SYSTEM AND METHOD FOR NATURAL GAS LIQUEFACTION

Field of the Invention

[0001] The present invention relates generally to the technology of natural gas liquefaction, and more particularly to a system and method for natural gas liquefaction employing a plurality of turboexpanders configured into a series arrangement.

Background of the Invention

[0002] To transport the natural gas in a more efficient way, it is important to liquefy it into liquefied natural gas (LNG) for transportation, which enables to shrink the volume of the natural gas by 600 times so it can be shipped to customers in other parts of the world. Many LNG liquefaction plants utilize a refrigeration cycle with mixed refrigerants where cooling is generally achieved by heat exchange using refrigerant with one or more compositions including propane, propylene, ethane, ethylene, methane and nitrogen or mixtures thereof, in a closed loop or open loop configuration. Mixed refrigerant cycles are efficient as they can closely approach the cooling curve of the natural gas and multi-component refrigerants at different stages of the liquefaction process utilizing the latent heat of refrigerant vaporization.

[0003] For the offshore natural gas liquefaction, nitrogen expander cycles are recommended, because it is safer and much less risk of environmental concern for the refrigerant leakage, comparing to mixed refrigerant based LNG processes. Furthermore, hydrocarbon refrigerants storage is not required for nitrogen cycles.

[0004] It is well known that Reversed Brayton Cycle is used for the liquefaction of natural gas. However, the performance of LNG process is limited by several factors, such as the maximum temperature approach limitation of the main cryogenic heat exchanger, and the limited expansion ratio achieved by a single expander. Normally the more expansion ratio the expander can achieve, the more efficient for the LNG liquefaction process, and the less refrigerant flow rate is required for the refrigeration cycles.

[0005] Prior arts have disclosed natural gas liquefaction processes based on Nitrogen Expander cycles utilizing dual/three turboexpanders in a closed-loop nitrogen refrigeration cycle. The nitrogen stream is split into two/three streams before expanded by

two/three expanders in parallel to reach different cooling temperature for the liquefaction of natural gas. The flow rate adjusting of the split nitrogen streams makes the cooling curves a close fit, which thus improves the process efficiency. As shown in FIG 12, there is provided a natural gas liquefaction system with a dual expanders in a parallel configuration in the prior art. The feed gas **101**, gas treatment module **102**, main cryogenic heat exchanger **103**, natural gas heat exchange means **131** natural gas pressure reduction means **104**, flash drum **105**, LNG **106**, flash gas heat exchange means **132**, flash gas compressor **107**, flash gas aftercooler **108**, fuel gas **109**, first refrigerant compressor **111**, first refrigerant aftercooler **112**, second refrigerant compressor **113**, second refrigerant aftercooler **114**, first refrigerant recompressor **115** , second refrigerant recompressor **117**, fourth refrigerant aftercooler **118**, first refrigerant heat exchange means **133** and second refrigerant heat exchange means **134** are similar to the corresponding components shown in FIG 1 (described in detail hereinbelow). The first turboexpander **119** and second turboexpander **120** are configured into a parallel arrangement so that the nitrogen stream from the first refrigerant heat exchange means **133** is split into two, one feeding into the first turboexpander **119** and the other into the second turboexpander **120**, the downstreams from both expanders are directly fed back into the second refrigerant heat exchange means **134**. However, the refrigerant mass flow rate in these processes is high.

[0006] Therefore, there is a need in the art to develop a natural gas liquefaction system and method with improved efficiency and reduced refrigerant flow rate.

Summary of the Invention

[0007] One objective of this invention is to provide an LNG production system with improved refrigeration efficiency.

[0008] One aspect of the present invention provides a liquefied natural gas (LNG) production system. In one embodiment, the LNG production system comprises a main cryogenic heat exchanger, a natural gas liquefaction subsystem, and a refrigeration subsystem comprising a plurality of refrigerant compressors configured into a series arrangement to perform multi-stage compressions of a refrigerant, a plurality of aftercoolers each of which being coupled to each of the plurality of refrigerant compressors to cool the compressed refrigerant, a plurality of turboexpanders coupled to the last

aftercooler and configured into a series configuration to perform multi-stage expansions of the compressed refrigerant, and a plurality of refrigerant heat exchange means coupled to both the first of the plurality of refrigerant compressors and the last of the plurality of turboexpanders, so that all components form a close refrigeration cycle; wherein the main cryogenic heat exchanger facilitates heat exchange between a pressurized natural gas passing through the natural gas liquefaction subsystem and a refrigerant passing through the refrigeration subsystem so that the pressurized natural gas in the natural gas liquefaction subsystem is liquefied by the refrigerant in the refrigeration subsystem.

[0009] In another embodiment of the LNG production system, the main cryogenic heat exchanger is a multi-stream heat exchanger.

[0010] In another embodiment of the LNG production system, the natural gas liquefaction subsystem comprises a gas treatment module for treating the pressurized natural gas so as to make it suitable for being liquefied, a natural gas heat exchange means fluidly/gaseously coupled with the gas treatment module and disposed within the main cryogenic heat exchanger for enabling the passing-through pressurized natural gas to exchange heat with countercurrent refrigerant flows, and a natural gas pressure reduction means fluidly/liquidusly coupled with the natural gas heat exchange means for controlling the reduction of the pressures of the pressurized liquefied natural gas from the natural gas heat exchange means so as to further reduce the temperature of the pressurized liquefied natural gas, yielding LNG and flash gas.

[0011] In another embodiment of the LNG production system, the natural gas pressure reduction means is Joule-Thomson (J-T) valve, two-phase expander or liquid expander.

[0012] In another embodiment of the LNG production system, the refrigeration subsystem comprises a first refrigerant compressor, a first refrigerant aftercooler coupled to the first refrigerant compressor, a second refrigerant compressor coupled to the first refrigerant aftercooler, a second refrigerant aftercooler coupled to the second refrigerant compressor, a first refrigerant recompressor coupled to the second refrigerant aftercooler, a third refrigerant aftercooler coupled to the first refrigerant recompressor, a second refrigerant recompressor coupled to the third refrigerant aftercooler, a fourth refrigerant aftercooler coupled to the second refrigerant recompressor, a first refrigerant heat exchange means disposed within the main cryogenic heat exchanger and coupled to the fourth

refrigerant aftercooler to intermediate cool the compressed refrigerant, a first turboexpander coupled to first refrigerant heat exchange means to first expand the compressed refrigerant, a second turboexpander coupled to the first turboexpander to second expand the first expanded refrigerant, and a second refrigerant heat exchange means disposed within the main cryogenic heat exchanger and coupled to the second turboexpander and the first refrigerant compressor. In further embodiment of the LNG production system, the refrigeration subsystem further comprises a third refrigerant heat exchange means disposed within the main cryogenic heat exchanger, wherein the upstream inlet of the third refrigerant heat exchange means is coupled to one downstream outlet of the first turboexpander while the downstream outlet of the third refrigerant heat exchange means is coupled to one upstream inlet of the second refrigerant compressor; and wherein during operation, the refrigerant after the expansion by the first turboexpander is split into two streams with a ratio of 30/70 to 60/40, one stream (30-60% of full stream) being introduced into the third refrigerant heat exchange means to serve as a cold stream in the main cryogenic heat exchanger, and the other stream (40-70% of full stream) being further expanded by the second turboexpander and then being introduced into the second refrigerant heat exchange means to serve as the coldest stream for the sub-cooling of the liquefied natural gas. In another further embodiment of the LNG production system, the refrigeration subsystem further comprises an inter-cooler disposed within the main cryogenic heat exchanger between the first and second turboexpanders. In another embodiment of the LNG production system, the refrigeration subsystem further comprises an inter-cooler disposed between one stream from the first turboexpander and the second turboexpander. In a further embodiment of the LNG production system, the refrigerant subsystem further comprises a third expansion device and a second intercooler, both being disposed between the second turboexpander and second refrigerant heat exchange means. The first turboexpander has the option to provide two split refrigerant streams, one feeding back to a fourth refrigerant heat exchange means disposed within the main cryogenic heat exchanger and the other to the second expansion device via the first intercooler.The second turboexpander has the option to provide two split refrigerant streams, one feeding back to a fifth refrigerant heat exchange means disposed within the main cryogenic heat exchanger and the other to the third expansion device via the second intercooler.

[0013] Another aspect of the present invention provides a method for producing liquefied natural gas by means of a single phase gaseous refrigerant in a close loop. In one embodiment, the method comprises providing a main cryogenic heat exchanger in which heat exchange occurs, providing a pressurized natural gas stream that flows through the main cryogenic heat exchanger to get liquefied, and providing cold energy to the main cryogenic heat exchanger by a refrigeration device; wherein the refrigeration device comprises a plurality of refrigerant compressors configured into a series arrangement to perform multi-stage compressions of a refrigerant, a plurality of aftercoolers each of which being coupled to each of the plurality of refrigerant compressors to cool the compressed refrigerant, a plurality of turboexpanders coupled to the last aftercooler and configured into a series configuration to perform multi-stage expansions of the compressed refrigerant, and a plurality of refrigerant heat exchange means coupled to both the first of the plurality of refrigerant compressors and the last of the plurality of turboexpanders, so that all components form a close refrigeration cycle.

[0014] The objectives and advantages of the invention will become apparent from the following detailed description of preferred embodiments thereof in connection with the accompanying drawings.

Brief Description of the Drawings

[0015] Preferred embodiments according to the present invention will now be described with reference to the Figures, in which like reference numerals denote like elements.

[0016] FIG 1 is a schematic drawing showing an LNG production system according to one embodiment of the present invention.

[0017] FIG 2 is a schematic drawing showing an LNG production system according to another embodiment of the present invention.

[0018] FIG 3 shows the Heat Flow-Temperature curves of the LNG production system shown in FIG 2.

[0019] FIG 4 is a schematic drawing showing an LNG production system according to another embodiment of the present invention.

[0020] FIG 5 shows the Heat Flow-Temperature curves of the LNG production system shown in FIG 4.

[0021] FIG 6 is a schematic drawing showing an LNG production system according to another embodiment of the present invention.

[0022] FIG 7 shows the Heat Flow-Temperature curves of the LNG production system shown in FIG 6.

[0023] FIG 8 is a schematic drawing showing an LNG production system according to another embodiment of the present invention.

[0024] FIG 9 is a schematic drawing showing an LNG production system according to another embodiment of the present invention.

[0025] FIG 10 is a schematic drawing showing an LNG production system according to another embodiment of the present invention.

[0026] FIG 11 is a schematic drawing showing an LNG production system according to another embodiment of the present invention.

[0027] FIG 12 is a schematic drawing showing an exemplary LNG production system in the prior art.

Detailed Description of the Invention

[0028] The present invention may be understood more readily by reference to the following detailed description of certain embodiments of the invention.

[0029] Throughout this application, where publications are referenced, the disclosures of these publications are hereby incorporated by reference, in their entireties, into this application in order to more fully describe the state of art to which this invention pertains.

[0030] The present invention provides a system and method to liquefy the natural gas using expander based refrigeration cycle in a simple and efficient way. The system and method uses turboexpanders in series arrangement, resulting in the advantages of simplicity and flexibility, low refrigerant flow rate requirement, low expansion ratio requirement for each expander, and competitive efficiency and power consumption, when compared with the existing prior art processes.

[0031] Referring now to FIG 1, there is provided an LNG production system in accordance with one embodiment of the present invention. The LNG production system **100** comprises a main cryogenic heat exchanger **3**, a natural gas liquefaction subsystem, and a refrigeration subsystem, where the main cryogenic heat exchanger **3** facilitates the heat exchange between the natural gas passing through the natural gas liquefaction subsystem and the refrigerant passing through the refrigeration subsystem so that the natural gas in the natural gas liquefaction subsystem is liquefied by the refrigerant in the refrigeration subsystem.

[0032] The main cryogenic heat exchanger **3** is a multi-stream heat exchanger, which integrates the heat transfer of cold and warm streams and optimizes the integrated cooling curve.

[0033] As shown in FIG 1, the natural gas liquefaction subsystem comprises a gas treatment module **2** for ensuring that the feed gas **1** is suitable for the natural gas liquefaction process, a natural gas heat exchange means **31** disposed within the main cryogenic heat exchanger **3** for enabling the passing-through natural gas to exchange heat with countercurrent refrigerant or other gaseous flows (e.g., flash gas flow as discussed below), a natural gas pressure reduction means (e.g., Joule-Thomson (J-T) valve, two-phase expander or liquid expander) **4** for controlling the reduction of the pressures of the cooled natural gas from the natural gas heat exchange means **31** so as to further reduce the temperature of the natural gas, yielding two-phase (vapor and liquid) streams, and a flash drum **5** for separating the two-phase streams into LNG **6** and flash gas. All components are fluidly coupled by conventional pipes/conduits; a 2/31 conduit coupling the downstream outlet of the gas treatment module **2** with the upstream inlet of the natural gas heat exchange means **31**; a 31/4 conduit coupling the downstream outlet of the natural gas heat exchange means **31** with the upstream inlet of the J-T valve **4**, and a 4/5 conduit coupling the downstream outlet of the J-T valve **4** and the upstream inlet of the flash drum **5**. The LNG **6** is stored by conventional means. For the flash gas, the natural gas liquefaction subsystem further comprises a flash gas heat exchange means **32** disposed within the main cryogenic heat exchanger **3** for recovering the cold energy by the natural gas flowing through the natural gas heat exchange means **32**, a flash gas compressor **7** for compressing the cold energy recovered flash gas, and a flash gas aftercooler **8** for cooling the compressed flash gas to yield fuel gas **9**. Conventional pipes/conduits

fluidly/gaseously coupled the components; a 5/32 conduit coupling one downstream outlet of the flash drum **5** and the upstream inlet the flash gas heat exchange means **32**; a 32/7 conduit coupling the downstream outlet of the flash gas heat exchange means **32** and the upstream inlet of the flash gas compressor **7**; and a 7/8 conduit coupling the downstream outlet of the flash gas compressor **7** and the flash gas aftercooler **8**.

[0034] The feed gas **1** from an external source is usually with a certain pressure (normally 20-60 barg), and is treated in the gas treatment module **2** for CO_2 removal, dehydration and mercury removal. At the cryogenic temperature of LNG, the existence of CO_2 and water could cause freezing in the main cryogenic heat exchanger. An outlet stream concentration of < 50ppm CO_2, and < 1ppm H_2O after gas treatment is required. The H_2S and Hg could cause corrosion in the aluminum brazed plate fin heat exchanger, i.e. the main cryogenic heat exchanger **3**, hence it is also necessary to remove the Hg to < 10 ng/Sm^3, and H_2S < 2 ppm in the gas treatment module **2** prior to the liquefaction process.

[0035] During operation of the natural gas liquefaction system, the high pressure natural gas after gas treatment goes through the natural gas heat exchange means **31** disposed within the main cryogenic heat exchanger **3** where it is been liquefied. The high pressure liquid which exits from main cryogenic heat exchanger **3** passes to the J-T valve **4** to reduce the pressure to ~1.2 bara. The pressure reduction of the high pressure stream results in the temperature drop to around -161 °C and formation of a two-phase stream, which is further separated the vapor and liquid in the flash drum **5**. The liquid is the LNG product, and transferred to a LNG storage tank. The flash gas is recovered the cold energy in the main cryogenic heat exchanger **3**. The cold flash gas serves as part of the refrigerant to recover the cold energy in the main cryogenic heat exchanger **3** before further compressed and used for fuel gas.

[0036] In principle, the refrigeration subsystem comprises a plurality of refrigerant compressors performing multi-stage compressions, a plurality of aftercoolers, a plurality of turboexpanders performing multi-stage expansions, and a plurality of refrigerant heat exchange means, where all components are coupled in a series configuration to form a close refrigeration cycle. The "plurality" means two or more in the present application. As shown in FIG 1, a first refrigerant compressor **11**, a first refrigerant aftercooler **12**, a second refrigerant compressor **13**, a second refrigerant aftercooler **14**, a first refrigerant

recompressor **15**, a third refrigerant aftercooler **16**, a second refrigerant recompressor **17**, a fourth refrigerant aftercooler **18**, a first refrigerant heat exchange means **33** disposed within the main cryogenic heat exchanger **3**, a first turboexpander **19**, a second turboexpander **20**, and a second refrigerant heat exchange means **34** disposed within the main cryogenic heat exchanger **3**. All these components are sequentially coupled by conventional pipes/conduits to form a close refrigeration loop; a 34/11 conduit coupling the downstream outlet of the second refrigerant heat exchange means **34** and the upstream inlet of the first refrigerant compressor **11**; a 11/12 conduit coupling the downstream outlet of the first refrigerant compressor **11** and the upstream inlet of the first refrigerant aftercooler **12**; a 12/13 conduit coupling the downstream outlet of the first refrigerant aftercooler **12** and the upstream inlet of the second refrigerant compressor **13**; a 13/14 conduit coupling the downstream outlet of the second refrigerant compressor **13** and the upstream inlet of the second refrigerant aftercooler **14**; a 14/15 conduit coupling the downstream outlet of the second refrigerant aftercooler **14** and the upstream inlet of the first refrigerant recompressor **15**; a 15/16 conduit coupling the downstream outlet of the first refrigerant recompressor **15** and the upstream inlet of the third refrigerant aftercooler **16**; a 16/17 conduit coupling the downstream outlet of the third refrigerant aftercooler **16** and the upstream inlet of the second refrigerant recompressor **17**; a 17/18 conduit coupling the downstream outlet of the second refrigerant recompressor **17** and the upstream inlet of the fourth refrigerant aftercooler **18**; an 18/33 conduit coupling the downstream outlet of the fourth refrigerant aftercooler **18** and the upstream inlet of the first refrigerant heat exchange means **33**; a 33/19 conduit coupling the downstream outlet of the first refrigerant heat exchange means **33** and the upstream inlet of the first turboexpander **19**; a 19/20 conduit coupling the downstream outlet of the first turboexpander **19** and the upstream inlet of the second turboexpander **20**; and a 20/34 conduit coupling the downstream outlet of the second turboexpander **20** and the upstream inlet of the second refrigerant heat exchange means **34**. The preferable refrigerant is nitrogen (N_2). The first and second refrigerant compressors **11, 13** can be driven by either electrical motor, gas engine or gas turbine, while the first and second recompressors **15, 17** driven by the second and first turboexpanders **20, 19**, respectively. The aftercoolers are typically aircooler or watercooler, and cool the compressed refrigerant to a temperature, for example ~40 °C, depending on the ambient condition.

[0037] During the operation of the refrigeration subsystem, the refrigerant discharged from the downstream outlet of the second refrigerant heat exchange means **34** has low pressure (typically 6 bara); the low pressure refrigerant is first compressed to ~50 bara by the first and second refrigerant compressors **11, 13,** and then further compressed to 90-100 bara by the first and second recompressors **15, 17**. Each of the downstreams of the refrigerant compressors and recompressors is cooled by one of the four aftercoolers **12, 14, 16, 18,** respectively to a temperature depending on the ambient condition. The high pressure refrigerant stream from the downstream outlet of the fourth aftercooler **18** enters into the first refrigerant heat exchange means **33** disposed in the main cryogenic heat exchanger **3** to be cooled down to an intermediate temperature, typically ~-27 °C, then into the first turboexpander **19** to expand to a pressure of ~24 bara, and then into the second turboexpander **20** to reduce the pressure to ~7 bara and reach a temperature of ~-153 °C. The refrigerant stream from the downstream outlet of the second turboexpander **20** at cryogenic temperature passes into the second refrigerant heat exchange means **34** disposed within the main cryogenic heat exchanger **3** and provides the main cold energy to liquefy the natural gas. After the cold is recovered in the main cryogenic heat exchanger **3**, the refrigerant stream flows into the first refrigerant compressor **11** again, and re-circulates in the close refrigerant loop.

[0038] Referring now to FIG 2, there is provided a LNG production system in accordance with another embodiment of the present invention. In order to highlight the specific features in this embodiment, the description of the similar features shown in FIG 1 will be omitted if not necessary. The refrigeration subsystem further comprises a third refrigerant heat exchange means **35** disposed within the main cryogenic heat exchanger **3**. The upstream inlet of the third refrigerant heat exchange means **35** is coupled to one downstream outlet of the first turboexpander **19** via a 19/35 conduit while the downstream outlet of the third refrigerant heat exchange means **35** is coupled to one upstream inlet of the second refrigerant compressor **13** via a 35/13 conduit. During operation, the refrigerant after the expansion by the first turboexpander **19** is split into two streams with a ratio of 30/70 to 60/40, one stream (30-60% of full stream) being introduced into the third refrigerant heat exchange means **35** to serve as a cold stream in the main cryogenic heat exchanger **3**, and the other stream (40-70% of full stream) being further expanded by the second turboexpander **20** and then being introduced into the second refrigerant heat

exchange means **34** to serve as the coldest stream for the sub-cooling of the pressurized liquefied natural gas. The stream split after the first turboexpander **19** can better distribute the cold energy according to heat demand for the natural gas liquefaction, since more cold energy is required for the condensing service at intermediate temperature than the sub-cooling for the natural gas at low temperature. This process in FIG 2 is flexible to the change of natural gas feed pressure, as the temperature difference between the cold and warm streams is evenly approached along the heat flow as shown in FIG 3. With the downstream split after the first turboexpander, the efficiency/specific power requirement improves 15-20% over the process described in FIG 1.

[0039] Referring now to FIG 4, there is provided a LNG production system in accordance with another embodiment of the present invention. In order to highlight the specific features in this embodiment, the description of the similar features shown in FIG 1 will be omitted if not necessary. The refrigeration subsystem further comprises an inter-cooler **36** disposed between the first and second turboexpanders **19**, **20**. The upstream inlet of the inter-cooler **36** is coupled to the downstream outlet of the first turboexpander **19** via a 19/36 conduit, and the downstream outlet of the inter-cooler **36** is coupled to the upstream inlet of the second turboexpander **20**. The high pressure refrigerant stream from the downstream outlet of the first turboexpander **19** is expanded to a pressure of ~24 bara before it enters the inter-cooler **36** to further cool down to ~-136 °C, and then enter the second turboexpander **20** to reduce the pressure to ~15 bara and reach a temperature of ~-153 °C. This downstream of the second turboexpander **20** at cryogenic temperature passes into the main cryogenic heat exchanger **3** and provides the main cold energy to liquefy the natural gas. After the cold is recovered in the main cryogenic heat exchanger **3**, the refrigerant stream flows into the first refrigerant compressor **11** again, and re-circulates in the close refrigerant loop. FIG 5 shows the cooling curve for the above described system shown in FIG 4. With the inter-cooler between the first and second expanders, the efficiency/specific power requirement improves 8-10% over the system and process described in FIG 1.

[0040] Referring now to FIG 6, there is provided a LNG production system in accordance with another embodiment of the present invention. In order to highlight the specific features in this embodiment, the description of the similar features shown in FIGS 1, 2 and 4 will be omitted if not necessary. In the refrigeration subsystem, the refrigerant

from the first turboexpander **19** is split into two streams. Then the inter-cooler **36** disposed between one stream from the first turboexpander **19** and the second turboexpander **20** via a 37/20 conduit. During operation, the high pressure refrigerant stream is cooled down to an intermediate temperature, e.g. ~-32 °C, before entering the first turboexpander **19**, and expanded to a pressure of ~30 bara before it is split into two streams. One stream enters the intercooler **37** disposed within the main cryogenic heat exchanger **3** again to further cool down to ~-111 °C, and then enter the second turboexpander **20** to reduce the pressure to ~10 bara and reach a temperature of ~-153 °C. This downstream of expander **20** passes into the main cryogenic heat exchanger **3** and provides the main cold energy at low temperature to liquefy the natural gas. Another stream split from the downstream of expander **19** directly passes through main cryogenic heat exchanger **3** to provide the cold energy at warm temperature to liquefy the natural gas. After the cold energy is recovered in the main cryogenic heat exchanger **3**, the both refrigerant streams flow into the first and second refrigerant compressors **11**, **13** respectively, and re-circulate in the close refrigerant loop. The refrigerant split after the first turboexpander helps better distribute the heat flow of refrigerant between warm and cold temperatures, thus better match the heat requirement of the natural gas during the de-superheating, condensing and sub-cooling phases from the warm to cold temperatures. The process in FIG 6 has further 5-7% efficiency improvement and 2-5% refrigerant flow rate reduction from the process in FIG 4. The cooling curves for the above processes in FIG 6 are shown in FIG 7.

[0041] Referring now to FIG 8, there is provided a LNG production system in accordance with another embodiment of the present invention. In order to highlight the specific features in this embodiment, the description of the similar features shown in FIGS 1, 2, 4 and 6 will be omitted if not necessary. In the refrigeration subsystem, the refrigerant from the second turboexpander **20** is split into two streams. The refrigeration subsystem further comprises a third refrigerant compressor **22** and a fifth refrigerant aftercooler **23** disposed between the second refrigerant compressor **13** and the first refrigerant recompressor **15**, a fifth refrigerant heat exchange means **38** for receiving one stream from the second turboexpander **20**, a sixth refrigerant heat exchange means **39** for receiving another stream from the second turboexpander **20**, and a second J-T valve disposed between the sixth and second refrigerant heat exchange means **39**, **34** for low pressure stage expansion.

[0042] Referring now to FIG 9, there is provided a LNG production system in accordance with another embodiment of the present invention. In order to highlight the specific features in this embodiment, the description of the similar features shown in FIGS 1, 2, 4, 6 and 8 will be omitted if not necessary. In comparison with FIG 8, the refrigeration subsystem further comprises a third recompressor **26** with an aftercooler **25**, and a third turboexpander **24** to substitute the second J-T valve.

[0043] FIGS 8, 9, 10, and 11 show the embodiments for the process using three-stage expansion, to provide three cold streams to supply the cold energy for the natural gas liquefaction. The refrigeration subsystem comprises an inter-cooler disposed between one stream from the first turboexpander and the second turboexpander, and a second inter-cooler disposed between one stream from the second turboexpander and the third expander. The downstream of the second expanders **20** has the option to split into two streams, with one stream serves as cold stream to supply cold for the natural gas, while the other stream is further cool down to a lower temperature, before it is further expanded by a 3rd expansion device **21** or **24**, as shown in FIGS 8, 9, and 11. The downstream of the first expanders **19** also has the option to split into two streams, with one stream serves as cold stream to supply cold for the natural gas, while the other stream is further cool down to a lower temperature, before it is further expanded by the second expander **20**, as shown in FIGS 8 and 9. The overall pressure expansion ratio for the three stages expansion is around 12-15, higher than the two stages expansion in processes described in FIGS 4 and 6. With the increased expansion ratio, the process efficiency can be further improved 4-8%, with refrigerant flow reduction of 30-40% from the process in FIG 6.

[0044] The above new processes have the following advantages:

[0045] Two nitrogen expanders in series allow a much closer temperature approach than a single expander, with a correspondingly large improvement in efficiency in terms of specific power consumption.

[0046] The configuration of the two expanders in series minimized the expansion ratio of each expander compared with a single expander process. For example in an effort to achieve an LNG production rate with a 9% of flash gas generation, the expansion ratio for each expander process is <4 in dual N_2 expander cycle in series arrangement, while it requires an expander ratio of 9.4 in the single expander process. In addition, it might make

the end users easy and comfortable to source expanders available in market, especially for the expanders in small capacity and power duty.

[0047] The dual expanders in series configuration possesses the flexibility to accommodate the scenario where no flash gas is produced in the LNG production while still maintaining the temperature approach in the main cryogenic heat exchanger not to exceed 30 °C which is required by widely used ALPEMA standard.

[0048] It is flexible to control the required cold N_2 temperature by adjusting the low pressure (2^{nd}) expander flow rate and expansion ratio for LNG subcooling, in order to produce LNG with different amount of flash gas if required.

[0049] For example, in Fig 2, the flow rate reduction of 19/35 can increase the inlet stream flow of second expander 20, thus can increase the expansion ratio to reach a lower outlet temperature, which further liquefy the natural gas to a lower temperature and reduced the flash gas amount after J-T expansion.

[0050] Applying the present invention, e.g. as shown in FIG 2, a split dual N_2 expander cycle in series arrangement, to a typical natural gas source, calculated energy efficiencies of around 0.35-0.50 kWh/kg can be achieved, depending on the external conditions and feed gas conditions.

[0051] Table 1: Performance data of the LNG processes with ambient temperature ~30 °C and feed gas pressure of 40 barg.

Figure	Description	Specific Power (kWh/kg)	Expansion Ratio	N2 flow (%)
FIG 1	Dual N_2 Expander in Series - no intercool	0.56	4.3 x 3.5 = 15.0	100%
FIG 2	Dual N_2 Expander in Series (split) - no intercool	0.50	4.0 x 3.7 = 14.8	118%
FIG 4	Dual N_2 Expander in Series - with intercool	0.51	3.6 x 1.6 = 5.8	152%
FIG 6	Dual N_2 Expander in Series (split) - with Intercool	0.49	3.2 x 3.0 = 9.6	149%

FIG 9	Three N_2 Expander in Series (split) - with intercool	0.47	1.6 x 4.6 x 2.0 = 14.7	103%
FIG 11	Three N_2 Expander in Series (split) - with intercool	0.48	1.4 x 2.9 x 3.4 = 14.0	115%
Prior Art	Dual N_2 Expander in Parallel (split) - with intercool	0.49	4.4 / 4.0	177%

[0052] While the present invention has been described with reference to particular embodiments, it will be understood that the embodiments are illustrative and that the invention scope is not so limited. Alternative embodiments of the present invention will become apparent to those having ordinary skill in the art to which the present invention pertains. Such alternate embodiments are considered to be encompassed within the scope of the present invention. Accordingly, the scope of the present invention is defined by the appended claims and is supported by the foregoing description.

CLAIMS

What is claimed is:

1. A liquefied natural gas (LNG) production system, comprising:

a main cryogenic heat exchanger;

a natural gas liquefaction subsystem; and

a refrigeration subsystem comprising:

a plurality of refrigerant compressors configured into a series arrangement and a plurality of refrigerant recompressors configured into a series arrangement, wherein the last outlet of the plurality of refrigerant compressors is coupled to the first inlet of the plurality of refrigerant recompressors so that a refrigerant is compressed in a multi-stage manner when it flows through the series compressors and recompressors; and wherein the compressors are driven by gas turbine or electrical motors and the recompressors are driven by expanders,

a plurality of aftercoolers each of which being coupled to each of the pluralities of refrigerant compressors and recompressors to cool the compressed refrigerant after each stage of compression; wherein the compressed refrigerant is not expanded before leaving the last outlet of the aftercoolers,

a plurality of turboexpanders configured into a series configuration, wherein the first inlet of the plurality of turboexpanders is coupled with the last outlet of the aftercoolers and the first outlet of the plurality of turboexpanders is coupled with the inlet of subsequent turboexpander to perform multi-stage expansions of the compressed refrigerant, and

a plurality of refrigerant heat exchange means coupled to both the first inlet of the plurality of refrigerant compressors and the last outlet of the plurality of turboexpanders, so that all components form a close refrigeration cycle;

wherein the main cryogenic heat exchanger facilitates heat exchange between a pressurized natural gas passing through the natural gas liquefaction subsystem and a refrigerant passing through the refrigeration subsystem so that the pressurized natural gas in the natural gas liquefaction subsystem is liquefied by the refrigerant in the refrigeration subsystem.

2. The LNG production system of claim 1, wherein the main cryogenic heat exchanger is a multi-stream heat exchanger.

3. The LNG production system of claim 1, wherein the natural gas liquefaction subsystem comprises:

a gas treatment module for treating the pressurized natural gas so as to make it suitable for being liquefied;

a natural gas heat exchange means fluidly/gaseously coupled with the gas treatment module and disposed within the main cryogenic heat exchanger for enabling the passing-through pressurized natural gas to exchange heat with countercurrent refrigerant flows; and

a natural gas pressure reduction means fluidly/liquidusly coupled with the natural gas heat exchange means for controlling the reduction of the pressure of the cooled pressurized natural gas from the natural gas heat exchange means so as to further reduce the temperature of the pressurized liquefied natural gas, yielding LNG and flash gas.

4. The LNG production system of claim 3, wherein the natural gas pressure reduction means is Joule-Thomson (J-T) valve, two-phase expander or liquid expander.

5. The LNG production system of claim 1, wherein the refrigeration subsystem comprises:

a first refrigerant compressor;

a first refrigerant aftercooler coupled to the first refrigerant compressor;

a second refrigerant compressor coupled to the first refrigerant aftercooler;

a second refrigerant aftercooler coupled to the second refrigerant compressor;

a first refrigerant recompressor coupled to the second refrigerant aftercooler;

a third refrigerant aftercooler coupled to the first refrigerant recompressor;

a second refrigerant recompressor coupled to the third refrigerant aftercooler;

a fourth refrigerant aftercooler coupled to the second refrigerant recompressor;

a first refrigerant heat exchange means disposed within the main cryogenic heat exchanger and coupled to the fourth refrigerant aftercooler to intermediate cool the compressed refrigerant;

a first turboexpander coupled to first refrigerant heat exchange means to first expand the compressed refrigerant;

a second turboexpander coupled to the first turboexpander to second expand the first expanded refrigerant; and

a second refrigerant heat exchange means disposed within the main cryogenic heat exchanger and coupled to the second turboexpander and the first refrigerant compressor.

6. The LNG production system of claim 5, wherein the refrigeration subsystem further comprises a third refrigerant heat exchange means disposed within the main cryogenic heat exchanger, wherein the upstream inlet of the third refrigerant heat exchange means is coupled to one downstream outlet of the first turboexpander while the downstream outlet of the third refrigerant heat exchange means is coupled to one upstream inlet of the second refrigerant compressor; and wherein during operation, the refrigerant after the expansion by the first turboexpander is split into two streams with a ratio of 30/70 to 60/40, one stream (30-60% of full stream) being introduced into the third refrigerant heat exchange means to serve as a cold stream in the main cryogenic heat exchanger, and the other stream (40-70% of full stream) being further expanded by the second turboexpander and then being introduced into the second refrigerant heat exchange means to serve as the coldest stream for the sub-cooling of the liquefied natural gas.

7. The LNG production system of claim 5, wherein the refrigeration subsystem further comprises an inter-cooler disposed within the main cryogenic heat exchanger and between the first and second turboexpanders.

8. The LNG production system of claim 6, wherein the refrigeration subsystem further comprises an inter-cooler disposed within the main cryogenic heat exchanger and between one stream from the first turboexpander and the second turboexpander.

9. The LNG production system of claim 7, wherein the refrigerant subsystem further comprises a third expansion device and a second intercooler, both being disposed between the second turboexpander and second refrigerant heat exchange means, and the second

turboexpander provides one stream to the third expansion device via the second intercooler.

10. The LNG production system of claim 7, wherein the refrigerant subsystem further comprises a third expansion device and a second intercooler, both being disposed between the second turboexpander and second refrigerant heat exchange means, and the second turboexpander provides two split refrigerant streams, one feeding back to a fifth refrigerant heat exchange means disposed within the main cryogenic heat exchanger and the other to the third expansion device via the second intercooler.

11. The LNG production system of claim 8, wherein the refrigerant subsystem further comprises a third expansion device and a second intercooler, both being disposed between the second turboexpander and second refrigerant heat exchange means, and the second turboexpander provides two split refrigerant streams, one feeding back to a fifth refrigerant heat exchange means disposed within the main cryogenic heat exchanger and the other to the third expansion device via the second intercooler.

12. A method for producing liquefied natural gas by means of a single phase gaseous refrigerant in a close loop, comprising

providing a main cryogenic heat exchanger in which heat exchange occurs;

providing a pressurized natural gas stream that flows through the main cryogenic heat exchanger to get liquefied; and

providing cold energy to the main cryogenic heat exchanger by a refrigeration device; wherein the refrigeration device comprises:

a plurality of refrigerant compressors configured into a series arrangement and a plurality of refrigerant recompressors configured into a series arrangement, wherein the last outlet of the plurality of refrigerant compressors is coupled to the first inlet of the plurality of refrigerant recompressors so that a refrigerant is compressed in a multi-stage manner when it flows through the series compressors and recompressors,

a plurality of aftercoolers each of which being coupled to each of the pluralities of refrigerant compressors and recompressors to cool the compressed

refrigerant after each stage of compression; wherein the compressed refrigerant is not expanded before leaving the last outlet of the aftercoolers,

a plurality of turboexpanders configured into a series configuration, wherein the first inlet of the plurality of turboexpanders is coupled with the last outlet of the aftercoolers and the first outlet of the plurality of turboexpanders is coupled with the inlet of subsequent turboexpander to perform multi-stage expansions of the compressed refrigerant, and

a plurality of refrigerant heat exchange means coupled to both the first inlet of the plurality of refrigerant compressors and the last outlet of the plurality of turboexpanders, so that all components form a close refrigeration cycle.

13. The method of claim 12, wherein the refrigeration device comprises:

a first refrigerant compressor;

a first refrigerant aftercooler coupled to the first refrigerant compressor;

a second refrigerant compressor coupled to the first refrigerant aftercooler;

a second refrigerant aftercooler coupled to the second refrigerant compressor;

a first refrigerant recompressor coupled to the second refrigerant aftercooler;

a third refrigerant aftercooler coupled to the first refrigerant recompressor;

a second refrigerant recompressor coupled to the third refrigerant aftercooler;

a fourth refrigerant aftercooler coupled to the second refrigerant recompressor;

a first refrigerant heat exchange means disposed within the main cryogenic heat exchanger and coupled to the fourth refrigerant aftercooler to intermediate cool the compressed refrigerant;

a first turboexpander coupled to first refrigerant heat exchange means to first expand the compressed refrigerant;

a second turboexpander coupled to the first turboexpander to second expand the first expanded refrigerant; and

a second refrigerant heat exchange means disposed within the main cryogenic heat exchanger and coupled to the second turboexpander and the first refrigerant compressor.

14. The method of claim 13, wherein the refrigeration device further comprises a third refrigerant heat exchange means disposed within the main cryogenic heat exchanger,

wherein the upstream inlet of the third refrigerant heat exchange means is coupled to one downstream outlet of the first turboexpander while the downstream outlet of the third refrigerant heat exchange means is coupled to one upstream inlet of the second refrigerant compressor; and wherein during operation, the refrigerant after the expansion by the first turboexpander is split into two streams with a ratio of 30/70 to 60/40, one stream (30-60% of full stream) being introduced into the third refrigerant heat exchange means to serve as a cold stream in the main cryogenic heat exchanger, and the other stream (40-70% of full stream) being further expanded by the second turboexpander and then being introduced into the second refrigerant heat exchange means to serve as the coldest stream for the sub-cooling of the liquefied natural gas.

15. The method of claim 13, wherein the refrigeration device further comprises an inter-cooler disposed within the main cryogenic heat exchanger between the first and second turboexpanders.

16. The method of claim 14, wherein the refrigeration device further comprises an inter-cooler disposed within the main cryogenic heat exchanger between one stream from the first turboexpander and the second turboexpander.

17. The method of claim 15, wherein the refrigerant device further comprises a third expansion device and a second intercooler, both being disposed between the second turboexpander and second refrigerant heat exchange means, and the second turboexpander provides one stream to the third expansion device via the second intercooler.

18. The method of claim 15, wherein the refrigerant subsystem further comprises a third expansion device and a second intercooler, both being disposed between the second turboexpander and second refrigerant heat exchange means, and the second turboexpander provides two split refrigerant streams, one feeding back to a fifth refrigerant heat exchange means disposed within the main cryogenic heat exchanger and the other to the third expansion device via the second intercooler.

19. The method of claim 16, wherein the refrigerant subsystem further comprises a third expansion device and a second intercooler, both being disposed between the second turboexpander and second refrigerant heat exchange means, and the second turboexpander provides two split refrigerant streams, one feeding back to a fifth refrigerant heat exchange means disposed within the main cryogenic heat exchanger and the other to the third expansion device via the second intercooler.