CLAIMS

1. A hydrogen liquefaction method, comprising:

providing a purified gaseous hydrogen feed stream, wherein the purified gaseous hydrogen feed stream comprises about 75% ortho-hydrogen and 25% para-hydrogen, and further wherein the purified gaseous hydrogen feed stream comprises a pressure within the range of 800kPa.G to 4,000kPa.G and a temperature of about 300K;

providing a first hydrogen circulation compressor and a second hydrogen circulation compressor, wherein the first hydrogen circulation compressor discharges a first hydrogen circulation compressor final stage discharge stream, and further wherein the second hydrogen circulation compressor discharges a second hydrogen circulation compressor final stage discharge stream;

combining the purified gaseous hydrogen feed stream and a mixed intermediate-pressure circulation gaseous hydrogen stream inside a second hydrogen circulation compressor forming a second hydrogen circulation compressor final stage discharge stream, wherein the second hydrogen circulation compressor final stage discharge stream comprises a higher pressure within the range of 3200kPa.G to 4000kPa.G;

splitting the second hydrogen circulation compressor final stage discharge stream into a first split gaseous hydrogen stream and a second split gaseous hydrogen stream;

cooling the first split gaseous hydrogen stream to about 82K inside a precooling main heat exchanger to form a first cold gaseous hydrogen stream;

purifying the first cold gaseous hydrogen stream inside a swing hydrogen absorption bed system to form a deep purified cold gaseous hydrogen stream;

passing the deep purified cold gaseous hydrogen stream through a fixed-bed catalyst ortho-para hydrogen converter, wherein the deep purified cold gaseous hydrogen stream forms a first p-H2 enriched gaseous hydrogen stream, wherein the first p-H2 enriched gaseous hydrogen stream comprises a new equilibrium composition of about 53% ortho-hydrogen and about 47% para-hydrogen, and further wherein the first p-H2 enriched gaseous hydrogen

stream increases in temperature due to the exothermic process of the ortho to para hydrogen conversion;

cooling the first p-H2 enriched gaseous hydrogen stream inside the precooling main heat exchanger to form a first cold p-H2 enriched gaseous hydrogen stream, wherein the temperature of the first cold p-H2 enriched gaseous hydrogen stream is reduced to 82K;

cooling the first cold p-H2 enriched gaseous hydrogen stream inside a catalyst filled intermediate-temperature ortho-para hydrogen converter of an intermediate temperature main heat exchanger to form a second cold p-H2 enriched gaseous hydrogen stream, wherein the second cold p-H2 enriched gaseous hydrogen stream comprises a temperature of about 40K;

converting ortho-hydrogen to para-hydrogen in the second cold p-H2 enriched gaseous hydrogen stream inside the catalyst filled intermediate-temperature ortho-para hydrogen converter of the intermediate temperature main heat exchanger, wherein the second cold p-H2 enriched gaseous hydrogen stream comprises a new equilibrium composition of about 11% ortho-hydrogen and about 89% para-hydrogen;

cooling the second cold p-H2 enriched gaseous hydrogen stream inside a catalyst filled low-temperature ortho-para hydrogen converter of a cold temperature main heat exchanger to form a subcooled high-pressure p-H2 enriched liquid hydrogen stream, wherein the subcooled high-pressure p-H2 enriched liquid hydrogen stream comprises a temperature of about 23.5K;

converting ortho-hydrogen to para-hydrogen in the subcooled high-pressure p-H2 enriched liquid hydrogen stream inside the catalyst filled low-temperature ortho-para hydrogen converter of the cold temperature main heat exchanger, wherein the subcooled high-pressure p-H2 enriched liquid hydrogen stream comprises a new equilibrium composition of about 1% ortho-hydrogen and about 89% para-hydrogen;

reducing the pressure of the subcooled high-pressure p-H2 enriched liquid hydrogen stream with a J/T valve to form a low-pressure liquid hydrogen product stream, wherein the low-pressure liquid hydrogen product stream comprises a pressure of about 50kPa.G and temperature of about 21.7K;

feeding the low-pressure liquid hydrogen product stream into a liquid hydrogen storage tank;

removing a flashed gaseous hydrogen stream from the liquid hydrogen storage tank through a pressure control valve;

feeding the flashed gaseous hydrogen stream into a hydrogen pressure let-down valve, wherein the flashed gaseous hydrogen stream exits the hydrogen pressure let-down valve as an optimized hydrogen Claude cycle hydrogen makeup stream; and

sending the optimized hydrogen Claude cycle hydrogen makeup stream to an optimized hydrogen Claude half-opened cycle system, wherein the optimized hydrogen Claude cycle hydrogen makeup stream mixes with a low-pressure thermosiphon hydrogen vapor stream to form a mixed first hydrogen thermosiphon vapor stream.

2. The hydrogen liquefaction method of claim 1, wherein the precooling main heat exchanger comprises a plate-fin brazed aluminum type heat exchanger.

3. The hydrogen liquefaction method of claim 1, wherein the intermediate temperature main heat exchanger comprises a plate-fin brazed aluminum type heat exchanger.

4. The hydrogen liquefaction method of claim 1, wherein the cold temperature main heat exchanger comprises a plate-fin brazed aluminum type heat exchanger.

5. The hydrogen liquefaction method of claim 1 further comprising the following steps:

providing a high-pressure circulation nitrogen stream, wherein the high-pressure circulation nitrogen stream comprises a pressure of about 4,425kPa.G and a temperature of about 313K;

cooling the high-pressure circulation nitrogen stream inside the precooling main heat exchanger;

splitting the high-pressure circulation nitrogen stream into the following three streams: a warm nitrogen turbo-expander feed stream, wherein the warm nitrogen turbo-expander feed stream comprises a temperature of about 286K; a cold nitrogen turbo-expander feed stream, wherein the cold nitrogen turbo-expander feed stream comprises a temperature of about 174K; and a subcooled high-pressure circulation liquid nitrogen stream, wherein the subcooled high-pressure circulation liquid nitrogen stream comprises a temperature of about 111K;

splitting the subcooled high-pressure circulation liquid nitrogen stream into a first subcooled high-pressure circulation liquid nitrogen stream and a second subcooled high-pressure circulation liquid nitrogen stream;

feeding the first subcooled high-pressure circulation liquid nitrogen stream into a first circulation liquid nitrogen pressure let-down valve, wherein the pressure of the first subcooled high-pressure circulation liquid nitrogen stream is reduced to about 40kPa.G, and further wherein the temperature of the first subcooled high-pressure circulation liquid nitrogen stream is reduced to about 80.3K;

introducing a low-pressure cold circulation nitrogen stream from the first circulation liquid nitrogen pressure let-down valve into a low-pressure nitrogen thermosiphon vessel, wherein the low-pressure cold circulation nitrogen stream is separated into a low-pressure thermosiphon nitrogen liquid stream and a low-pressure thermosiphon nitrogen vapor stream;

introducing the low-pressure thermosiphon nitrogen liquid stream into the precooling main heat exchanger;

vaporizing the low-pressure thermosiphon nitrogen liquid stream inside the precooling main heat exchanger;

mixing the totally vaporized low-pressure thermosiphon nitrogen liquid stream with the low-pressure thermosiphon nitrogen vapor stream in the precooling main heat exchanger to form a low-pressure thermosiphon nitrogen mixed stream;

warming the low-pressure thermosiphon nitrogen mixed stream in the precooling main heat exchanger;

flowing the warmed low-pressure thermosiphon nitrogen mixed stream out of the precooling main heat exchanger as a low-pressure circulation gaseous nitrogen stream, wherein the low-pressure circulation gaseous nitrogen stream is employed as a feed stream for a first nitrogen circulation compressor;

compressing the low-pressure circulation gaseous nitrogen stream inside the first nitrogen circulation compressor to a pressure about 525kPa.G to form a first nitrogen circulation compressor discharge stream;

commingling the first nitrogen circulation compressor discharge stream from the first nitrogen circulation compressor with an intermediate-pressure circulation gaseous nitrogen stream to form a mixed intermediate-pressure circulation gaseous nitrogen stream;

flowing the second subcooled high-pressure circulation liquid nitrogen stream to a second circulation liquid nitrogen pressure let-down valve, wherein the pressure of the second subcooled high-pressure circulation liquid nitrogen stream is reduced to about 565kPa.G, and further wherein the temperature of the second subcooled high-pressure circulation liquid nitrogen stream is reduced to about 98K;

removing an intermediate-pressure cold circulation nitrogen stream from the second circulation liquid nitrogen pressure let-down valve;

introducing the intermediate-pressure cold circulation nitrogen stream to an intermediate-pressure nitrogen thermosiphon vessel, wherein the intermediate-pressure cold circulation nitrogen stream is separated into an intermediate-pressure thermosiphon nitrogen liquid stream and an intermediate-pressure thermosiphon nitrogen vapor stream;

introducing the intermediate-pressure thermosiphon nitrogen liquid stream into the precooling main heat exchanger;

vaporizing the intermediate-pressure thermosiphon nitrogen liquid stream in the precooling main heat exchanger;

mixing the totally vaporized intermediate-pressure thermosiphon nitrogen liquid stream with the intermediate-pressure thermosiphon nitrogen vapor stream in the precooling main heat exchanger to form an intermediate-pressure thermosiphon nitrogen mixed stream;

warming the intermediate-pressure thermosiphon nitrogen mixed stream in the precooling main heat exchanger;

mixing the intermediate-pressure thermosiphon nitrogen mixed stream with a cold nitrogen turbo-expander discharge stream to form a first nitrogen mixed stream, wherein the first nitrogen mixed stream comprises a temperature of about 105K;

warming the first nitrogen mixed stream in the precooling main heat exchanger;

mixing the first nitrogen mixed stream with a warm nitrogen turbo-expander discharge stream to form a second nitrogen mixed stream, wherein the combined second nitrogen mixed stream comprises a temperature of about 180K;

warming the second nitrogen mixed stream in the precooling main heat exchanger to a temperature of about 311K;

flowing the second nitrogen mixed stream out of the precooling main heat exchanger as the intermediate-pressure circulation gaseous nitrogen stream;

expanding the high-pressure warm nitrogen turbo-expander feed stream in a warm nitrogen turbo-expander to form the warm nitrogen turbo-expander discharge stream, wherein the warm nitrogen turbo-expander discharge stream comprises a lower pressure of about 543kPa.G and a temperature of about 180K;

expanding the high-pressure cold nitrogen turbo-expander feed stream in a cold nitrogen turbo-expander to form the cold nitrogen turbo-expander discharge stream, wherein the cold nitrogen turbo-expander discharge stream comprises a lower pressure of about 560kPa.G and a temperature of about 105K; and

compressing the mixed intermediate-pressure circulation gaseous nitrogen stream in a second nitrogen circulation compressor to the high-pressure circulation nitrogen stream, wherein the high-pressure circulation nitrogen stream comprises a pressure of about 4425kPa.G.

6. The method of claim 5, further comprising a warm temperature coldbox, wherein the

warm temperature coldbox comprises perlites, and further wherein the warm temperature coldbox comprises the precooling main heat exchanger, a first hydrogen purification absorption bed, a second hydrogen purification absorption bed, the fixed-bed catalyst ortho-para hydrogen converter, the first circulation liquid nitrogen pressure let-down valve, the low-pressure nitrogen thermosiphon vessel, the second circulation liquid nitrogen pressure let-down valve, and the intermediate-pressure nitrogen thermosiphon vessel.

7. The hydrogen liquefaction method of claim 5, wherein the first nitrogen circulation compressor comprises a multistage compressor with a cooler on each stage discharge.

8. The hydrogen liquefaction method of claim 7, wherein the first nitrogen circulation compressor comprises a two-stage oil-free reciprocating compressor.

9. The hydrogen liquefaction method of claim 7, wherein the first nitrogen circulation compressor comprises a three-stage oil-free reciprocating compressor.

10. The hydrogen liquefaction method of claim 5, wherein the second nitrogen circulation compressor comprises a multistage compressor with a cooler on each stage discharge.

11. The hydrogen liquefaction method of claim 10, wherein the second nitrogen circulation compressor comprises a four-stage integrally-geared type centrifugal compressor.

12. The hydrogen liquefaction method of claim 11, wherein the four-stage integrally-geared type centrifugal compressor is integrated with the warm nitrogen turbo expander and the cold nitrogen turbo-expander to form an integrated nitrogen compander.

13. The hydration liquefaction method of claim 5, wherein the warm nitrogen turbo-expander and the cold nitrogen turbo-expander are arranged in parallel with about the same expansion pressure ratio in range of 7 to 8.

14. The hydrogen liquefaction method of claim 5, wherein the first nitrogen circulation compressor is combined with the integrated nitrogen compander on a common integral-gear.

15. The hydrogen liquefaction method of claim 1, further comprising:

providing a high-pressure circulation hydrogen stream, wherein the high-pressure circulation hydrogen stream comprises a pressure within the range of about 3,500kPa.G to 4,400kPa.G and a temperature of about 313K;

cooling the high-pressure circulation hydrogen stream in the precooling main heat exchanger to form a first cold high-pressure circulation hydrogen stream, wherein the first cold high-pressure circulation hydrogen stream comprises a temperature of about 82K;

further cooling the first cold high-pressure circulation hydrogen stream in the intermediate temperature main heat exchanger;

withdrawing a first hydrogen turbo-expander feed stream from the further cooled first cold high-pressure circulation hydrogen stream, wherein the first hydrogen turbo-expander feed stream comprises a temperature within the range of 61K to 65K, and further wherein the remaining further cooled first cold high-pressure circulation hydrogen stream is further cooled to a temperature of about 40K;

removing a second cold high-pressure circulation hydrogen stream from the intermediate temperature main heat exchanger;

cooling the second cold high-pressure circulation hydrogen stream in the cold temperature main heat exchanger to form a subcooled high-pressure circulation liquid hydrogen stream, wherein the subcooled high-pressure circulation liquid hydrogen stream comprises a temperature of about 32K;

splitting the subcooled high-pressure circulation liquid hydrogen stream into a first subcooled high-pressure circulation liquid hydrogen stream and a second subcooled high-pressure circulation liquid hydrogen stream;

reducing the pressure of the first subcooled high-pressure circulation liquid hydrogen stream in a first circulation liquid hydrogen pressure let-down valve to about 50kPa.G forming a low-pressure cold circulation hydrogen stream, wherein the low-pressure cold circulation hydrogen stream comprises a temperature of about 21.7K, and further wherein the low-pressure cold circulation hydrogen stream comprises vapor flash-out;

separating the low-pressure cold circulation hydrogen stream in a low-pressure hydrogen thermosiphon vessel into a low-pressure thermosiphon hydrogen vapor stream and a low-pressure thermosiphon hydrogen liquid stream;

vaporizing the low-pressure thermosiphon hydrogen liquid in the cold temperature main heat exchanger;

mixing the totally vaporized low-pressure thermosiphon hydrogen liquid with the mixed first hydrogen thermosiphon vapor stream to form a mixed low-pressure thermosiphon hydrogen stream;

warming the mixed low-pressure thermosiphon hydrogen stream to form a cold low-pressure circulation gaseous hydrogen stream, wherein the cold low-pressure circulation gaseous hydrogen stream comprises a temperature of about 38.5K;

further warming the cold low-pressure circulation gaseous hydrogen stream in the intermediate temperature main heat exchanger to form an intermediate temperature low-pressure circulation gaseous hydrogen stream, wherein the intermediate temperature low-pressure circulation gaseous hydrogen stream comprises a temperature of about 80.3K;

further warming the intermediate temperature low-pressure circulation gaseous hydrogen stream in the precooling main heat exchanger to form a low-pressure circulation gaseous hydrogen stream, wherein the low-pressure circulation gaseous hydrogen stream comprises a temperature of about 311K;

compressing the low-pressure circulation gaseous hydrogen stream in the first hydrogen circulation compressor to form a first hydrogen circulation compressor discharge stream, wherein the first hydrogen circulation compressor discharge stream comprises a pressure of 790kPa.G;

commingling the compressed first hydrogen circulation compressor discharge stream with an intermediate-pressure circulation gaseous hydrogen stream to form a mixed intermediate-pressure circulation gaseous hydrogen stream;

reducing the pressure of the second subcooled high-pressure circulation liquid hydrogen stream in a second circulation liquid hydrogen pressure let-down valve to form an intermediate-pressure cold circulation hydrogen stream, wherein the intermediate-pressure

cold circulation hydrogen stream comprises a pressure of about 815kPa.G and a temperature of about 30.7K, and further wherein the intermediate-pressure cold circulation hydrogen stream comprises vapor flash-out;

separating the intermediate-pressure cold circulation hydrogen stream in an intermediate-pressure hydrogen thermosiphon vessel into an intermediate-pressure thermosiphon hydrogen liquid stream and an intermediate-pressure thermosiphon hydrogen vapor stream;

vaporizing the intermediate-pressure thermosiphon hydrogen liquid stream in the cold temperature main heat exchanger;

mixing the totally vaporized intermediate-pressure thermosiphon hydrogen liquid stream with the second hydrogen thermosiphon vapor stream to form a mixed hydrogen vapor stream;

further warming the mixed hydrogen vapor stream in the cold temperature main heat exchanger to form a first cold intermediate-pressure circulation gaseous hydrogen stream, wherein the cold intermediate-pressure circulation gaseous hydrogen stream comprises a temperature of about 38.5K;

mixing the first cold intermediate-pressure circulation gaseous hydrogen stream with the second hydrogen turbo-expander discharge stream to form a second cold intermediate-pressure circulation gaseous hydrogen stream;

warming the second cold intermediate-pressure circulation gaseous hydrogen stream in the intermediate temperature main heat exchanger to form an intermediate temperature intermediate-pressure circulation gaseous hydrogen stream, wherein the intermediate temperature intermediate-pressure circulation gaseous hydrogen stream comprises a temperature of about 80.3K;

further warming the intermediate temperature intermediate-pressure circulation gaseous hydrogen stream in the precooling main heat exchanger to form an intermediate-pressure circulation gaseous hydrogen stream, wherein the intermediate-pressure circulation gaseous hydrogen stream comprises a temperature of about 311K;

expanding a high-pressure first hydrogen turbo-expander feed stream in a first hydrogen turbo-expander to form a lower pressure as a lower pressure first hydrogen turbo-expander discharge stream;

further expanding the lower pressure first hydrogen turbo-expander discharge stream in a second hydrogen turbo-expander to form a second hydrogen turbo-expander discharge stream, wherein the second hydrogen turbo-expander discharge stream comprises a pressure of about 805kPa.G and a temperature of about 38K;

compressing the second split gaseous hydrogen stream in a second hydrogen exp-compressor to form a higher pressure as a second hydrogen exp-compressor discharge stream;

further compressing the second hydrogen exp-compressor discharge stream in a first hydrogen exp-compressor to form a first hydrogen exp-compressor discharge stream, wherein the first hydrogen exp-compressor discharge stream comprises a pressure in the range of about 3,500kPa.G to 4,400kPa.G; and

cooling the first hydrogen exp-compressor discharge stream in an exp-compressor discharge cooler to form the high-pressure circulation hydrogen stream, wherein the high-pressure circulation hydrogen stream comprises a temperature of about 313K.

16. The method of claim 15, wherein the first hydrogen exp-compressor is driven by the first hydrogen turbo-expander to form a first expander set, and the second hydrogen exp-compressor is driven by the second hydrogen turbo-expander to form a second expander set.

17. The method of claim 16, wherein the first expander set and the second expander set are arranged in serial connection.

18. The method of claim 16, wherein the first expander set and the second expander set are magnetic bearing type sets.

19. The method of claim 15, wherein the first hydrogen circulation compressor and the second hydrogen circulation compressor are integrated by a common crank shaft to form an integrated hydrogen circulation compressor.

20. The method of claim 15, further comprising a cold temperature coldbox, wherein the cold temperature coldbox comprises a multilayer insulation vacuum, and further wherein the cold temperature coldbox comprises product liquid hydrogen pressure let-down valve, the liquid hydrogen storage tank pressure control valve, the first circulation liquid hydrogen pressure let-down valve, the low-pressure hydrogen thermosiphon vessel, the second circulation liquid hydrogen pressure let-down valve, the intermediate-pressure hydrogen thermosiphon vessel, the first hydrogen turbo-expander, the second hydrogen turbo-expander, the intermediate temperature main heat exchanger, and the cold temperature main heat exchanger.