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THE STUDY ON A NEW LIQUEFACTION CYCLE DEVELOPMENT FOR LNG PLANT

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ABSTRACT

With worldwide LNG demand increasing rapidly, LNG liquefaction plants and liquefaction processes are higher value-added industries. Therefore a variety of thermodynamic cycles have been developed for liquefaction of natural gas to meet the requirements on high efficiency, large capacity, or simple equipment. Recently, there has been an increase in research and development of LNG-FPSO technologies in offshore liquefied natural gas (LNG) service instead of land-based LNG plants. While onshore LNG facilities have traditionally focused on power efficiency as a key criterion for process design and equipment selection, offshore LNG would require not only power efficiency but also safety and compactness. A new natural gas liquefaction cycle is proposed in this paper. The structure of the new cycle is based on the SMR (Single Mixed Refrigerant) liquefaction cycle which has a very simple structure. The proposed liquefaction cycle has liquid-vapor separator to separate MR into HK (Heavy Key) and LK (Light Key) components, and each key is compressed separately after the main cryogenic heat exchanger, and then mixed again to make a single MR. The proposed cycle can be optimized using the temperature profiles in cryogenic heat exchanger and compressor power using each separated compressor. The proposed cycle has improved into several process cycles that are to increase its efficiency and to simplify its cycle structure. The proposed liquefaction cycle has a simple structure with high compactness and power efficiency, therefore the proposed cycle could be suitable for not only large scale land-based LNG plant but also for the LNG-FPSO liquefaction process.

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INTRODUCTION

Thermodynamic process for the liquefaction of natural gas has evolved since 1970's (Barron, 1985; Roberts, 2002; Andress, 2004; Flynn, 2005; Venkatarathnam, 2008; Chang, 2009, Lee, 2010) in order to meet a number of challenges, including the demand of greater efficiency and larger capacity. A liquefaction system is primarily composed of a series of compressors, coolers, expanders, and heat exchangers. Natural gas is cooled-down to LNG temperature in thermal contact with closed-cycle refrigerant(s). In order to reduce the input power for liquefaction, it is crucial to reduce entropy generation due to the temperature difference between hot stream (including feed gas and hot refrigerants) and cold refrigerants in the heat exchangers.

Since the feed gas is mostly a mixture of different hydrocarbons, its enthalpy varies nonlinearly with temperature along the liquefaction process.

For high liquefaction efficiency, it is important to reduce the entropy generation due to temperature difference in heat exchangers. Generally mixed refrigerant (MR) cycles are effective in reducing the temperature difference with a small number of its equipments (Venkatarathnam, 2008). On the other hand, pure component refrigerant cycles are simple and easy in operation, but require a large number of refrigeration stages (Andress, 2004). Numerous liquefaction processes have been developed so far with different refrigerants and different cycles, but only a few are practically in use.

The most popular liquefaction process under operation is based on propane pre-cooled mixed refrigerant (C3MR) cycle (Gaumer Jr., 1973) by Air Products and Chemicals Inc. Feed gas is pre-cooled to approximately -33 ℃ by multi-stage propane (C3) JT cycle, and then liquefied and subcooled to -150 ℃ by mixed refrigerant (MR) through a large spiral wound heat exchanger. An appropriate composition of MR allows liquefaction and sub-cooling of feed gas in a single heat exchanger over wide temperature range, leading to a high thermodynamic efficiency with minimum number of components. However, since the C3 cycle has to cool both feed gas and MR cycle, the thermal load of propane cycle becomes enormous, and the C3MR reaches a technical limit on the propane compressor for applications to 5 MTPA (million tons per annum) or greater. For substantial increase in liquefaction capacity, the cold end of C3MR cycle is recently equipped with nitrogen Brayton cycle. This three-cycle process (called AP-X^{TM}) allows decreasing the propane and MR flow rates so as to achieve a capacity up to 8 MTPA (Roberts, 2002).

Another successful liquefaction process under operation is based on cascade cycle (Andress, 2004) by Conoco Phillips. The process consists of three JT cycles, which use methane (C1), ethylene (C2), and propane (C3) as pure component refrigerant. Each JT cycle has two or three stages of refrigeration to reduce the temperature difference in heat exchangers. Since no mixture is used, the process is simple, easy, and robust in operation. The cycle also has disadvantages of its huge process size and large number of equipments.

The simplest structure of natural gas liquefaction process is SMR (Single Mixed Refrigerant) process, because the process has only one series of compressors and one main cryogenic heart exchanger that covers the whole range of natural gas liquefaction from atmosphere temperature to cryogenic temperature(Sweanson, 1977). A basic schematic diagram of SMR cycle is shown in Fig. 1. The SMR cycle has very simple structure with one heat exchanger, but the efficiency of the cycle is very low, so the cycle has been used for the small size of natural gas liquefaction plants.

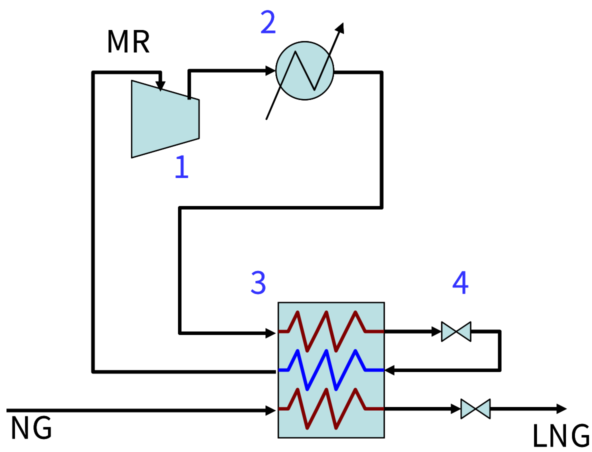

Fig. 1. Schematic Diagram of SMR Process

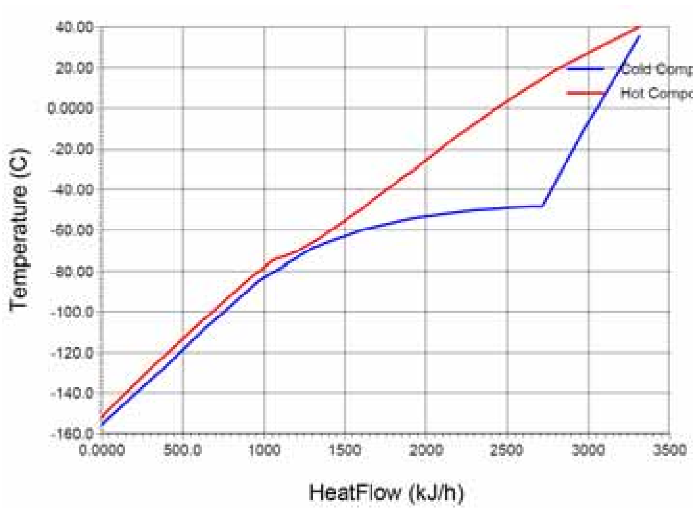

Fig. 2 Temperature-Heat Flow Diagram of SMR Cycle

Fig. 2 shows the temperature-heat flow diagram of SMR cycle after an optimization work. After the optimization, SMR cycle has the matter of large gap between the temperature

profiles of the hot and cold components in the pre-cooling zone (-60 ℃ ~ 40 ℃) of the heat exchanger, because C3 component in MR starts vaporizing in the pre-cooling zone. After optimizing SMR cycle, the temperature profiles in the liquefaction zone of the main heat exchanger is very close, meanwhile pre-cooling zone has a gap widen as shown in fig. 2.
Many other processes also use mixed refrigerant in different ways (Venkatarathnam, 2008). In dual mixed refrigerant (DMR) process developed by SHELL, the propane pre-cooling cycle of C3MR is replace with MR JT cycle to remove the bottleneck of propane compressor. The LINDE process has three JT cycles like cascade process, but with MRs on all three cycles. IFP/AXENS developed a new liquefaction process called LIQUEFIN^{TM}, which is also two MR JT cycles.

CYCLE DESIGN

Process Simulation Bases

The liquefaction cycle design depends to an extent on the composition, pressure, and temperature of feed gas. For the purpose of design and performance comparison between the existing cycles and proposed cycles, the feed gas has been defined as a standard mole composition of methane (C1) 91.3%, ethane (C2) 5.4%, propane (C3) 2.1%, i-butane (IC4) 0.5%, n-butane (NC4) 0.5%, and nitrogen (N2) 0.2%. The feed gas is required to cool from 32 ℃ at 5 MPa to -150 ℃ for flash expansion to LNG storage tank, therefore the pressurized LNG is expanded and sub-cooled to LNG storage tank at slightly above atmospheric pressure. The pressure of LNG storage tank is 121 kPa.
In order to investigate the feasibility and to estimate the performance of the proposed liquefaction cycle, the detailed specifications are given as follows:

- Refrigerant temperature after the coolers: 40 ℃
- Pressure drop through main heat exchanger: 100 kpa
- Minimum approach temperature in main heat exchanger: 3 ℃
- Pressure ratio of each compressor: 2 ~ 2.8
- The adiabatic efficiency of all compressors: 75%

Aspen HYSYS^{TM} has been used to simulate the processes. The thermodynamic properties of feed gas and refrigerant are calculated by Peng-Robinson (for EOS: Equation of Status) with Lee-Kesler (for Enthalpy Calculation) methods in Aspen HYSYSTH simulator.

Selection of Basic Cycles for Development

Recently there are a lot of studies of liquefaction cycle developments for LNG-FPSO and small scale plants, not only for onshore base-load plants. It is because the development demands of LNG-FPSO and small scale plants have increased. These small or medium scale liquefaction processes require not only high power efficiency but also high compactness. Since the liquefaction process for LNG-FPSO would be implemented and operated on the limited area of the floating structure, compactness is very important factor in the selection of liquefaction cycle. The efficiency is also very important factor, because the liquefaction process consumes large amount of energy in the LNG-FPSO. For the compactness, SMR liquefaction cycle is selected for the basic structure of the proposed liquefaction cycle. For the efficiency, DMR liquefaction cycle could be also selected for the performance modification based on the basic structure of SMR cycle.

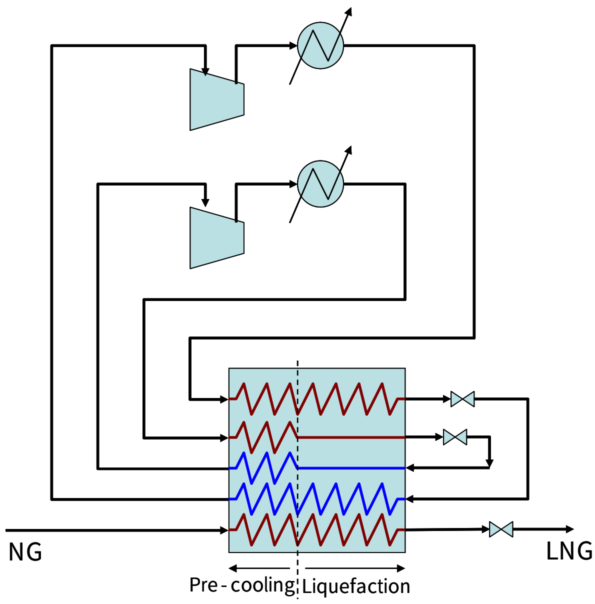

Fig. 3 Simplified Conceptual Diagram of DMR Cycle

Fig. 3 shows most simplified conceptual diagram of DMR cycle. As shown in Fig 3, DMR has two refrigerant cycles, and each cycle has one series of compressors and refrigerant flows in the heat exchanger. The two refrigerants are mixed component refrigerants that consist of nitrogen, methane, ethane, and propane generally. One of the cycles pre-cools the pre-cooling zone in the heat exchanger, and the other cycle liquefies the natural gas to LNG. The compositions of the each cycle are different because of its effective temperature range. The compositions of the each cycle have to be optimized independently, and managed to keep the exact compositions during the operation.

In this study, DMR cycle would be structurally modified into SMR cycle. To keep the performance of DMR cycle, there have to be two refrigerant streams in main heat exchanger, and to keep the number of refrigerants in the cycle, the single MR has to be separated in the proposed cycle. Therefore MR is separated into two kind of MR using a vapor-liquid separator, and the separated MRs have their refrigerant roles in the main cryogenic heat exchanger. After the main heat exchanger, each MR has been compressed separately, and then mixed again to become the single MR.

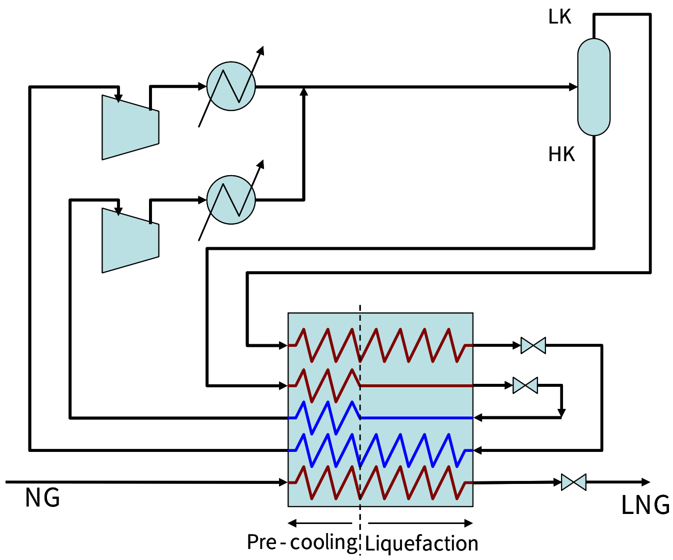

Fig. 4 Schematic Diagram of Proposed Process (Basic Type, Cycle-1)

Basic Type of Proposed Cycle (Cycle-1)

Fig. 4 shows the schematic diagram of the basic type (Cycle-1) of the proposed liquefaction cycle. MR is separated into liquid and vapor refrigerants in a vapor-liquid separator as shown in the figure. The liquid refrigerant is called HK (Heavy Key) and the vapor refrigerant is called LK (Light Key). In the vapor-liquid separator, HK constitutes the refrigerant composition that is relatively heavier than LK. There is single MR in the proposed cycle, but the MR is separated into two kind of MR as shown in Fig 4, and then the separated MRs have their refrigerant roles in the main cryogenic heat exchanger as two MR refrigerants. The MRs are mixed after its compressor and after-cooler. The refrigerant consists of nitrogen, methane, ethane, and propane as used in C3MR.

The compressor outlet pressures of the MRs are same, but the inlet pressures of the MRs could be different. Therefore the proposed cycle could be optimized using the inlet pressure levels and their number of stages of the MR's compressors. After the optimization of Cycle-1, the number of stages of LK compressor is 4 and the number of stages of HK compressor is 2.

LK and HK have their refrigerant roles in the cycle. HK pre-cools the refrigerants and natural gas as shown in Fig. 4, and LK pre-cools LK refrigerant and liquefies natural gas to -150 ℃.

Every multi-component refrigerant have to be optimized to find the appropriate compositions of MR. After designing the structure of liquefaction process, there are many process variables for optimization such as compressor pressures and MR composition. Two end conditions of feed gas and production LNG are given. The lowest pressure of MR, that is inlet pressure of MR compressor (130 kPa), is chosen to be slight higher than atmosphere pressure for safety. There are several process variables in the optimization procedure:

- MR composition (N_2, C_1, C_2, C_3)
- MR flow rate
- High pressure of MR compressor
- Inlet pressure of HK MR compressor
- Pre-cooling temperature using HK

The object function is the value of total compression power, and the constraint is that the value of minimum approach temperature of main heat exchanger is greater than 3 ℃. The number of unknowns in MR composition including MR flow rate is 4. The other unknowns are the high pressure of MR compressor, inlet pressure of HK MR compressor, and pre-cooling temperature.

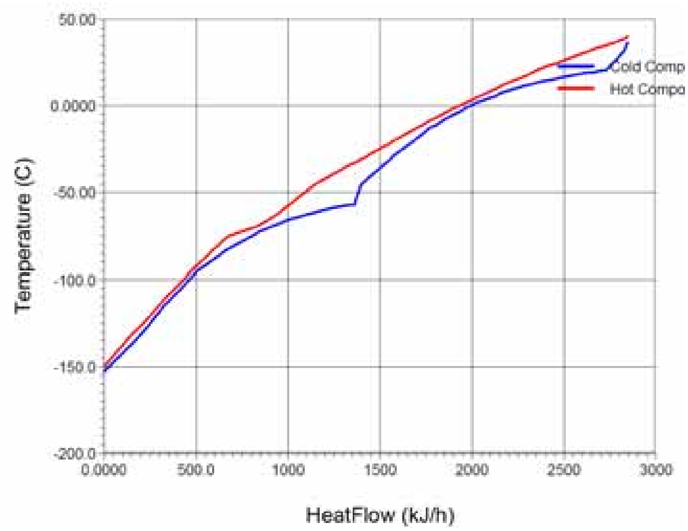

Fig. 5 Temperature-Heat Flow Diagram of Cycle-1

Fig. 5 shows the temperature-heat flow diagram of Cycle-1. In the figure, the gap between the hot and cold component temperature profiles starts increasing at about -60 ℃, that is very similar to that of SMR cycle, but the cold component profile is quite different above the temperature. There is one more C3 vaporizing point in Cycle-1 because of the different pressure of HK, which is higher than LK pressure. Therefore there are two bending points in cold component profile, and the liquefaction cycle could be optimized using the two bending points.

The specific power of Cycle-1 to liquefy 1 kg of LNG is 0.3204 kWh/kg LNG, that indicates very high efficiency comparing with SMR cycle (0.4760 kWh/kg LNG). The proposed cycle could achieve the high performance, decreasing the gap between the hot and cold component temperature profiles in the pre-cooling zone as shown in Fig. 5.

Improvement of Proposed Cycle (Cycle-2)

There are 4 stages in LK compressor, and 2 stages in HK compressor in Cycle-1. The last stages of the compressors of LK and HK could be combined to one stage of compressor. Therefore, the structure of compressor system becomes 3 stages of LK compressor, 1 stage of HK compressor, and lastly 1 stage of MR (LK + HK) compressor. After the combination of the compressors, there is liquid in the refrigerant in the mixing point of LK and MK after the each after-cooler. Therefore, a vapor-liquid separator is necessary after the mixing point of LK and MK, and a new refrigerant liquid is generated from the vapor-liquid separator. The new liquid is called HHK (Heavy Heavy Key) because the new liquid refrigerant is heavier than HK.

HHK could be used as a new refrigerant in the proposed cycle. Fig. 6 shows the schematic diagram (Cycle-2) of the other type of the proposed liquefaction cycle. HHK refrigerant is expanded after the vapor-liquid separator and it becomes low temperature to pre-cool the natural gas and the other refrigerants.

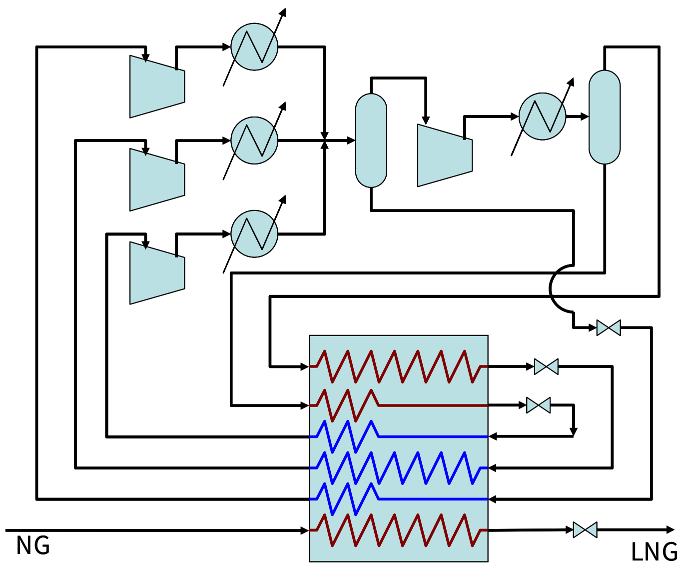

Fig. 6 Schematic Diagram of Proposed Process (Cycle-2)

Fig. 7 shows the temperature-heat flow diagram of Cycle-2. In the figure, the gap between the hot and cold component temperature profiles is very similar to that of Cycle-1 but closer than Cycle-1, because there are three bending points in cold component temperature profile, and the liquefaction cycle could be optimized using these three bending points.

The specific power of Cycle-2 is 0.3085 kWh/kg LNG, that indicates highest efficiency in the proposed cycles. Cycle-2 could achieve the high performance, decreasing the gap between the hot and cold component temperature profiles in the pre-cooling zone using three bending points.

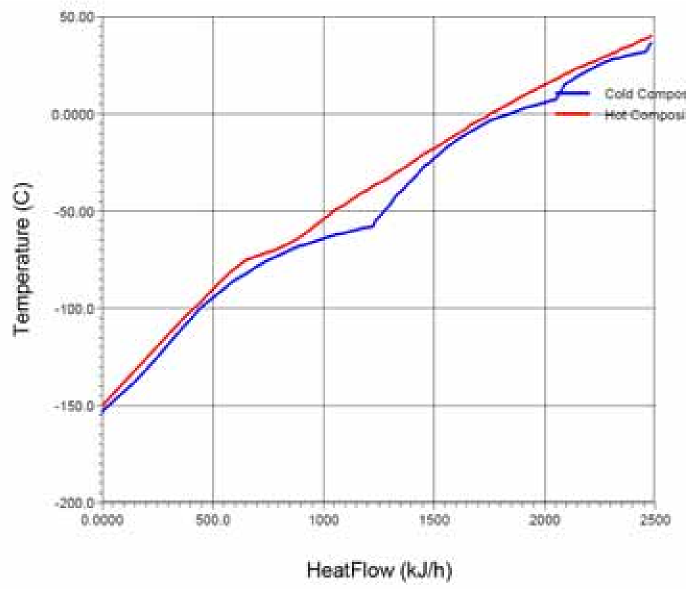

Fig. 7 Temperature-Heat Flow Diagram of Cycle-2

Improvement of Proposed Cycle (Cycle-3)

Cycle-2 has 3 parallel compressor series as shown Fig. 6. The performance of Cycle-2 is very high but the structure of Cycle-2 is somewhat complicated. Cycle-2 would be improved here. HHK liquid from vapor-liquid separator could be mixed with HK liquid as shown in Fig. 8. Therefore the structure of proposed cycle has been improved.

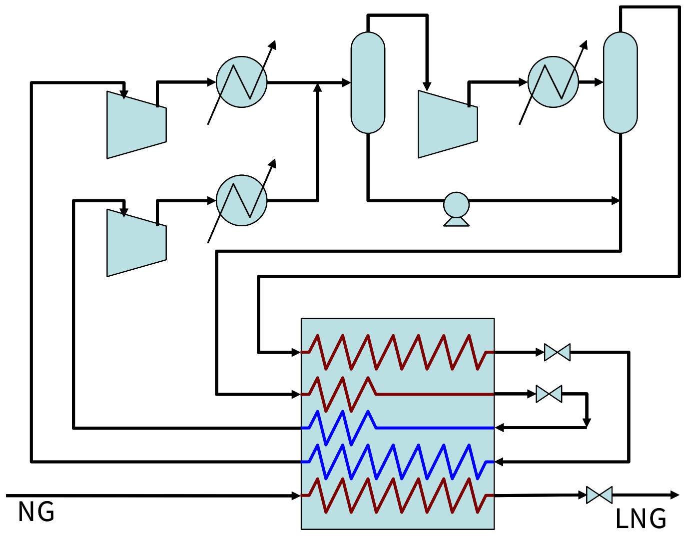

Fig. 8 Schematic Diagram of Proposed Process (Cycle-3)

Fig.9 shows the temperature-heat flow diagram of Cycle-3. There are two bending points because the main cryogenic heat exchanger has only two cold streams, so the efficiency of the proposed cycle is somewhat decreased, but the structure is simplified. The specific power of Cycle-3 is 0.3281 kWh/kg LNG.

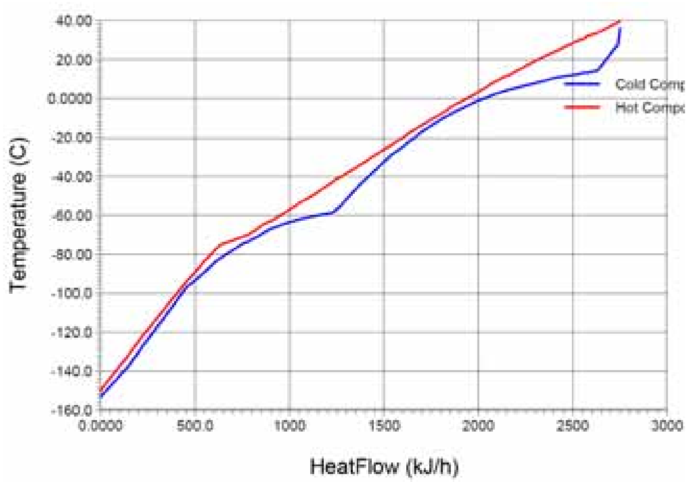

Fig. 9 Temperature-Heat Flow Diagram of Cycle-3

RESULTS AND DISCUSSION

SMR and the proposed cycles are designed and simulated in Aspen HYSYS^{TM}, and then optimized. Both of SMR and proposed cycles have only one mixed refrigerant, but the

proposed cycles have two or three MR streams in the main cryogenic heat exchangers.
The liquefaction work can be reduced if the temperature difference between hot and cold streams is made small, but the small difference requires as large size of heat exchanger. Therefore this problem is a constrained optimization, in which the constraint is temperature difference between hot and cold streams in the main heat exchanger, and the object function is compressor work minimization. The temperature difference in the heat exchanger is chosen not to be less than 3 ℃ in this study.
The capital and operating costs are very important factors in the selection of natural gas liquefaction cycle for LNG plant or LNG-FPSO. The capital cost could be expressed by the number of main equipments such as compressors and heat exchangers in the liquefaction process. Operating cost could be expressed by power consumption in the liquefaction process. The compressor power consumption has a large proportion in the power consumption in the liquefaction process.
Table 1 shows the performance comparison of proposed cycles. MRs used in the liquefaction cycles consist of methane, ethane, propane, and nitrogen only. The performance criterion is the efficiency of SMR cycle. As a result of comparison, Cycle-2 (Fig. 6) shows best efficiency, but Cycle-3 should show best performance according to the simplicity of the liquefaction cycle and its power efficiency.
In the table, the compressor power consumption means the total power consumption of refrigerant compressors for 5 MTPA LNG Plant, and the number of main equipments is the sum of the number of compressors, Pre-chillers, and MCHE sections. The number of main equipments expresses the degrees of compactness and capital cost requirement.

Table 1 Performance Comparison of SMR, Cascade, C3MR and Proposed Cycles for 5 MTPA

Liquefaction Cycles		Compressor Power Consumption		No. of Main Equipments			
		[MW]	% to SMR	Compre-ssors	Pre-Chiler	MCHE	Sum
SMR		272	100%	4		2	6
Cascade		254	93%	8		3	11
C3MR		168	62%	7	6	1	14
KSMR Cycles	Cycle-1	183	67%	6		2	8
	Cycle-2	176	65%	6		2	8
	Cycle-3	187	69%	5		2	7

The proposed cycle has potential advantages in practice over the existing cycles. Simplicity and compactness are coherent merits of SMR cycle, and the proposed cycle has been developed based on the SMR cycle. Based on this SMR cycle, we have modified the cycle to increase the efficiency of the cycle. Cycle-1 is the basic structure of the proposed cycle, and the cycle shows the basic concept of the proposed cycles very well. Cycle-2 has been improved based on Cycle-1 to increase it efficiency. Cycle-3 also has been improved based on Cycle-3 to simplify the refrigerant compressor system and the main cryogenic heat exchanger. Efforts are continued towards the practical development of efficient liquefaction process based on the proposed cycles.

CONCLUSIONS

A new single mixed refrigerant cycle is proposed for natural gas liquefaction. The proposed cycle has been developed based on SMR cycle, but the cycle has two MR streams in main cryogenic heat exchanger to improve its power efficiency. There are three types in the proposed liquefaction cycle.

To investigate the feasibility, the proposed cycles are simulated with Aspen HYSYS™ and optimized, and the results are compared with SMR process. It may be concluded that the proposed liquefaction cycles could have a reasonably high efficiency and compactness, so the cycles have the potential not only for large scale land-based LNG plant but also for LNG-PFSO liquefaction process. Towards practical development, further studies are recommended for the optimal operating conditions and the combination of fractionation process.

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LIST TABLES

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