold end refrigeration (20K to 80K) is achieved by turbo-expansion and/or isenthalpic expansion and/or vaporization of light gases such as H₂, He, Ne, etc The primary refrigeration is from turbo-expansion due to its high efficiency; however, this equipment is limited in capacity due to the technology of expansion of low molecular weight gases. This is typically partially offset by use of multiple expanders in series or parallel (e.g., 2x50%, 3x33%, etc . . .). However, in the case of hydrogen liquefaction equipment, the limiting capacity constraint of the low molecular weight turbine is on the order of 10 to 30 times less than the limiting capacity constraint of other major process equipment.

[0007] A typical hydrogen liquefaction process may include a precooling section consisting of dual N₂ expanders (1 warm and 1 cold N₂ expanders) and cooling/liquefaction section consisting of H₂ or He expanders. In this example, if one designs the LH₂ liquefaction capacity for maximum utilization of the single warm and cold N₂ turbine frames, then the resulting number of H₂ or He turbine units is in the order of 10.

[0008] Therefore, there is a need for a process and apparatus for an arrangement, which allows for utilization of the larger capacities possible of other equipment.

BRIEF SUMMARY OF THE INVENTION

[0009] The present invention is directed to a device and a method and apparatus that satisfies at least one of these needs.

[0010] A hydrogen liquefaction apparatus comprising a precooling zone and a cooling/liquefaction zone. The precooling zone, which comprises a plurality a precooling units, cools a H₂ feed stream to a first intermediate temperature followed by cooling/liquefaction in the cooling/liquefaction zone. The cooling/liquefaction zone comprises N units such that each unit receives at least a portion of the hydrogen stream, which is split from the precooling zone, wherein the number of Precooling units is less than N. This is surprising and contrary to the conventional wisdom as discussed, supra, and shown in Table I.

[0011] In a first embodiment, the intermediate temperature is in the range of 70K to 300K, and preferably in the range of 70K to 100K. In one embodiment, the precooling zone cools the H₂ stream with a refrigerant comprising one or more of ammonia, mixed hydrocarbons, nitrogen or other know refrigerant.

[0012] In another embodiment, the cooling/liquefaction zone cools the H₂ steam with a refrigerant comprising one or more of hydrogen, helium, neon.

[0013] In another embodiment, there is an intermediate cooling zone where the hydrogen stream is cooled to a second intermediate temperature. Where the number of units of the warm section is less than number of units of the colder section. In optional embodiments, it is possible to include multiple levels of cooling, e.g., (1) water, (2) NH₃ refrigerant, (3) mixed hydrocarbon refrigerant, (4) N₂ refrigerant, and (5) H₂ and/or He refrigerant.

[0014] In another embodiment, at least a portion of the low-pressure refrigerant stream(s) received from the cooling/liquefaction units is sent to a refrigerant precooling unit. At least a portion of the HP refrigerant stream is cooled against lower pressure return refrigerant stream(s).

[0015] In one embodiment, a hydrogen liquefaction apparatus can include: a precooling cold box having a heat

exchanger disposed therein, wherein the heat exchanger is configured to cool down a feed stream within the precooling cold box by indirect heat exchange between the feed stream and a precooling refrigerant; a plurality of liquefaction cold boxes in fluid communication with the precooling cold box, wherein each liquefaction cold box comprises its own heat exchanger, wherein each heat exchanger within the plurality of liquefaction cold boxes is configured to liquefy the feed stream by indirect heat exchange with a liquefaction refrigerant; a precooling refrigeration system configured to provide refrigeration to the precooling zone; and a liquefaction refrigeration system configured to provide the liquefaction refrigerant to the plurality of liquefaction cold boxes, wherein there are M total precooling cold boxes and N total liquefaction cold boxes, wherein M is less than N.

[0016] In optional embodiments of the apparatus:

[0017] the liquefaction refrigeration system comprises a recycle compression system and an expansion system, wherein the recycle compression system is configured to compress the liquefaction refrigerant and the expansion system is configured to expand the liquefaction refrigerant;

[0018] there are M total recycle compression systems and/or N total liquefaction expansion systems;

[0019] the recycle compression system comprises one or more recycle compressors;

[0020] the one or more recycle compressors are arranged in parallel and/or series;

[0021] liquefaction expansion system comprises one or more liquefaction expanders, wherein the one or more liquefaction expanders are arranged in parallel and/or series;

[0022] the liquefaction refrigerant is selected from the group consisting of hydrogen, neon, helium, and combinations thereof;

[0023] the liquefaction refrigerant comprises one or more of hydrogen, neon, and helium;

[0024] the precooling system comprises a precooling refrigeration cycle;

[0025] the precooling refrigerant is selected from the group consisting of nitrogen, argon ammonia, carbon monoxide, carbon dioxide, water, hydrocarbon, mixed hydrocarbons, fluorocarbons, and combinations thereof;

[0026] the precooling refrigerant comprises one or more of nitrogen, argon ammonia, carbon monoxide, carbon dioxide, water, hydrocarbon, mixed hydrocarbons, and fluorocarbons;

[0027] the liquefaction refrigeration system comprises a single, common recycle compression system;

[0028] the apparatus can further include an intermediate cold box in fluid communication with the precooling cold box and the plurality of liquefaction cold boxes, wherein the intermediate cold box is disposed between the precooling cold box and the plurality of liquefaction cold boxes; and/or

[0029] the ratio of N total liquefaction cold boxes to M total precooling cold boxes is between 1.25 and 3.0 ($1.25 \leq N/M \leq 3.0$).

[0030] In another embodiment, a liquefaction apparatus can include: a first cooling cold box configured to receive a feed stream at an initial temperature T_0 and cool the feed stream to form a cooled feed stream at a cooled temperature T_1 ; a first precooling withdrawal line configured to remove the cooled feed stream from the first cooling cold box; a means for splitting the cooled feed stream, wherein the means for splitting the cooled feed stream are in fluid communication with the precooling withdrawal line, a plu-

rality of secondary cold boxes in fluid communication with the means for splitting the cooled feed stream, wherein the plurality of secondary cold boxes are configured to receive the cooled feed stream from the means for splitting the cooled feed stream and liquefy the cooled feed stream therein to form a liquefied stream at a liquefaction temperature T_L , wherein there are M total first cooling cold boxes and N total secondary cold boxes, wherein M is less than N.

[0031] In optional embodiments of the apparatus:

[0032] each secondary cold box comprises its own heat exchanger(s), wherein each heat exchanger within the plurality of secondary cold boxes is configured to liquefy the cooled feed stream by indirect heat exchange with a liquefaction refrigerant;

[0033] the apparatus can further include: a liquefaction refrigeration system, the liquefaction refrigeration system comprising a recycle compression system and an expansion system, wherein the recycle compression system is configured to compress a liquefaction refrigerant and the expansion system is configured to expand the liquefaction refrigerant;

[0034] the apparatus can further include: a means for combining the liquefaction refrigerant, wherein the means for combining the liquefaction refrigerant is configured to receive the liquefaction refrigerant from a warm end of each of the plurality of secondary cold boxes via a plurality of pipes and then send the liquefaction refrigerant, after being combined, to the first cooling cold box via a first return line;

[0035] the apparatus can further include: a second precooling withdrawal line configured to remove the liquefaction refrigeration stream from a cold end of the first cooling cold box; and/or

[0036] the apparatus can further include a means for splitting the liquefaction refrigeration stream, wherein the means for splitting the liquefaction refrigeration stream are in fluid communication with the second precooling withdrawal line.

[0037] In yet another embodiment, a method for the liquefaction of hydrogen can include the steps of: precooling a hydrogen feed stream in a precooling cold box having a heat exchanger disposed therein to form a cooled hydrogen stream, wherein the heat exchanger is configured to cool down the feed stream within the precooling cold box by indirect heat exchange between the hydrogen feed stream and a precooling refrigerant; withdrawing the cooled hydrogen stream from the precooling cold box; and introducing the cooled hydrogen stream to a plurality of liquefaction cold boxes, wherein the cooled hydrogen stream liquefies within the plurality of liquefaction cold boxes by indirect heat exchange against a liquefaction refrigerant to form a product hydrogen stream in each of the plurality of liquefaction cold boxes, wherein the product hydrogen stream is in liquid form or pseudo-liquid form, wherein there are M total precooling cold boxes and N total liquefaction cold boxes, wherein M is less than N.

[0038] In optional embodiments of the method:

[0039] the liquefaction refrigeration system comprises a recycle compression system and an expansion system, wherein the recycle compression system is configured to compress the liquefaction refrigerant and the expansion system is configured to expand the liquefaction refrigerant;

[0040] there are M total recycle compression systems and N total liquefaction expansion systems;

[0041] the recycle compression system comprises one or more recycle compressors;

[0042] the one or more recycle compressors are arranged in parallel or series;

[0043] liquefaction expansion system comprises one or more liquefaction expanders, wherein the one or more liquefaction expanders are arranged in parallel or series;

[0044] the liquefaction refrigerant is selected from the group consisting of hydrogen, neon, helium, and combinations thereof;

[0045] the liquefaction refrigerant comprises one or more of hydrogen, neon, and helium;

[0046] the precooling system comprises a precooling refrigeration cycle;

[0047] the precooling refrigerant is selected from the group consisting of nitrogen, argon, ammonia, carbon monoxide, carbon dioxide, water, hydrocarbon, mixed hydrocarbons, fluorocarbon and combinations thereof;

[0048] the precooling refrigerant comprises one or more of nitrogen, argon, ammonia, carbon monoxide, carbon dioxide, water, hydrocarbon, mixed hydrocarbons, and fluorocarbons;

[0049] the cold end refrigeration cycle comprises a single, common recycle compression system;

[0050] the method can also include an intermediate cold box in fluid communication with the precooling cold box and the plurality of liquefaction cold boxes, wherein the intermediate cold box is disposed between the precooling cold box and the plurality of liquefaction cold boxes;

[0051] the temperature at a cold end of the precooling cold box is in the range of 30K to 250K;

[0052] the temperature at a warm end of the liquefaction zone is in the range of 30K to 150K; and/or

[0053] the ratio of N total liquefaction cold boxes to M total precooling cold boxes is between 1.25 and 3.0 ($1.25 \leq N/M \leq 3.0$).

[0054] In another embodiment, the liquefaction method can include the steps of: introducing a feed stream into a pre-cooling cold box at an initial temperature T_0 and cooling the feed stream therein to form a cooled feed stream at a cooled temperature T_1 ; withdrawing the cooled feed stream from the pre-cooling box using a first precooling withdrawal line; splitting the cooled feed stream into a first cooled feed stream and a second cooled feed stream; providing a plurality of subcooling boxes, wherein the plurality of subcooling cold boxes comprise a first subcooling cold box and a second subcooling cold box; introducing the first cooled feed stream into the first subcooling cold box under conditions effective for subcooling the first cooled feed stream to form a first product stream at a product temperature T_L , wherein the first product stream is in liquid form or a pseudo-liquid form; introducing the second cooled feed stream into a second subcooling cold box under conditions effective for subcooling the second cooled feed stream to form a second product stream, wherein the second product stream is in liquid form or pseudo-liquid form; withdrawing the first and second product streams from the first and second subcooling cold boxes; and combining the first and second product streams into a final product stream.

[0055] In optional embodiments of the liquefaction method:

[0056] each secondary cold box comprises its own heat exchanger, wherein each heat exchanger within the plurality

of secondary cold boxes is configured to liquefy the feed stream by indirect heat exchanger with a liquefaction refrigerant;

[0057] the liquefaction method can also include: a liquefaction refrigeration system, the liquefaction refrigeration system comprising a recycle compression system and an expansion system, wherein the recycle compression system is configured to compress a liquefaction refrigerant and the expansion system is configured to expand the liquefaction refrigerant;

[0058] the liquefaction method can also include: a means for combining the liquefaction refrigerant, wherein the means for combining the liquefaction refrigerant is configured to receive the liquefaction refrigerant from a warm end of each of the plurality of secondary cold boxes via a plurality of pipes and then send the liquefaction refrigerant, after being combined, to the first cooling cold box via a first return line;

[0059] the liquefaction method can also include: a second precooling withdrawal line configured to remove the liquefaction refrigeration stream from the first cooling cold box;

[0060] the liquefaction method can also include: a means for splitting the liquefaction refrigeration stream, wherein the means for splitting the liquefaction refrigeration stream are in fluid communication with the second precooling withdrawal line; and/or

[0061] the feed stream consists essentially of hydrogen.

[0062] The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention.

[0063] It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims. The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages will be better understood from the following description when considered in connection with the accompanying figures. It is to be expressly understood, however, that the figures are provided for the purpose of illustration and description only and are not intended as a definition of the limits of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0064] For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0065] FIG. 1 is a process flow diagram of an embodiment of the prior art.

[0066] FIG. 2 is an embodiment of the prior art.

[0067] FIG. 3 provides an embodiment of the present invention.

[0068] FIG. 4 provides another embodiment of the present invention.

[0069] FIG. 5 provides yet another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0070] Certain embodiments of the invention allow for a reduction in capital expenditures by reducing the number of precooling zones in a hydrogen liquefaction apparatus having a plurality of cold end liquefaction zones. In certain embodiments, the hydrogen liquefaction apparatus can have N cold-end liquefaction zones while also having less than N (e.g., N-1, N-2, N-3, etc . . .) precooling zones.

[0071] As shown in FIG. 1, prior art hydrogen liquefaction units use two identical trains 1a, 1b running separately from each other. Each train includes a precooling zone 10 and a liquefaction zone 5. In the case of FIG. 1, the refrigeration for the precooling zone 10 is provided by a closed loop refrigeration circuit 11, which is provided by compression 2, 4, 6, and expansion 5, 7 of a precooling refrigerant Refrigeration for the liquefaction zone 5 is provided by a second closed loop refrigeration circuit 13.

[0072] FIG. 2 provides a flow chart of a hydrogen liquefaction unit having five trains, with each train having six main sections: hydrogen compression, nitrogen compression, precooling, cooling, liquefaction, and storage. All of these identical trains would be run independently from each other (i.e., the operating conditions of each train have little to no bearing on the operating conditions of another train).

[0073] FIG. 3, which represents an embodiment of the present invention, provides a process flow diagram showing how a hydrogen liquefaction unit, which has two liquefaction zones 20, 25, can have a single precooling zone 10. Refrigeration for the precooling zone 10 is provided by compression 2, 4, 6, and expansion 5, 7 of a precooling refrigerant that is configured to cool the hydrogen feed to a first intermediate temperature in the range of 70K to 300K, more preferably 70K to 100K.

[0074] In one embodiment, the precooling refrigerant can be ammonia, mixed hydrocarbons, nitrogen, or any other known refrigerant.

[0075] Following the precooling zone, the hydrogen feed gas is split 17, 19 and sent to two separate liquefaction zones 20, 25, wherein the hydrogen is condensed 23a, 23b and following removal of any non-condensed gases in gas liquid separator 39, the liquid hydrogen is ultimately sent to a hydrogen liquid storage tank 40. In certain embodiments, the hydrogen can exit the heat exchanger in pseudo-liquid form. As used herein, pseudo-liquid form may include a supercritical fluid that is any substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist.

[0076] In another optional embodiment, boil-off gas 42, 43 that is withdrawn from hydrogen liquid storage tank 40 can be rewarmed in one or both liquefaction zones before being combined and rewarmed more in the precooling zone 10. The warmed boil-off gas can then be compressed 50 to become recycled boil-off gas 52, which can be fed into the hydrogen feed, and/or optionally, can provide make-up gas to the hydrogen recycle (not shown).

[0077] The cold end refrigerant 22, which was also cooled in the precooling zone 10, is withdrawn from the precooling zone 10 and then split into two streams 12, 14, wherein the cold end refrigerant is expanded in a set of turbines (15a, 15b), which preferably have different incoming tempera-

tures, to provide cooling energy for the two liquefaction zones. After providing this cooling energy, the cold end refrigerant is withdrawn from a warm end of the liquefaction zone 20, 25, and further warmed in the precooling zone 10. After fully warming, the cold end refrigerant is then compressed 24 again as part of its refrigeration cycle. As an optional embodiment, each of the expansion turbines of the set of turbines (15a, 15b) can be two or more turbines in parallel.

[0078] FIG. 4 provides an alternate embodiment in which there is again a single precooling zone 10 for the hydrogen feed stream. In this embodiment, however, the cold end refrigerant is not used to provide any precooling energy (e.g., the cold end refrigerant does not reenter the precooling zone 10 for rewarming, but instead enters a separate heat exchanger 30 to provide cooling to one portion of the cold end refrigerant). Rather, all of the precooling of the hydrogen feed stream is done by the precooling refrigerant in the closed loop refrigeration circuit 11. In this way, there is a set of simple standardized modular precooling exchanger(s) and cold box(s) and a separate set of complex custom exchangers and cold box(s). The custom complex set may also comprise most of the project specific complexities such as H₂ Feed, purification, and precooling refrigeration cycle.

[0079] The refrigeration balance between the set of simple exchangers and the set of complex exchangers is made by adjusting the flow split of HP refrigerant between the simple and complex cores (as shown in figure) and/or by splitting one of the lower pressure refrigerant return streams between the simple and complex cores. The number of simple exchangers/cold boxes is independent of the number of complex exchangers/cold boxes. Similarly, there may be a set of modular simple standardized liquefaction exchangers/cold boxes with integrated liquefaction refrigerant system such that the more complex, site specifics (such as H₂ product subcooling and boil-off return) may be managed in a separate customized exchanger/cold box.

[0080] As in FIG. 3, the hydrogen feed stream is again split into two 17, 19 and then further cooled and liquefied in multiple (in this embodiment two) liquefaction zones 20, 25. In FIG. 4, the cold end refrigerant is split into two streams 31, 33, with one stream 31 being first cooled in the precooling zone 10 and the second stream 33 being cooled in a second heat exchanger 30. This second heat exchanger does not include any cooling of the hydrogen feed stream, which thereby allows for greater flexibility of cooling temperatures in this second heat exchanger. For example, the cold end refrigerant 33 in this section could be cooled to a lower temperature than the cold end refrigerant 31 in the precooling zone. Put another way, the cold end temperature of the second heat exchanger can differ from the cold end temperature of the precooling zone.

[0081] Following the first cooling, the two cold end refrigerant streams can be mixed together before being split into two and sent to the two separate liquefaction zones. By combining the two cold end refrigerant streams together, the two streams used for liquefaction the hydrogen in the liquefaction zone should have substantially similar temperatures, thereby allowing identical trains to be used, which greatly reduces engineering design and fabrication costs, thereby reducing complexity. Therefore, the embodiment shown in FIG. 4 provides an advantage of being able to alter the temperature of the cold end refrigerant prior to introducing it to the hydrogen liquefaction unit without that

temperature being directly tied to the hydrogen feed gas that is to be liquefied, and can provide the option for a modular (standardized package) for a portion of the precooling refrigeration system.

[0082] While FIG. 4 does not show the boil-off gas recycle, those of ordinary skill in the art will recognize that the boil-off gas recycle shown in FIG. 3 can also be used with the embodiment shown in FIG. 4. Therefore, the lack of this element in FIG. 4 should not be interpreted to be limiting.

[0083] FIG. 5 provides a process flow chart in accordance with an embodiment of the present invention. As can be seen, this embodiment includes five trains for the liquefaction unit. Therefore, in this embodiment, $N=5$. However, only one train for precooling is needed. This means that the embodiment shown includes four less precooling trains than the embodiments of the prior art. Therefore, embodiments of the present invention are able to produce the same amount of liquid hydrogen as the methods of the prior art, while doing so with less capital expenditures.

[0084] Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations could be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods, and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

[0085] The present invention may suitably comprise, consist or consist essentially of the elements disclosed and may be practiced in the absence of an element not disclosed. Furthermore, if there is language referring to order, such as first and second, it should be understood in an exemplary sense and not in a limiting sense. For example, it can be recognized by those skilled in the art that certain steps can be combined into a single step or reversed in order.

[0086] The singular forms “a”, “an”, “own”, and “the” include plural referents, unless the context clearly dictates otherwise.

[0087] “Comprising” in a claim is an open transitional term which means the subsequently identified claim elements are a nonexclusive listing (i.e., anything else may be additionally included and remain within the scope of “comprising”). “Comprising” as used herein may be replaced by the more limited transitional terms “consisting essentially of” and “consisting of” unless otherwise indicated herein.

[0088] “Providing” in a claim is defined to mean furnishing, supplying, making available, or preparing something. The step may be performed by any actor in the absence of express language in the claim to the contrary a range is expressed, it is to be understood that another embodiment is from the one.

[0089] Optional or optionally means that the subsequently described event or circumstances may or may not occur. The description includes instances where the event or circumstance occurs and instances where it does not occur.

[0090] Ranges may be expressed herein as from about one particular value, and/or to about another particular value. When such particular value and/or to the other particular value, along with all combinations within said range.

[0091] All references identified herein are each hereby incorporated by reference into this application in their entireties, as well as for the specific information for which each is cited.

What is claimed is:

1. A method for the liquefaction of hydrogen, the method comprising the steps of:

precooling a hydrogen feed stream in a precooling cold box having a heat exchanger disposed therein to form a cooled hydrogen stream, wherein the heat exchanger is configured to cool down the feed stream within the precooling cold box by indirect heat exchange between the hydrogen feed stream and a precooling refrigerant; withdrawing the cooled hydrogen stream from the precooling cold box; and

introducing the cooled hydrogen stream to a plurality of liquefaction cold boxes, wherein the cooled hydrogen stream liquefies within the plurality of liquefaction cold boxes by indirect heat exchange against a liquefaction refrigerant to form a product hydrogen stream in each of the plurality of liquefaction cold boxes, wherein the product hydrogen stream is in liquid form or pseudo-liquid form,

wherein there are M total precooling cold boxes and N total liquefaction cold boxes, wherein M is less than N.

2. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the liquefaction refrigeration system comprises a recycle compression system and an expansion system, wherein the recycle compression system is configured to compress the liquefaction refrigerant and the expansion system is configured to expand the liquefaction refrigerant.

3. The method for the liquefaction of hydrogen as claimed in claim 2, wherein there are M total recycle compression systems and N total liquefaction expansion systems.

4. The method for the liquefaction of hydrogen as claimed in claim 2, wherein the recycle compression system comprises one or more recycle compressors.

5. The method for the liquefaction of hydrogen as claimed in claim 4, wherein the one or more recycle compressors are arranged in parallel or series.

6. The method for the liquefaction of hydrogen as claimed in claim 2, wherein liquefaction expansion system comprises one or more liquefaction expanders, wherein the one or more liquefaction expanders are arranged in parallel or series.

7. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the liquefaction refrigerant is selected from the group consisting of hydrogen, neon, helium, and combinations thereof.

8. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the liquefaction refrigerant comprises one or more of hydrogen, neon, and helium.

9. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the precooling system comprises a precooling refrigeration cycle.

10. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the precooling refrigerant is selected from the group consisting of nitrogen, argon, ammonia, carbon monoxide, carbon dioxide, water, hydrocarbon, mixed hydrocarbons, fluorocarbon and combinations thereof.

11. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the precooling refrigerant comprises one or more of nitrogen, argon, ammonia, carbon monoxide, carbon dioxide, water, hydrocarbon, mixed hydrocarbons, and fluorocarbons.

12. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the cold end refrigeration cycle comprises a single, common recycle compression system.

13. The method for the liquefaction of hydrogen as claimed in claim 1, further comprising an intermediate cold box in fluid communication with the precooling cold box and the plurality of liquefaction cold boxes, wherein the intermediate cold box is disposed between the precooling cold box and the plurality of liquefaction cold boxes.

14. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the temperature at a cold end of the precooling cold box is in the range of 30K to 250K.

15. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the temperature at a warm end of the liquefaction zone is in the range of 30K to 150K.

16. The method for the liquefaction of hydrogen as claimed in claim 1, wherein the ratio of N total liquefaction cold boxes to M total precooling cold boxes is between 1.25 and 3.0 ($1.25 \leq N/M \leq 3.0$).

17. A liquefaction method comprising the steps of:

introducing a feed stream into a pre-cooling cold box at an initial temperature T_0 and cooling the feed stream therein to form a cooled feed stream at a cooled temperature T_1 ;

withdrawing the cooled feed stream from the pre-cooling box using a first precooling withdrawal line;

splitting the cooled feed stream into a first cooled feed stream and a second cooled feed stream;

providing a plurality of subcooling boxes, wherein the plurality of subcooling cold boxes comprise a first subcooling cold box and a second subcooling cold box introducing the first cooled feed stream into the first subcooling cold box under conditions effective for subcooling the first cooled feed stream to form a first

product stream at a product temperature T_L , wherein the first product stream is in liquid form or a pseudo-liquid form;

introducing the second cooled feed stream into a second subcooling cold box under conditions effective for subcooling the second cooled feed stream to form a second product stream, wherein the second product stream is in liquid form or pseudo-liquid form;

withdrawing the first and second product streams from the first and second subcooling cold boxes; and combining the first and second product streams into a final product stream.

18. The liquefaction method as claimed in claim 17, wherein each secondary cold box comprises its own heat exchanger, wherein each heat exchanger within the plurality of secondary cold boxes is configured to liquefy the feed stream by indirect heat exchanger with a liquefaction refrigerant.

19. The liquefaction method as claimed in claim 18, further comprising a liquefaction refrigeration system, the liquefaction refrigeration system comprising a recycle compression system and an expansion system, wherein the recycle compression system is configured to compress a liquefaction refrigerant and the expansion system is configured to expand the liquefaction refrigerant.

20. The liquefaction method as claimed in claim 18, further comprising a means for combining the liquefaction refrigerant, wherein the means for combining the liquefaction refrigerant is configured to receive the liquefaction refrigerant from a warm end of each of the plurality of secondary cold boxes via a plurality of pipes and then send the liquefaction refrigerant, after being combined, to the first cooling cold box via a first return line.

21. The liquefaction method as claimed in claim 18, further comprising a second precooling withdrawal line configured to remove the liquefaction refrigeration stream from the first cooling cold box.

22. The liquefaction method as claimed in claim 21, further comprising a means for splitting the liquefaction refrigeration stream, wherein the means for splitting the liquefaction refrigeration stream are in fluid communication with the second precooling withdrawal line.

23. The liquefaction method as claimed in claim 17, wherein the feed stream consists essentially of hydrogen.

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