Research on liquefaction process of FLNG unit with propane precooling device and double nitrogen expander

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Abstract

Along with the further development of global natural gas exploration and development, more and more deepwater gas fields, marginal gas fields and associated gas fields have been found. As a new development technology of offshore deepwater gas fields, a floating LNG unit which integrates production, storage and offloading into one (FLNG), with its advantages of lower investment, shorter construction period and reusability, is warmly welcomed today. By investigating the latest liquefaction technology of natural gas both at home and abroad, and combining with the FLNG production project under construction, the study reported in this paper concluded that the nitrogen expansion liquefaction technology with precooling device is the first choice for liquefaction technology of natural gas for FLNG equipment. And based on that, this paper conducted optimized analysis of the FLNG equipment liquefaction process, and established a HYSYS simulation. The result indicated that three-stage propane refrigeration technology adopted in the precooling period is able to reduce the temperature to 273.16 K, 258.16 K and 238.16K respectively, and thus the compression power during the precooling period is reduced, while the precooling effect of natural gas is improved. In addition, double nitrogen expansion refrigeration technology is employed during the super-cooling period, the division temperature of two-stage refrigeration is chosen to be 178.16 K, the total compression function drops to the lowest value, the refrigeration effect is improved and the liquefaction ratio during the whole process reaches 95%. Therefore, the three-stage liquefaction technology with propane precooling device and double nitrogen expander is better adapted to offshore gas fields, and is suitable for FLNG equipment.

Keywords: FLNG, Propane precooling, Nitrogen Expansion and Liquefaction, Technological Process, HYSYS Simulation

1 Introduction

Since the 1990s, along with the decrease in the number of discovered large-scale offshore gas fields, the exploitation of ocean natural gas has gradually turned into a small-scale dispersed type from a large-scale centralized type, which has become increasingly important [1]. As to the development of deepwater gas fields and those projects in which the consumer market is far away from gas fields, the traditional development mode of offshore natural gas, including the construction of offshore platforms, the laying of subsea natural gas transport pipelines and the building of infrastructures such as onshore LNG factory roads and LNG outer-transportation ports, has the features of high investment, long construction period and delayed cash returns [2]. To address those shortcomings, FLNG combines the liquefaction, storage and offloading processes together, and simplifies the development process of marginal fields, and has the advantages of low cost, quick production and high benefit, as well as some other advantages. The FLNG concept is based on a ship-like vessel that will be able to produce, store and offload LNG in a marine environment. In some designs being considered, the concept includes production, storage, and re-gasification onboard a self-propelled LNG carrier [6, 16]. Because of the limitation of technology and economics, the construction of FLNG has not been industrialized. At the Asian Commercialization Conference of FLNG, Songhurst summarized 15 FLNG projects around the world, among which most are still at the conceptual design stage, as shown in Table 1 [3]. And it is reported that DSME will complete the establishment of the world's first FLNG unit in 2015 [4].

2 Study of the Liquefaction Process of FLNG

FLNG mainly includes five subsystems, namely pretreatment, liquefaction, storage, transportation and usage of natural gas, as shown in Figure 1. The natural gas liquefaction production process mainly consists of two parts: pretreatment and liquefaction. Natural gas with more than 90% methane content is purified firstly through three removal processes (dehydration, removal of hydrocarbon and removal of acid gas), and then with the application of an advanced expansion refrigeration process or external refrigeration source, methane in

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natural gas is liquefied under the low-temperature condition of 113.16 K [8-10].

TABLE 1 Statistics of foreign FLNG projects

Responsible Department	**Design Company**	**Processing (106t/a)**	**Liquefaction process**
Flex LNG	Kanfa/Costain	1.7	Double nitrogen expansion
Hoegh LNG	CB &. I Lummus	1.6~2.0	Methane-nitrogen expansion
SBMLinde	Linde	2.5	Mixed refrigerant
Shell	Shell	3.5	Mixed refrigerant
Aker/Statioil	Aker	5.8	Mixed refrigerant
Bluewater	Air Products	unknown	Nitrogen expansion & Mixed refrigerant
BW Offshore	Mustang	1.0	Nitrogen expansion
Hamworthy	Hamworthy	0.5~2.2	Nitrogen expansion
Teekay	Mustang	0.5~1.0	Nitrogen expansion
Exmar EBLV Excelerate	Black & Veatch	1.0~2.0	Mixed refrigerant
Saipem	Air Products	1.0~2.5	Nitrogen expansion & Mixed refrigerant
TGE Marine	TGE	0.4~1.5	Mixed refrigerant
ConocoPhillips	ConocoPhillips	5.0	Optimized cascade
Sevan Marine	Kanfa	1.5	Nitrogen expansion
Inpex	JGC/KBR	4.5	Mixed refrigerant

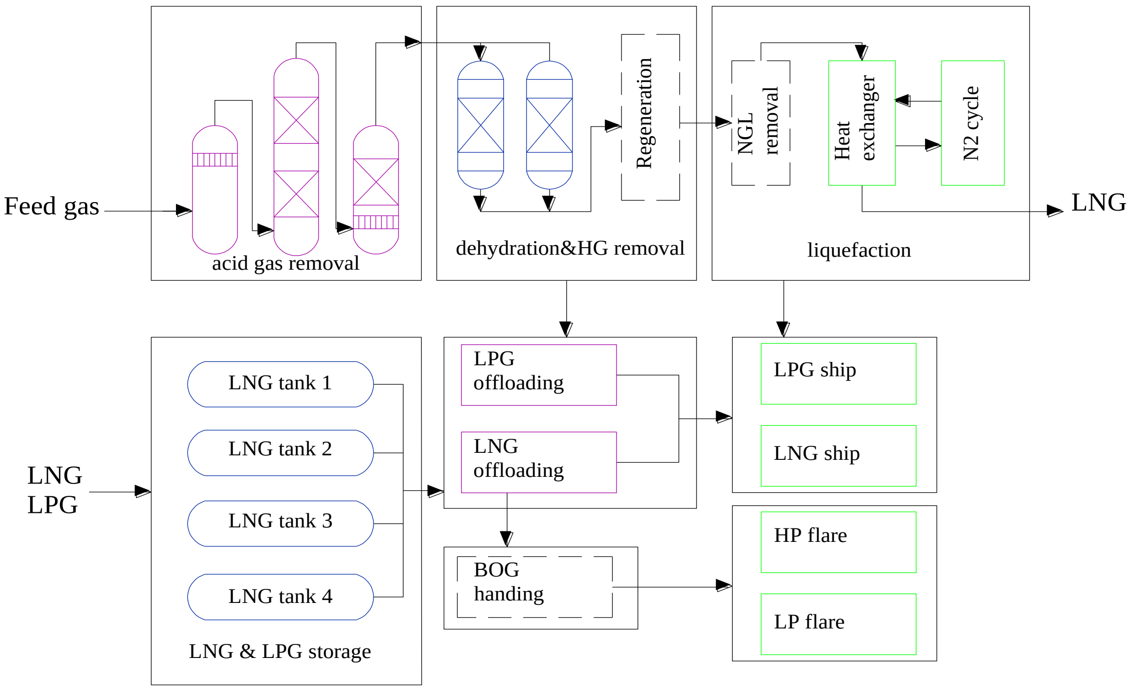

FIGURE 1 Flow diagram of production, storage and unloading device of FLNG unit

2.1 PRETREATMENT OF NATURAL GAS

Natural gas usually contains acid gas, water and impurities in varying degrees before entering the liquefaction process, such as H_2S, CO_2, H_2O, organic sulfides, etc. These will have a serious impact on the exploitation, gathering and treatment of natural gas. Therefore, the feed gas must be pretreated before liquefaction to get purified natural gas, in this way preventing freezing, blocking and corroding of equipment and pipeline at low temperature. Table 2 shows the purified gas processing standards of a LNG factory and the allowed maximum contents of impurities [4,5].

TABLE 2 Maximum allowed impurity content in purified gas

Impurity	Content Limit	Impurity	Content Limit
H_2O	$<0.1\times10^{-12}$kg/m^3	Total sulphur	$10\sim50\times10^{-6}$kg/m^3
CO_2	$(50\sim100)\times10^{-12}$kg/m^3	Hg	$<0.01\times10^{-12}$kg/m^3
H_2S	3.5×10^{-6}kg/m^3	Aromatics	$(1\sim10)\times10^{-6}$
COS	$<0.1\times10^{-6}$	C_5^+	$<70\times10^{-6}$kg /m^3

Note: the contents of H2O, CO2, COS and aromatics refer to their volume faction

2.2 LIQUEFACTION TECHNOLOGY OF NATURAL GAS

The method of natural gas liquefaction is to take its heat away constantly through a heat exchanger, so that finally the natural gas is liquefied [9]. Nowadays, the mature natural gas liquefaction techniques include the throttling refrigeration cycle, expansion refrigeration cycle, cascade refrigeration cycle, mixed refrigerant cycle, mixed refrigerant with precooling refrigeration cycle and so on [10,15].

Natural gas liquefaction equipment as the key production factor of a FLNG device will directly affect the whole device's operation and applicability. Nowadays there are several liquefaction processes being suggested to be used in FLNG, among which the single mixed refrigerant liquefaction process (MCRC) is applied in Mobil's design; Shell and APCI suggest the Sunrise project adopting a double-stage mixed refrigerant process (DMR); BHP company advises the application of a modified nitrogen expansion liquefaction cycle as FLNG's liquefaction process; Merlin & Costain believe a two-stage nitrogen expander process is economical and viable, etc.[14,17].

2.2.1 Techno-economic comparison between different liquefaction processes

Combined with technological features of different refrigeration cycles, three existing onshore basic liquefaction technology processes (nitrogen expansion, mixed refrigerant, cascade refrigeration) have been adjusted and combined; then six natural gas liquefaction processes were selected to be simulated and optimized, and the concluding comparison of properties of each refrigeration cycle is shown in Table 3 [13].

Through the simulation and optimization of the above six natural gas liquefaction processes, it is believed that nitrogen expansion with a precooling refrigeration process is the first choice for the FLNG liquefaction process; that is, double nitrogen expansion liquefaction process with propane precooling process, mixed refrigerant–nitrogen expansion (parallel) liquefaction process, and mixed refrigerant–nitrogen expansion (series) liquefaction process.

3 Study of FLNG Liquefaction Technology Process

Floating natural gas liquefaction equipment (FLNG) is installed with FPSO (floating production, storage and transportation system), which mainly consists of propane precooling and nitrogen expansion.

3.1 BASIC TECHNOLOGY DATA

A certain deepwater gas field in the South China Sea was selected as a basic model, its natural gas handling capacity being 40 × 10^4 Sm^3/h. The components of natural gas after being dehydrated and removal of acid are shown in Table 4, and the designed load ranges from 50% to 110%.

3.2 NATURAL GAS LIQUEFACTION TECHNOLOGY PROCESS

Natural gas liquefaction technology which directly affects the whole equipment's operation and applicability is the key part in the FLNG equipment. Meanwhile, high-level internal security, realized modularization, ease of operation, convenient to start up and close down, being adaptable to different air sources to a certain extent, etc.

Comparing the six offshore natural gas liquefaction technologies (shown in Table 3), it is believed that the double nitrogen expansion with propane precooling liquefaction process is more suitable for the floating-type natural gas liquefaction process. Nitrogen is selected as a single refrigerant for the double nitrogen expansion liquefaction process, and is characterized by concise and secure design, being easy to start up and close down, high anti-sloshing ability, insensitivity to gas components and variation of flow rate. However, for the reasons that its power consumption is still high, and the circulation flow rate of nitrogen is too great, a suite of propane precooling equipment is added. This will not only decrease the refrigeration capacity of nitrogen circulation, but also increase the efficiency of the whole technological process. Meanwhile, it has fairly high offshore adaptability, and a schematic of the process is shown in Figure 2 [6,13].

3.3 OPTIMIZATION OF LIQUEFACTION TECHNOLOGY PROCESS

The key operation parameters of the double nitrogen expansion liquefaction process with propane precooling process have a huge influence on the performance of the whole FLNG technology process. Based on Zhu Jian-lu and others' research work, the study reported in this paper optimized two key technical parameters: the stages of the propane precooling process and the division temperature of the two-stage nitrogen expansion refrigeration process. The above research which is based on maintaining good security, limiting risk, and improving offshore adaptability will further reduce the total compression power consumption and improve refrigeration efficiency.

TABLE 3 Parameter comparison of six kinds of natural gas liquefaction processes

Parameters of liquefaction technology	**Double nitrogen expansion**	**three-stage propane pre-cooling with double nitrogen expansion**	**Mixed refrigerant- Nitrogen expansion(parallel)**
Single refrigerant flow rate($10^5 m^3/h$)	15.18	N_2: 10.28 C_2: 0.75	N_2: 7.11 C_2: 2.36
Single power consumption(10^4kW)	10.34	7.83	7.29
Ratio of the total gas consumption	4.91%	3.71%	3.46%
Ratio of power consumption (kWh/m^3)	0.56	0.42	0.39
Liquefaction rate	0.93	0.93	0.93
Influence of Shake	low	low	middle
Storage requirements of inflammable refrigerant	/	low	middle
Offshore adaptability	high	high	middle
Flow changes sensitivity of feed gas	middle	middle	low
Component changes sensitivity of feed gas	low	low	middle
Comprehensive performance	good	optimal	good
Parameters of liquefaction technology	Mixed refrigerant- Nitrogen expansion(series)	Single mixed refrigerant	Mixed refrigerant with propane pre-cooling
Single refrigerant flowrate($10^5 m^3/h$)	N_2: 4.76 C_2: 3.49	5.29	MR: 5.20 C_2: 1.96
Single power consumption(10^4kW)	6.46	5.33	5.01
Ratio of the total gas consumption	3.14%	2.53%	2.39%
Ratio of power consumption (kWh/m^3)	0.36	0.29	0.27
Liquefaction rate	0.93	0.93	0.93
Influence of Slosh	middle	high	high
Storage requirements of inflammable refrigerant	middle	high	high
Offshore adaptability	middle	low	low
Flow changes sensitivity of feed gas	middle	middle	middle
Component changes sensitivity of feed gas	middle	low	low
Comprehensive performance	good	poor	poor

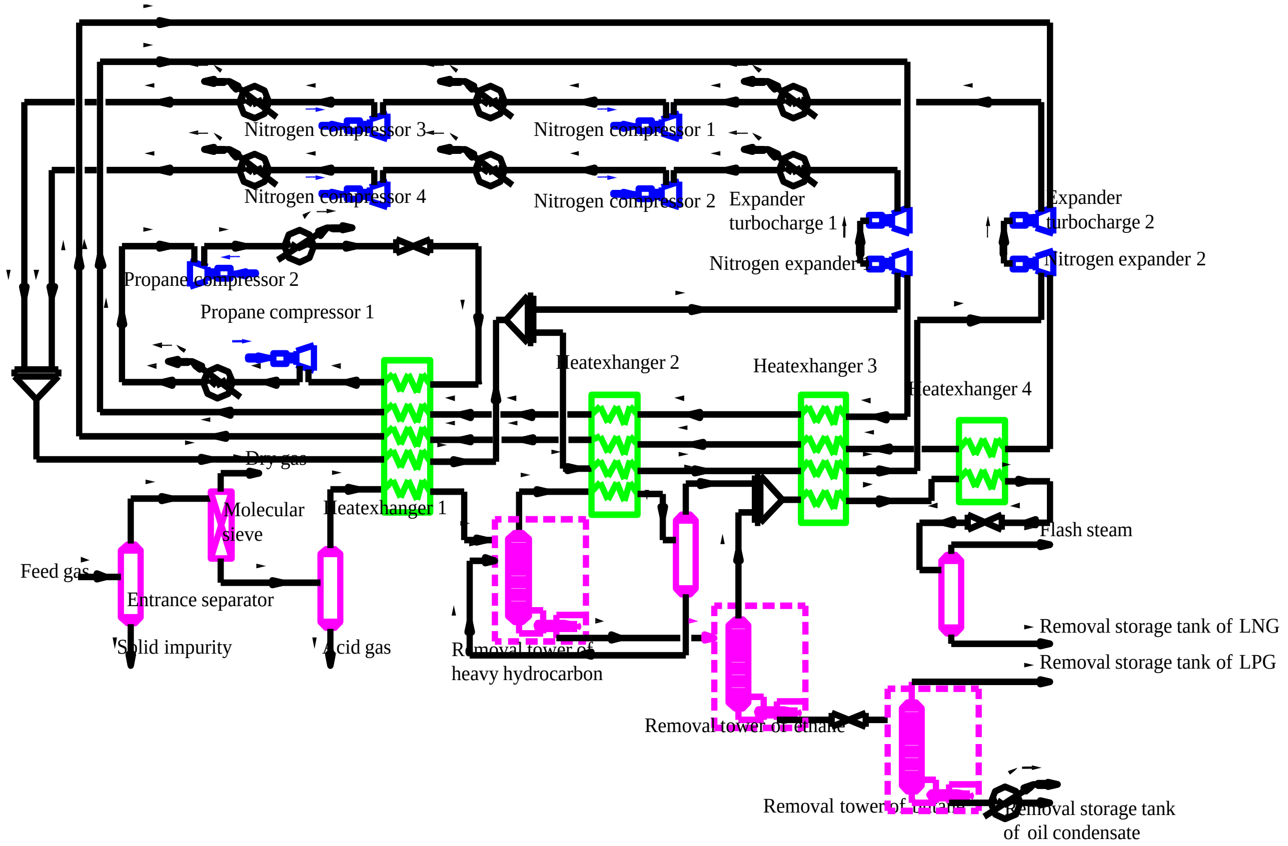

FIGURE 2 Flow chart of liquefaction process with propane precooling device and double nitrogen expander

TABLE 4 Mole fraction of each component of the purified gas from the South China Sea

Component	**C1**	**C2**	**C3**	**i-C4**
Content	0.93046	0.05939	0.00322	0.00016
Component	n-C4	i-C5	CO2	N_2
Content	0.0001	0.00001	0.0005	0.0066

Designed temperature: 308.16 K
Designed pressure: 7.6 MPa
FLNG technology process mainly consists of: natural gas precooling unit and natural gas refrigeration unit

3.3.1 Stage Optimization of Propane Precooling Process

Propane precooling technology is usually classified into single-stage refrigeration technology and multi-stage refrigeration technology [7,16], while for large- or medium-scale refrigeration technology, two-stage or three-stage refrigeration is usually employed.

A comparison of temperatures and compression power consumptions for the different propane refrigeration stages (shown in Table 5) shows that the compression power consumption of the three-stage refrigeration technology is 43120 kW relative to single- and two-stage refrigeration technology.

TABLE 5 Different temperature and compressor power consumption corresponding to different stages of propane refrigeration

Stage of propane refrigeration series	**Temperature(K)**			**Compressor power**
	first stage	second stage	Third stage	
first stage	238.16			46018
second stage	258.16	238.16		44585
Third stage	273.16	258.16	238.16	43120

In addition, if the high pressure liquefied nitrogen precooling only exchanges heat with propane of the third stage, the temperature difference is comparatively large, and the propane total circulation volume is 5864 kmol.

The application of three-stage refrigeration technology in exchanging heat with liquefied nitrogen separately could decrease the propane circulation volume to 5800 kmol. Therefore, the three-stage propane refrigeration process could be applied as a natural gas precooling technology for FLNG.

3.3.2 Division temperature for two-stage nitrogen expansion refrigeration

The natural gas, after propane precooling, enters into the two-stage nitrogen expansion liquefaction process. Here the natural gas is liquefied into high-pressure liquid through the first stage of nitrogen circulation, while the second stage of nitrogen circulation sub-cools the liquefied natural gas to reach storage conditions under ordinary pressure. The division temperature of these two refrigeration stages is actually the adjustment and assignment of refrigeration capacities during the above two refrigeration cycles. The total compression power consumption varies along with the change of division point, and the total consumption reaches a minimum when the division temperature is 178.16 K. Therefore, 178.16 K is selected as the division temperature.

In addition, a gas turbine with the same parameters could be employed in the compressor drivers of these two refrigeration cycles, which is convenient for design, construction and maintenance.

4 HYSYS simulation of liquefaction technology process

According to liquefaction technology of FLNG, double nitrogen expansion with three-stage propane precooling liquefaction is established under the HYSYS environment. The details are shown in Fig. 3. Through the selection of a reasonable thermodynamic model, the application of the P-R equation to a hydrocarbon system to calculate the vapor–liquid phase equilibrium properties can meet a project's computational accuracy [11].

The P-R state equation is as follows:

$$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)+b(V-b)} \quad , \qquad (1)$$

where P is the system pressure (MPa), T is the system temperature (K), V is the system volume (m3) and a, b are coefficients.

The parameter mixing rule and the expression of its (one component in the mixture) fugacity in the P-R equation can refer to the reference books [12].

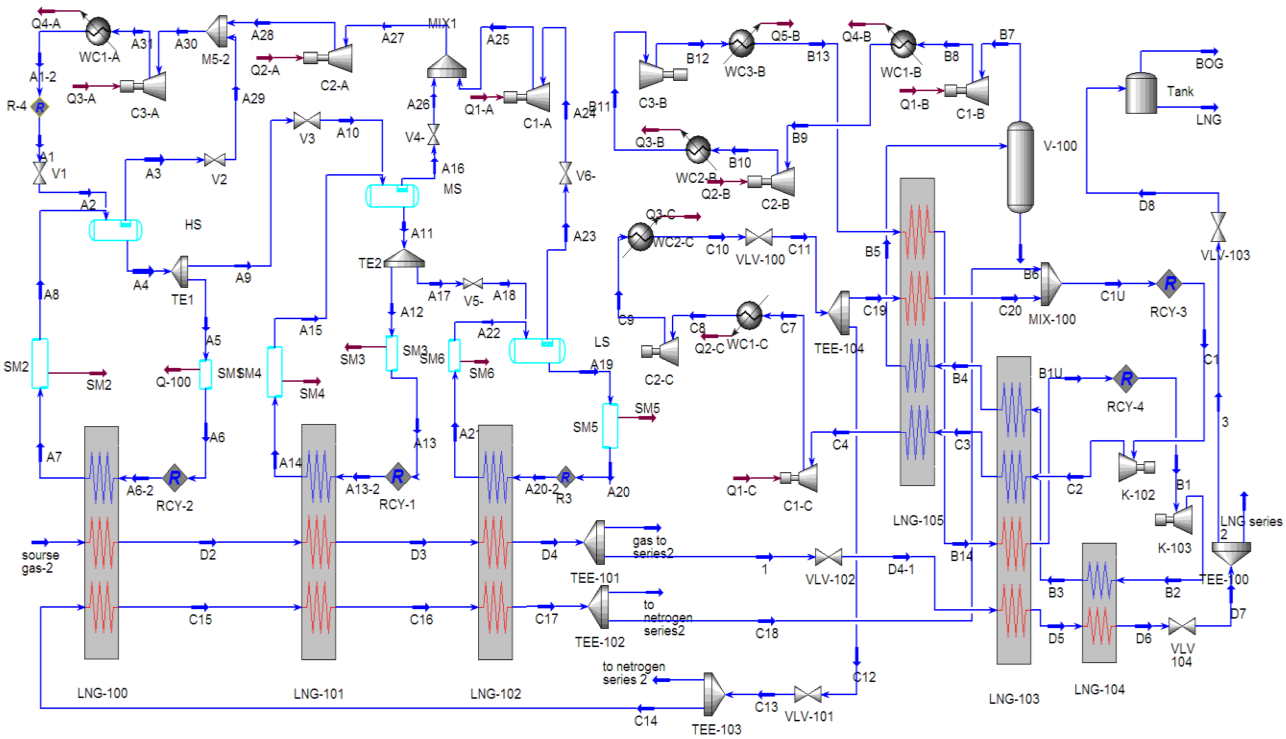

FIGURE 3 Schematic of HYSYS simulation of FLNG liquefaction process

4.1 ANALYSIS OF COMPUTATION RESULTS

Through the HYSYS simulation, the logistics parameters at each main node in this technology process are obtained.

1) Logistics information for natural gas can be seen in Table 6.

2) Logistics information for propane precooling circulation can be seen in Table 7.

3) Logistics information for nitrogen first-stage refrigeration circulation can be seen in Table 8.

4) Logistics information for nitrogen second-stage refrigeration circulation can be seen in Table 9.

TABLE 6 Gas logistics information in HYSYS simulation

	sourse gas-2	D2	D3	D4	D5	D6	D7	LNG	BOG
Fraction of gas	1	1	1	1	0	0	0	0	1
Temperature(K)	304.16	273.172929	258.1714	238.16	178.16	117.902	120.256	113.677	113.677
pressure(kPa)	7001.325	6986.325	6971.325	6956.325	6901.325	6851.325	301.325	121.325	121.325
Molar flow (kgmole/h)	16970.30138	16970.3	16970.3	16970.3	8485.151	8485.151	8485.151	16115.58	854.7255
Mass flow(kg/h)	289485.9775	289486	289486	289486	144743	144743	144743	275012.1	14473.83

TABLE 7 Propane information in HYSYS simulation

	A20-2	A21	A13-2	A14	A6-2	A7
Fraction of gas	0	0.4	0	0.4	0	0.4
Temperature(K)	236.1675	238.4508	258.1714	258.7968	278.1730	278.6532
pressure(kPa)	149.034	139.034	312.5244	297.5244	573.1622	558.1622
Molar flow (kgmole/h)	3801.732	3801.732	3702.221	3702.221	4313.213	4313.213
Mass flow(kg/h)	167645	167645	163256.8	163256.8	190199.7	190199.7

TABLE 8 Logistics information of the first stage of nitrogen refrigeration in HYSYS simulation

	C1	C2	C3	C4	C8	C11	C14
Fraction of gas	1	1	1	1	1	1	1
Temperature(K)	233.1774	178.16	228.1164	299.16	304.16	304.0998	304.0395
pressure(kPa)	6826.325	2190.599	2175.599	2160.599	4729.917	6911.325	6871.325
Molar flow (kgmole/h)	40098.82	40098.82	40098.82	40098.82	40098.82	40098.82	12814.98
Mass flow(kg/h)	1123288	1123288	1123288	1123288	1123288	1123288	358985.9

TABLE 9 Logistics information of the second stage of nitrogen refrigeration in HYSYS simulation

	B1	B2	B3	B4	B5	B9	B11	B13
Fraction of gas	1	1	1	1	1	1	1	1
Temperature(K)	178.16	114.902	177.9998	228.1164	299.16	304.16	304.16	304.16
pressure(kPa)	6891.325	1195.694	1180.694	1165.694	1150.694	2396.337	4893.629	6951.325
Molar flow (kgmole/h)	15560.21	15560.21	15560.21	15560.21	15560.21	15560.21	15560.21	15560.21
Mass flow(kg/h)	435888.1	435888.1	435888.1	435888.1	435888.1	435888.1	435888.1	435888.1

It is concluded from Table 6 that natural gas first enters into the third-stage propane precooling equipment, in the gas phase, its temperature decreasing from 304.16 K to 273.16 K, then 258.16 K and finally 238.16 K. Soon afterwards, it enters into the second-stage nitrogen expansion liquefaction equipment. Through this second-stage refrigeration, its temperature further decreases from 178.16 K to 113.16 K and reaches the FLNG storage requirement of low temperature. The whole process, with few pieces of equipment and compact equipment layout, is simple and occupies a small area. What is more, the realization of modularization is comparatively easy and shows better performance improvement effects.

From the analysis of the refrigerant's components, it can be seen that in the third-stage propane precooling technology process (shown in Table 7), even though some propane exists in the gas–liquid phase, as pure components, its gas–liquid separation process is influenced by boat shaking to a relatively small degree; meanwhile, from Tables 8 and 9, it can be seen that in the double nitrogen expansion circulation process, nitrogen always exists in the gaseous phase, and is not much influenced by shaking, resulting in good offshore adaptability.

5 Conclusion

Through the above analysis, the double nitrogen expansion with three-stage propane precooling liquefaction technology has the following advantages:

1) Good offshore adaptability: in FLNG equipment, nitrogen is totally operated in the gaseous phase, and propane which is barely influenced by boat shaking exists in the gas–liquid phase as pure components. Furthermore, because of its few pieces of auxiliary equipment together with rapid starting and stopping, FLNG is fairly adaptable under a hostile sea environment.

2) Compact equipment, small area occupied: this liquefaction technology process with a small amount of equipment is simple, and thus its compactness, security

and economic efficiency are improved.

3) The technology is insensitive to changes in feed gas temperature, pressure and components, but the total power consumption can be reduced by decreasing temperature and increasing pressure appropriately.

Traditional natural gas liquefaction technology cannot completely satisfy the design criteria of offshore natural gas liquefaction. Therefore, the nitrogen expansion liquefaction process with precooling is put forward to be the first choice for FLNG equipment. However, because of the limited treatment capacity of the nitrogen expansion liquefaction process with precooling, it is only available for medium or small floating natural gas liquefaction processes. In a stable sea area with huge handling capacity, a mixed refrigerant liquefaction process or even cascading liquefaction process can be considered, while when the handling capacity is not huge and the sea state is unstable, the nitrogen expansion liquefaction process is suggested to be applicable

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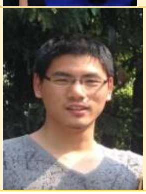

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