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Design of single mixed refrigerant natural gas liquefaction process considering load variation

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ABSTRACT

This study presents a comprehensive design approach to determine optimal equipment size and operating conditions while considering process load variation. We applied the suggested approach to PRICO® Single Mixed Refrigerant (SMR) process to take account of the feed gas load reduction owing to depletion of natural gas fields. The suggested approach differs from a traditional one in that it performs design and optimization with several steady-state operation regimes depending on the load variation. The economics of each design approach is evaluated by the economic assessment model that reflects the annual profit under the varying production rate according to the actual production profiles of the gas field wells, Maui and Kapuni in New Zealand. The proposed design approach makes a loss in the compressor equipment cost. However, it reduces the operation cost over a wide range of operations, leading to the overall improvement of economics in a gas well along its lifetime production. This study also conducts a quantitative analysis between the load capacity that a single train must bear and the key economic variables through a case study on two-train operation. This provides insight into the economics and operability of the process depending on the number of trains.

1. Introduction

Environmental concerns and limited availability of fuel resources have increased interests in natural gas and made natural gas the fastest growing fuel (1.6% per annum, p.a.) among other dominant fossil fuel resources. In particular, liquefied natural gas (LNG) grows seven times faster than the pipeline gas trade owing to its flexible means of transport in response to regional supply and demand fluctuations and long-distance trades (BP, 2017). Despite the geological mismatch between natural gas fields and consumers, the traditional natural gas upstream processing is mainly carried out onshore (Lee et al., 2012). However, recent developments in the technology of LNG floating production, storage, and offloading (LNG-FPSO) have facilitated installing conventional onshore LNG processing facilities into the sea, which allows scattered small- and mid-sized offshore gas reserves to be economically recovered with lower infrastructure requirements than that of the traditional onshore fixed facilities (Yang et al., 2018).

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Nomenclature

AD	Annual depreciation
AGP	Annual gross profit
AOCF	Annual operating cash flow
AS	Annual sales
ATPC	Annual total production cost
C3MR	Propane pre-cooled mixed refrigerant
CAPEX	Capital expenditure
DMR	Dual mixed refrigerant
FLNG	Flating LNG
FPSO	Floating production, storage, and offloading
GA	Genetic algorithm
LNG	Liquefied natural gas
MACRS	Modified accelerated cost recovery system
MFCP	Mixed fluid cascade process
MR	Mixed refrigerant
MTPA	Million tons per annum
NGL	Natural gas liquid
NLP	Nonlinear programming
NPV	Net present value
OPEX	Operational expenditure
PMR	Parallel mixed refrigerant
PSE	Process sysems engineering
SC	Startup cost
SMR	Single mixed refrigerant
TAC	Total annualized cost
TACF	Total annual cash flow
h_j	Predefined equality constraints
h_p	Convergence of process simulator
ΔT_{min}	Minimum temperature difference
W_c	Power consumption
g_i	Inequality constraints
s_k	Hidden constraints
LMTD	Logarithmic average of the temperature difference
p	Penalty function
P	Pressure
T	Temperature
T^{dew}	Dew point temperature
UA	Heat transfer coefficient × heat exchange area
x	Vector of desicion variables
β	Present value factor
γ	Penalty function value
ΔP	Pressure drop
θ	Tax rate
x	Decision variables

Liquefying natural gas requires significant energy use to satisfy cryogenic temperature around −160 °C. This energy intensive yet necessary process has drawn the attention of many researchers to improving energy efficiencies, especially via process simulation and optimization in the process systems engineering (PSE) society. Numerous liquefaction processes have been introduced with different refrigerant types and process configurations over the last decades, mainly for large-scale liquefaction processes (WorleyParsons, 2013). Since raw feed gas is mainly hydrocarbon mixture, the enthalpy varies nonlinearly along temperature change during cooling and liquefaction. Mixed refrigerant (MR) cycles effectively reduce the temperature difference between the refrigerant cycle and natural gas, while pure refrigerant cycles are relatively simple but require more number of refrigeration stages. Representative processes using a pure refrigerant are ConocoPhillips optimized cascade® process and turbo expander using nitrogen. Dual mixed refrigerant (DMR), propane pre-cooled mixed refrigerant (C3MR) with or without a nitrogen refrigeration cycle, parallel mixed refrigerant (PMR), and mixed fluid cascade process (MFCP) are the example processes using MR for large-capacity LNG production. Among the major companies having MR technologies are Air Product and Chemicals Inc. (APCI), Shell, Statoil/Linde, and Axens (WorleyParsons, 2013). These processes with MR have been hot topics for research in design and optimization, producing numerous research articles regarding new configurations, exergy analysis, and design optimization with different objective functions and algorithms. For further information regarding aforementioned liquefaction cycles and the overall review in LNG plants, please see the review articles (Lee et al., 2017; Lim et al., 2013). Also, Qyyum et al. (2017) and Khan et al. (2017) give a thorough review and extensive literature analysis specifically on the optimization of natural gas liquefaction process in PSE community and future direction in LNG industry.

The small-scale NG liquefaction process, typically less than 1 million tons per annum (MTPA), is often used as a peak shaving plant to compensate unmet demand for natural gas (Mingot and Cristiani, 1997). Single mixed refrigerant (SMR) liquefaction process is promising when it comes to the offshore application due to its compactness, lightweight, and simplicity. Recent studies on SMR liquefaction process includes energy (Xu et al., 2014) and exergy analysis (Mehrpooya and Ansarinasab, 2015; Mokarizadeh Haghighi Shirazi and Mowla, 2010; Qyyum et al., 2018), process alternative configurations (Xiong et al., 2016), use of modified/combined optimization algorithms (Aspelund et al., 2010; Khan and Lee, 2013; Lee et al., 2002; Morin et al., 2011; Na et al., 2017; Park, 2015; Pham et al., 2017, 2016; Qyyum et al., 2018), consideration of external factors such as ambient temperature (Moein et al., 2015; Park et al., 2016; Xu et al., 2013), various objective functions (besides energy/power consumption), problem formulations (Cao et al., 2016; Lee et al., 2017; Lee and Moon, 2016; Mehrpooya and Ansarinasab, 2015; Nguyen Van and de Oliveira Júnior, 2018), new modeling approaches (Vikse et al., 2018), and efficient operation systems (Won and Kim, 2017; Won and Lee, 2017).

The majority of these studies focus on the design and/or optimization with a minimum amount of the energy or unit power consumption as an objective function, e.g. compression work; only a few economic analyses are presented. Lee and Moon, (2016) perform energy and cost analysis of SMR process with two different objective functions of compression energy and the total annualized cost (TAC) using genetic algorithm (GA). Castillo and Dorao, (2012) conduct cost minimization of SMR process using an integrated model for a decision-making framework where multi-levels and multi-objectives are solved simultaneously. Nguyen et al. (2017) carry out simple comparative economic evaluation study of floating LNG (FLNG) facilities with various number of trains for liquefaction process. However, the abovementioned economic studies are carried out based on a single steady-state operating regime, either with a simple economic evaluation model (no optimization) or without considering the economic efficiency according to the number of trains. This design approach might lead to a miscalculation of costs, given the fluctuation in feed gas conditions and an overall natural gas production rate considering well depletion. As small gas fields can be exhausted in a few years and peak shaving offshore floating facilities can be relocated to new gas fields, the optimal design values and operating conditions derived by a single steady-state regime and feedstock information without considering uncertainties may be not optimal. Moreover, since the capital investment for small-scale application accounts for a large portion in the total cost, economic evaluation according to the number of trains should not be ignored.

Considering the significance of a proper design approach for natural gas liquefaction process, a few studies addressing the uncertainty issues have been recently reported. Tsay and Baldea, (2018) presents scenario-free optimization of PRICO® SMR process with the uncertainty in feed natural gas composition using a pseudo-transient continuation concept for multi-stream heat exchangers and compressors. The article claims that undersized multi-stream heat exchanger is recommended for flexible operation and energy efficiency. Park, (2015) integrates design and control and optimizes PRICO® SMR process given the uncertainty in feed gas load. The author evaluates the system with