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Optimal liquefaction process cycle considering simplicity and efficiency for LNG FPSO at FEED stage

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A B S T R A C T

In this paper, the offshore selection criteria for the optimal liquefaction process system are studied to contribute to the future FEED engineering for the liquefied natural gas (LNG) floating, production, storage, and offloading (LNG FPSO) liquefaction process system.

From the foregoing, it is clear that offshore liquefaction plants have process requirements different from those of the traditional onshore liquefaction plants. While thermodynamic efficiency is the key technical process selection criterion for large onshore liquefaction plants, the high-efficiency pre-cooled mixed refrigerant and optimized cascade plants that dominate the onshore LNG installations are unlikely to meet the diverse technical and safety needs of offshore liquefaction facilities. Offshore liquefaction technology developers are rightly focusing on process simplicity, low weight, small footprint, and other criteria. The key criteria that influence process selection and plant optimization for the offshore liquefaction cycle lead to some trade-offs and compromises between efficiency and simplicity. In addition, other criteria for offshore liquefaction cycles should also be considered, such as flexibility, safety, vessel motion, refrigerant storage hazard, proven technology, simplicity of operation, ease of start-up/shutdown, and capital cost.

First of all, this paper proposes a generic mixed refrigerant (MR) liquefaction cycle based on four configuration strategies. The 27 feasible MR liquefaction cycles from such generic MR liquefaction cycle are configured for optimal synthesis. From the 27 MR liquefaction cycles, the top 10 are selected based on the minimum amount of power required for the compressors. Then, one MR liquefaction cycle is selected based on simplicity among the 10 MR process cycles, and this is called a “potential MR liquefaction cycle.”

Second, three additional offshore liquefaction cycles – DMR for SHELL LNG FPSO, C_3MR for onshore projects, and the dual N_2 expander for FLEX LNG FPSO – are considered for comparison with the potential MR liquefaction cycle for the selection of the optimal offshore liquefaction cycle.

Such four cycles are compared based on simplicity, efficiency, and other criteria. Therefore, the optimal operating conditions for each cycle with four LNG capacities (4.0, 3.0, 2.0, and 1.0 MTPA) are calculated with the minimum amount of power required for the compressors. Then the preliminary equipment module layout for the four cycles are designed as multi-deck instead of single-deck, and this equipment module layout should be optimized to reduce the area occupied by the topside equipment at the FEED stage. In this paper, the connectivity cost, the construction cost proportional to the deck area, and the distance of the main cryogenic heat exchanger (MCHE) and separators from the centerline of the hull are considered objective functions to be minimized. Moreover, the constraints are proposed to ensure the safety and considering the deck penetration of the long equipment across several decks. Considering the above, mathematical models were formulated for them. For example, the potential MR liquefaction cycle has a mathematical model consisting of 257 unknowns, 193 equality constraints, and 330 inequality constraints. The preliminary optimal equipment module layouts with four LNG capacities (4.0, 3.0, 2.0, and 1.0 MTPA) are then obtained using mixed-integer nonlinear programming (MINLP).

Based on the above optimal operating conditions and equipment module layouts for the four potential offshore liquefaction cycles, trade-offs between simplicity and efficiency are performed for actual offshore application, and finally, the potential MR liquefaction cycle is selected for the optimal liquefaction cycle for LNG FPSO.

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Nomenclature

x_i, y_i	coordinates of the geometrical center of equipment item i
z_i	height from the bottom of equipment i to the piping connection point of equipment item i
$U_{i,j}$	relative distance in the z-coordinates between equipment items i and j if i is higher than j
$TD_{i,j}$	total rectilinear distance between equipment items i and j
FA	deck area
X^{max}, Y^{max}	dimensions of the deck area
$V_{i,k}$	1 if equipment item i is assigned to deck k; otherwise, 0
$Z_{i,j}$	1 if equipment items i and j are allocated to the same deck; otherwise, 0
O_i	1 if the length of equipment item i is equal to a_i (i.e., parallel to the x-axis); otherwise, 0
$E1_{i,j}$, $E2_{i,j}$	non-overlapping binary variables
In addition, i, j	equipment number
k	deck number

1. Introduction

1.1. Motivation

The demand for oil and gas will not abate in the near future. Peak oil is a fast-approaching reality, and the oil prices may rise again, destabilizing the oil market. On the other hand, the demand for fossil fuels is increasing exponentially, making countries and oil companies eager to explore new reserves. Smaller and difficult oil and gas fields, which were previously uneconomical, are looking more attractive as alternatives for fossil fuel production. Offshore floating liquefied natural gas (LNG) production is the key differential that may ensure the development of some of these fields.

LNG is one of the methods of transporting natural gas over long distances that have been introduced. Numerous projects and researches on issues related to it are currently being undertaken. The aim of these studies is to find new efficient methods of producing and transporting LNG. One of the conductive topics is floating, production, storage, and offloading (FPSO). The technical risk, equipment design and availability, topside design, ease of modularization, plant performance and operation, delivery schedule, and safety and environmental impact of offshore areas in this process have been evaluated. These engineering studies have further proven that this liquefaction technology is an outstanding candidate for offshore LNG projects (Foss, 2007).

Critically, the cost of FPSO is massively greater than those of land-based LNG units. In addition, the technical challenges of FPSO are difficult to overcome, but FPSO is essentially the only option to extract natural resources for many fields. As the prices of oil and gas increase, the investment required for FPSO looks more attractive (Mokhateb, Finn, & Shah, 2008). With the realization of large FPSO facilities for oil production, and more recently, LPG production, LNG FPSO projects appear to be increasingly more likely in the future.

This study focused on the optimal liquefaction cycle to realize LNG FPSO in future projects. It is expected to contribute tremendously to actual offshore application.

Table 1
LNG trains by liquefaction process.

Liquefaction process	Licensor	% of market
Propane pre-cooled MR	APCI	77
Optimized cascade	Conoco-Phillips	9
Single refrigerant MR	APCI	5
Classic cascade	Marathon/Phillips	1
Teal dual-pressure MR		1
Prico single-stage MR	Black & Veatch	2
MR processes (DMR)	Shell	4
Multifluid cascade	Linde-Statoil	1
AP-X process	APCI	0

1.2. Key technical process selection criteria between offshore and onshore natural gas liquefaction

Offshore natural gas liquefaction has process requirements different from that of the traditional onshore liquefaction. While thermodynamic efficiency is arguably the most important process selection criteria for onshore natural gas liquefiers, other factors have become more important for offshore projects.

Thermodynamic efficiency is likely to remain critically important. For offshore applications, however, criteria such as compactness and process simplicity have become more significant considerations.

1.2.1. Onshore liquefaction process

The logical starting point for any new LNG production scheme should be the existing industry and processes. The baseload LNG industry now has a more-than-40-year history, starting with the permanent operations of the Camel plant in Algeria in 1964. The earliest plants consisted of fairly simple liquefaction processes based on either the cascaded refrigeration or single mixed refrigerant (SMR) processes, and the train capacities were less than 1 MTPA. In 1972, Brunei Lumut 1 utilized the first two-cycle process using a propane pre-cooled mixed refrigerant (C_3MR) developed by Air Products and Chemicals Int. (APCI). This process became the dominant liquefaction process technology by the late 1970s and continues to be the workhorse of the LNG industry today. During this period, APCI and others have made significant improvements on the original C_3MR process. The economies of scale, improved process simulation tools, and improved equipment performance (i.e., liquid expanders and gas turbine drivers) have all dramatically decreased the installed liquefaction plant costs, improved the performance, and increased the capacity of the liquefaction trains. The continued development of the traditional LNG plant design can be seen by comparing the recently commissioned plants to the current and planned facilities. Less than five years ago, Foster Wheeler and Chiyoda Corp. of Japan completed an engineering, procurement, and construction (EPC) contract for Oman LNG. At the time of the start-up (February 2000 for Train 2), this plant had the largest trains in operation at 3.3 MTPA, and set a benchmark for process efficiency with a reported average specific power of 10.15 kW per ton per day of LNG (McLachlan, Ayres, Vink, & Al Mukhainy, 2002). Five years later, the installed train capacities were over 5 MTPA, with projects in development for 7.8 MTPA. The liquefaction process typically accounts for 30–40% of the capital of the overall plant and has a large impact on the utilities and operating costs. The selection of the appropriate cycle is critical for cost-effective LNG projects. Historically, liquefaction cycle selection was an easy choice to make: APCI C_3MR. Table 1 shows the baseload liquefaction trains currently operating, in various stages of construction, and the planned ones (in the case of AP-X).

Table 1 shows two key points (DOE/EIA, 2003; Meyer, 2004; Shukri, 2004).