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Process Design and Optimization of Natural Gas Liquefaction Processes

Sekwang Yoon[a], Habin Cho[a], Dong-Ha Lim[b], Jin-Kuk Kim*[a]

[a]Department of Chemical Engineering, Hanyang University, Wangimni-ro, Seongdong-gu, Seoul, 133-791, Republic of Korea
[b]Energy Technology Team, GS Engineering and Construction, Namdaemun-ro 5-go, Joong-gu, Seoul, Republic of Korea
jinkukkim@hanyang.ac.kr

The design of liquefaction cycles requires detailed investigation for heat exchange between natural gas stream and refrigerant fluid streams to minimize shaft power consumed in the compressors of refrigeration cycles. Heat Integration study is essential for evaluating the effectiveness of heat exchange in the liquefaction cycles, as this conceptual technique provides graphical indication for the constrained part of heat exchange, with which systematic design guidelines for improving the efficiency of liquefaction cycles can be obtained. Recently, great attention has been paid to the design and optimization of natural gas liquefaction cycles for FPSO (Floating Production Storage and Offloading) applications. In this study, N_2 expander cycles and SMR (Single mixed refrigerant) cycles have been studied as the compactness of the cycle is very high, which is one of key criteria for the selection of liquefaction technology in LNG (Natural Liquefied Gas) FPSO applications. Investigation has been made to minimize shaftpower required for the cycles. Optimization framework has been developed such that GA (genetic algorithm) optimizer is interacted with process simulators, which avoids considerable efforts for building process model and simulating it within the optimizer. Case study will be presented to discuss how the new optimization strategy is effectively applied in the design of liquefaction cycles.

1. Introduction

New initiative in LNG (liquefied natural gas) market is to utilize offshore facility which can support the production of stranded gas. Still, onshore LNG plants is a main route for producing LNG in the industry, but great attention has been being paid to the development of offshore floating applications in these days (Festen et al., 2009). One of key processing elements in the LNG plant is a liquefaction process in which the pre-treated natural gas is converted in a liquid form by loosing heat to the refrigeration cycle. The amount of shaft power or electricity to drive compressors employed in the refrigeration cycle is very huge and therefore, it is essential to select the most appropriate technology for the liquefaction cycle and to operate the cycle at optimal conditions (Del Nogal et al., 2008).

Figure 1 illustrates a few cases about how the natural gas is liquefied. The upper line indicates cold streams to be cooled down in LNG liquefaction process, while the line below shows the profile of cold streams generated by the cycle, which removes the heat from the profile above. For conventional refrigeration cycles operating at the modest low temperature, a simple refrigeration cycle is used. If the level of cold requirement is very low, for example, -150 ^oC for LNG liquefaction, complex arrangement for the cycle is necessary to reduce thermodynamic inefficiency in the cycle (Smith, 2005). One of

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ways for improving energy efficiency is to mix a few refrigerant fluids and use them in a simple cycle, which allows the change of cooling profile continuously during phase change at the same operating pressure. A set of cycles, which use a single fluid per each cycle, can be coupled and heat exchange can be cascaded throughout operating temperature range. On the other hand, nitrogen can be employed in refrigeration cycle to provide cooling. Nitrogen expander cycle is less energy-efficient, but ensures high compactness. It is common to select these options together strategically and combine in a holistic manner, for example, multi-levels of propane-based pure refrigerant cycles are cascaded with mixed refrigeration (MR) cycle (e.g. C3MR, propane-precooled MR, cycle), or two different mixed refrigeration cycles are cascaded (e.g. DMR, dual mixed refrigerant, cycle). The key element in the design of such refrigeration cycles is to match two profiles as thermodynamically-efficient as possible. Process Integration methods have been proved to be very effective for heat recovery problem (Friedler et al. 2009), and the graphical interpretation of refrigeration cycle and its investigation with the aid of Process Integration has been widely used.

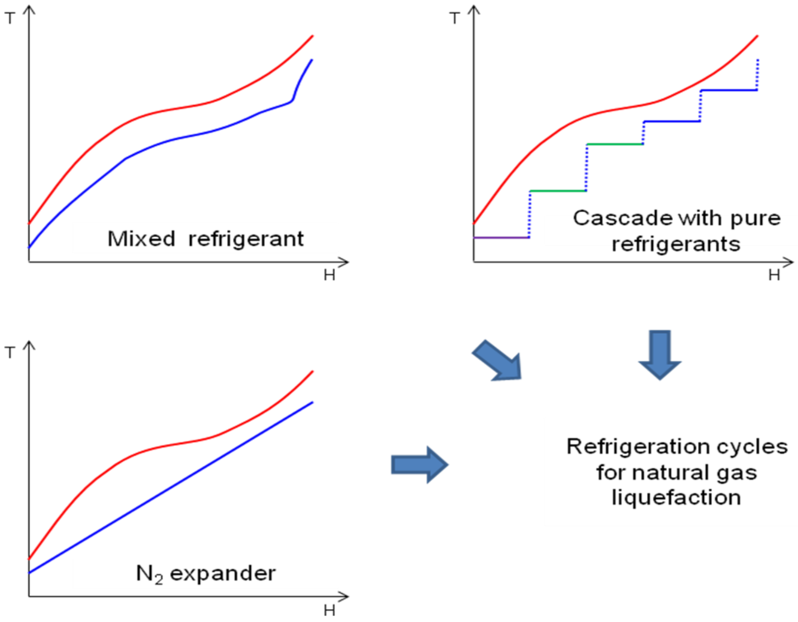

Figure 1: Design of Liquefaction Cycles

However, the optimization of liquefaction cycle is not straightforward, because optimization model requires carrying out considerable computation associated with calculation of thermodynamic properties and, hence, is highly nonlinear. Also, heat integration analysis is not simple, due to self-cooling feature of LNG refrigeration cycles (i.e. some part of streams in the refrigeration cycle is cooled by the refrigeration cycle itself). The current study aims to develop a new optimization framework which can optimise the refrigeration cycle effectively, but avoid computational burden for building process models and optimizing highly nonlinear mathematical models. Case studies have been carried out to demonstrate the applicability and effectiveness of the proposed method for optimizing SMR (single mixed refrigerant) cycle and dual N_2 expander cycle.

2. Simulation and Optimization Framework

Conventional optimization method is either to formulate the equation-based model for the design problem and solve it with a deterministic optimization solver, or to apply a stochastic optimization solver for the simulation model of the process. The simulation model or equation-based model for the refrigeration cycle includes calculation of thermodynamic properties, and implicit nature in the computation as well as high nonlinearity related to properties calculations requires considerable computational efforts and resources. In this work, it is proposed to build the process to be optimised using a commercial simulator which has been proven to be robust in simulating chemical processes. The simulator is interacted with external optimizer solver. In this study, GA (genetic algorithm) function available in MATLAB® is used for the solver, and Aspen HYSYS® for the simulator. The external optimizer generates a set of potential decision variables and passes them to the simulator, in which simulation is carried out to determine operating conditions. The obtained process conditions and parameters are passed to the solver, in which the objective function is calculated and evaluated, and new set of design variables are populated (Figure 2). Iterations between the simulator and the optimizer are continued, based on the optimization algorithm of GA solver, until the optimal solution is attained. Computer programming is required to build interfaces between MATLAB and Aspen HYSYS® for the exchange of decision variables and to execute the simulator.

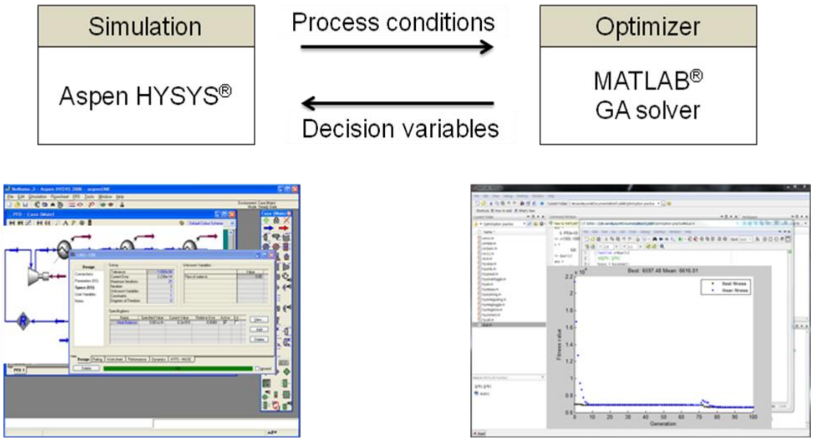

Figure 2: Optimization Framework

3. Case Study

First case study is to optimize SMR (single mixed refrigerant) process which is shown in Figure 3. In order to reduce energy requirements for the SMR process, MR compositions should be optimized, together with flowrate and operating pressures, which determine the shape of composite curves. With the aid of optimization solver, optimal conditions can be found, with which the gap between cold and hot composite curves can be evenly reduced throughout the heat exchanger.

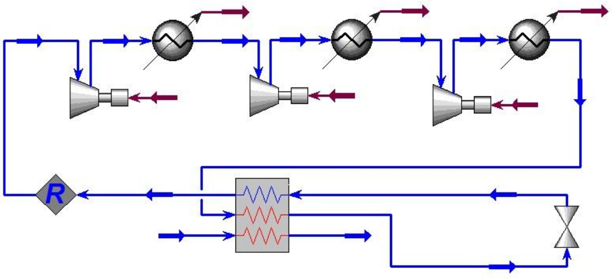

Figure 3: AspenHYSYS® simulation of a SMR process

Table 1 provides natural gas feed conditions and compositions, and optimization is carried out to minimize the shaft power demand. In principle, more detailed costing function can be evaluated in the optimizer. For the simulation, Peng-Robinson package is taken for equation of state, and four components (i.e. methane, ethane, propane and nitrogen) are used. Table 2 shows optimal results with about 10% reduction in the shaft power requirement, compared to the base case. Figure 4 gives how energy composite curves are changed after the optimization, and the temperature gap between two profiles becomes narrower for the optimal conditions when both composite curves are compared.

Table 1: Feed gas compositions and data for simulation (Shah and Hoadley, 2007)

Natural gas (NG) conditions		Feed gas composition	
NG inlet temperature	25 ^oC	Methane	0.9693
NG inlet pressure	5500 kPa	Ethane	0.0294
NG flowrate	1000 kmol/h	Propane	0.0006
LNG outlet temperature	-145 ^oC	n-Butane	0.0001
Ambient temperature	20 ^oC	Nitrogen	0.0006
Compressor efficiency	75%		
ΔTmin	5 ^oC		

Table 2: Comparison of results for SMR process

Base case			Optimal result		
Shaftpower		7338 kW	Shaftpower		6615 kW
MR	Methane	0.25	MR	Methane	0.9693
composition	Ethane	0.30	composition	Ethane	0.0294
	Propane	0.30		Propane	0.0006
	Nitrogen	0.15		Nitrogen	0.0001
MR	flowrate	3365 kmol/h	MR	flowrate	3212 kmol/h
	Inlet pressure to the compressor	4500 kPa		Inlet pressure to the compressor	4500kPa
	Inlet pressure to HX	400 kPa		Inlet pressure to HX	447 kPa

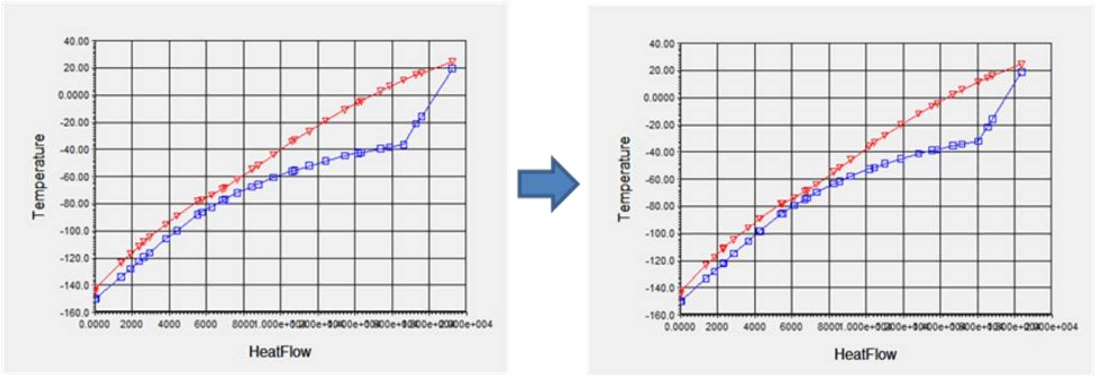

Figure 4: Optimization of SMR process

Second case study is to apply the developed optimization framework to the design of dual nitrogen expander cycle as shown in Figure 5. Each nitrogen cycle is operated at different pressure and both cycles are coupled in terms of heat exchange, and key decision variables for the optimization are operating pressures and stream flowrates of the cycles, and partition temperature between two cycles. Peng-Robinson package is taken for property calculation, and 5 ^oC is used for minimum temperature approach.

Figure 6 shows how energy composite curves are changed through the optimization. Table 3 provides the comparison between base case and optimal case. With the appropriate setting of operating conditions for the nitrogen cycle, energy efficiency can be improved. About 5 % of compression duty is reduced from the optimization. This case again shows the benefit of using the developed automated method, which systematically screens different operating conditions and identifies optimal conditions in confidence.

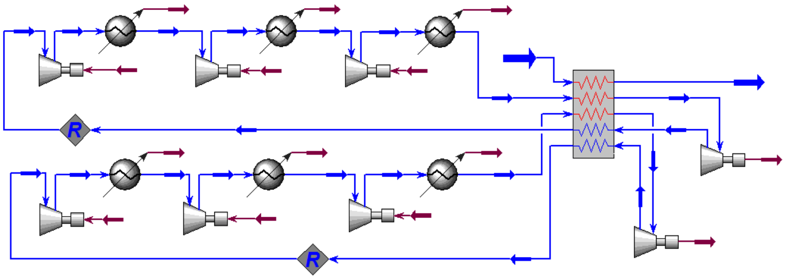

Figure 5: Aspen HYSYS® simulation of a dual N_2 expander process

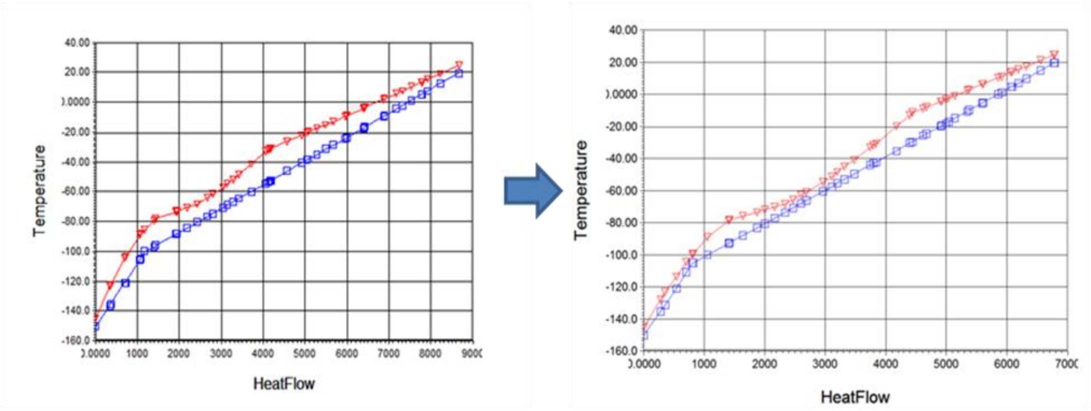

Figure 6: Optimization of dual N_2 expander process

4. Conclusions and future work

The paper addresses the new development of optimization framework which fully exploits the benefit of a process simulator and improves computational performance by simultaneously using an optimizer and the simulator. The design of LNG liquefaction cycle is studied and the developed optimization model is applied to minimize shaft power requirements for the given natural gas feed.

Although difficulties associated with finding an optimal solution for the design problem, is much reduced, the developed method is limited to process synthesis problems. Optimization of structural changes required in the flowsheet is yet fully automated, which is one of future works for the authors.

Acknowledgement

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