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Thermodynamic design of natural gas liquefaction cycles for offshore application

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ABSTRACT

A thermodynamic study is carried out for natural gas liquefaction cycles applicable to offshore floating plants, as partial efforts of an ongoing governmental project in Korea. For offshore liquefaction, the most suitable cycle may be different from the on-land LNG processes under operation, because compactness and simple operation are important as well as thermodynamic efficiency. As a turbine-based cycle, closed Claude cycle is proposed to use NG (natural gas) itself as refrigerant. The optimal condition for NG Claude cycle is determined with a process simulator (Aspen HYSYS), and the results are compared with fully-developed C3-MR (propane pre-cooled mixed refrigerant) JT cycles and various N2 (nitrogen) Brayton cycles in terms of efficiency and compactness. The newly proposed NG Claude cycle could be a good candidate for offshore LNG processes.

1. Introduction

Offshore LNG (liquefied natural gas) production is one of emerging plant markets, including FPSO (floating production storage and offloading). The most suitable thermodynamic cycle for offshore liquefaction of natural gas [1–4] may be different from the on-land processes under operation, such as propane-precooled mixed-refrigerant (C3-MR) process. Thermodynamic efficiency is obviously an important criterion in selecting any liquefaction cycles. According to Barclay and Denton [2], additional factors to consider for offshore liquefaction are compactness, ease of operation, and safety. Furthermore, other constraints in marine environment may be imposed such as vessel motion, modularity of equipment, and small refrigerant inventory.

Turbine-based LNG processes have advantages in these cycle selection criteria over the traditional Joule–Thomson (JT) cycles with MR [1–3]. The simplest cycle to employ a turbine (or an expander) is reverse-Brayton cycle (simply called “Brayton cycle”) [1,5,6], as widely used in peak-shaving plants. The refrigerant of Brayton cycle for LNG processes is nitrogen (N2) or mixture of nitrogen and methane [1], since it should remain in gas phase at LNG temperatures. A variety of modifications can be made on standard Brayton cycle to improve thermodynamic efficiency and to more closely meet the requirements of offshore plants, as reported in [7].

Claude cycle is another candidate for offshore LNG process, as commonly used in cryogenic liquefaction plants of nitrogen, oxygen, and hydrogen [8–10]. The historic success of a large-scale helium liquefier by Samuel Collins was accomplished with a serial combination of Claude cycles [8,9]. However, the direct application of open Claude cycle to LNG processes is not so easy, mainly because natural gas (NG) is a mixture of different hydrocarbons and the phase separation at liquid receiver complicates the composition of working fluid. On the other hand, some modifications on Claude cycle may be considered for natural gas liquefaction, especially for offshore application.

This study intends to perform thermodynamic design on various turbine-based cycles and compare the results with the reputed C3-MR process in terms of efficiency and other factors that should be considered for offshore application. An excellent book by Venkatarathnam [1] describes the evolution of LNG processes from simple to very sophisticated processes under operation in large base-load plants. A parallel design basis to the book is constructed in this study for the purpose of selecting offshore LNG processes. This is part of our ongoing efforts supported by the LNG Plant R&D Center under the MOLIT (Ministry of Land, Infrastructure, and Transport) of Korean government.

2. Selection of thermodynamic cycles

2.1. Existing C3-MR JT cycles

Most of LNG processes under operation are based on C3-MR JT cycles, as schematically shown in Fig. 1 [1–3]. The logical starting

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Nomenclature

FOM	figure of merit
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P_H	high-pressure of cycle (MPa)
s	specific entropy (kJ/kg K)
$\dot{S}_{gen}$	entropy generation rate (kW/K)
T	temperature (K)
$\dot{W}$	power input or output (kW)
x	expander flow ratio

Subscripts

0	ambient
1, 2, ...	location of cycle
AC	after-cooler
C	compressor
E	expander or turbine
F	feed of natural gas
HX	heat exchanger
LNG	liquefied natural gas
M	mixing
min	minimum
V	JT valve

point of considering a thermodynamic cycle for offshore liquefaction should be this cycle. The NG feed is pre-cooled to around 240 K by four-stage C3 JT cycle, and then condensed and subcooled to LNG temperature by two-stage MR JT cycle. With optimized composition and operating pressure of MR, the combined cycles achieve a great thermodynamic efficiency. It is noted that the expansion in both C3 and MR cycles is basically an "isenthalpic" process through JT valve or simple throttle device.

2.2. Standard and modified N2 Brayton cycles

Brayton cycle is an excellent gas refrigeration cycle including the "isentropic" process with turbine or work-producing expander [1,5–7,9]. The theoretical isentropic process is, however, difficult to closely realize in practice with cryogenic turbines, which is the main reason why Brayton cycle is not so efficient in LNG process. On the other hand, an N2 Brayton cycle has merits for peak-shaving or offshore plants, since N2 is inexpensive, non-flammable, and safe to handle. In practical systems, N2 is compressed to a very high-pressure, typically greater than 10 MPa [1].

Lately, the present authors have presented a thermodynamic study on standard and modified N2 Brayton cycles [7]. The efficiency of standard Brayton cycle shown in Fig. 2(a) can be significantly improved by modifying the cycle in various ways with an additional turbine. Two modified cycles shown in Fig. 2(b) and (c) have been recommended, as called "two-stage" and "dual-turbine" cycles, respectively. In two-stage cycle, two turbines are arranged in series, but in dual-turbine cycle, two turbines are arranged in parallel with the same pressure ratio.

2.3. New proposal – NG Claude cycle

Claude liquefaction cycle is a combined system of isentropic (turbine or expander) and isenthalpic (JT valve) processes. Most of the cryogenic liquefaction plants for nitrogen, oxygen, and hydrogen have been developed upon a basis of open Claude cycle [8,9], as shown in Fig. 3(a). The high-pressure gas is branched from the main stream, expanded through an expander, and mixed with the low-pressure return stream. The high-pressure stream to be liquefied is cooled down through heat exchangers and is finally expanded through a JT valve to the liquid receiver.

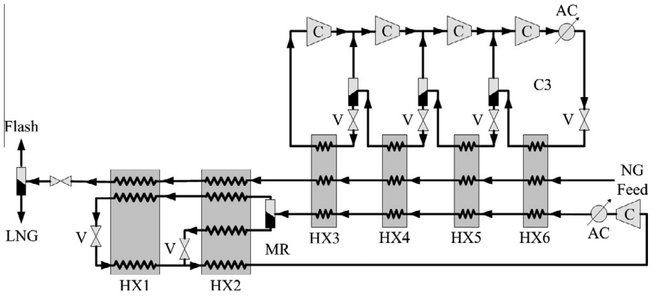

Fig. 1. Propane pre-cooled mixed refrigerant (C3-MR) JT cycle (HX: heat exchanger, *V*: JT valve, *C*: compressor, AC: after-cooler).

In order to apply the Claude cycle to natural gas liquefaction, it is proposed to use a closed Claude cycle so that the NG feed is cooled down and liquefied in a separate stream passing through a series of multi-stream heat exchangers, as shown in Fig. 3(b). In addition, it is proposed to use the natural gas (NG) itself as refrigerant in the closed cycle, called "NG Claude Cycle". This cycle may be considered an MR (mixed refrigerant) Claude cycle, whose refrigerant has the same composition as the NG feed. An evident advantage of using NG as refrigerant is to eliminate the need of refrigerant inventory in offshore plants. The first attempt of this study is the thermodynamic design of NG Claude towards its best performance.

3. Simulation and optimization

3.1. Thermodynamic efficiency

The thermodynamic performance of a liquefaction system is evaluated as the work required per unit mass of liquefied gas [1]. By combining the first and second laws of thermodynamics, there exists an absolute minimum in the required work per unit mass, which is expressed as the exergy (flow availability) of LNG [8,9].

$$\dot{W}_{\min}/\dot{m}_F = (h_{LNG} - h_0) - T_0(s_{LNG} - s_0) \tag{1}$$

where h and s are specific enthalpy and entropy, respectively, and T_0 is the ambient temperature at which heat is rejected by the liquefaction system.

The thermodynamic efficiency called "figure of merit" (FOM) for liquefaction is defined as the minimum input power divided by the actual input power [1].

$$FOM = \frac{\dot{W}_{\min}}{\dot{W}} = \frac{\dot{m}_F[(h_{LNG} - h_0) - T_0(s_{LNG} - s_0)]}{\dot{W}_C - \dot{W}_E} \tag{2}$$

In practice, the output power from expander or turbine ($\dot{W}_E$) may be used to help compress the refrigerant or may be dissipated in a brake, but for the purpose of comparison, it is taken into account as negative power in the denominator of Eq. (2) for Brayton and Claude cycles [8].

Thermodynamic irreversibility [9] is the difference between denominator and numerator of Eq. (2), which can be expressed as the sum of entropy generation rate at each component multiplied by the ambient temperature. In the liquefaction systems considered in this study, the components are classified as heat