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Maximization of the power production in LNG cold energy recovery plant via genetic algorithm

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Abstract−This paper presents an optimization model via genetic algorithm (GA) to maximize the power generation potential of a liquefied natural gas (LNG) cold energy recovery plant. LNG releases a large amount of cold energy during vaporization prior to transport for service, and this cold energy can be effectively utilized to generate power using a heat engine. We performed a thermodynamic analysis for a power generation system combining the organic rankine cycle (ORC) driven by LNG exergy and the direct expansion cycle. Both LNG and the working fluid in the combined ORC are light hydrocarbon mixtures, and their physical properties were estimated using the Peng-Robinson equation. We conducted a thorough investigation of the effects that the working fluid composition brought about on the thermal efficiency of the heat engine through an analysis using Aspen HYSYS interfaced with a GA-based Matlab solver. The results showed that optimization of the working fluid composition led to an increase of 58.4% in the performance of the combined ORC in terms of the net work.

Keywords: LNG, Combined ORC, Working Fluid, Aspen HYSYS, Genetic Algorithm

INTRODUCTION

The liquefaction of natural gas into liquefied natural gas (LNG) is the only practical means for mass transport of natural gas, though it is accompanied by considerable energy consumption at the LNG plants. Preparative regasification at the LNG terminals releases a large amount of energy, and seawater is generally used as the heat source for the LNG regasification, with the vast amount of cold energy discarded without any beneficial effects [1].

Researchers have published numerous studies in the search for applications that can use the cold energy from LNG, including air separation, ethylene separation, liquefied CO_2 production, freezing of food, hydrogen/helium liquefaction, freeze-drying, low temperature crushing, and others [2]. Among these, power generation systems would be the most attractive way to apply the LNG cold energy due to the significant economic benefits and flexibility of installation. In fact, the power generation systems utilizing the cold energy of LNG have been pioneered by Japan since the 1980s and these are still in use [1].

The power generation systems using the cold energy from LNG are classified according to their operating principle. The most primitive and simplest method is to produce power through direct expansion. Another method uses the organic Rankine cycle (ORC) to generate power by recovering the cold energy from LNG treating it as a heat sink. In ORC, the boiling point of the organic working fluids is used to recover heat from a low-temperature heat source, such as seawater [3]. This cycle can also be combined with the direct expansion, which is then referred to as "combined ORC".

The type and composition of the working fluid affects the thermodynamic design of the ORC system, which should take into account the optimal energy utilization, economic performance and reduction of exergy losses [4]. Thus, selecting optimal organic working fluids is essential to improve the efficiency of the power generation system, and this issue has drawn significant attention [5-11].

Although a pure or a mixture working fluid can be used in ORC, a pure working fluid is less effective for heat transfer because LNG used as the heat sink is a mixture of hydrocarbon components. In case of a mixture working fluid, it is possible to set the dew point curve of the working fluid close to the boiling point curve of LNG by adjusting the composition of the working fluid. As such, the choice of an optimal composition is closely related to its thermophysical properties and the heat energy requirement in the cycle. The selection process of an optimal composition involves a trade-off between the thermodynamic specifications, safety, environmental concerns, and economic conditions [4,12-15].

Many researchers have applied genetic algorithm (GA) to seek optimal operating conditions for various systems, including propane pre-cooled mixed refrigerant LNG plants [16], an integrated solar combined cycle (ISCCS) [17], and a dual pressure combined cycle power plant [18].

We conducted a thermodynamic analysis of the combined ORC driven by the LNG exergy to generate power. The system applies a combination of a direct expansion cycle and ORC. We thoroughly investigated the effects that the composition of the working fluid mixture containing light hydrocarbons prevails on the thermal efficiency of the heat engine. The analysis was carried out in Aspen

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HYSYS linked to Matlab, with which the actxserver command was used to implement GA from the Matlab optimization toolbox. The Peng-Robinson equation was employed to calculate the physical properties of LNG and the working fluid, both of which are hydrocarbon mixtures. Different from pure working fluids, a mixture working fluid is more advantageous in placing the boiling point curve of LNG close to the dew point curve of the working fluid to improve the heat transfer efficiency. In general, this can be achieved by adjusting the composition of the working fluid.

This work reports an optimization model via GA to maximize the power generation potential of LNG cold energy recovery plant.

Table 1. The physical properties of LNG and the working fluid used in this work [15]

Components	Mole fraction	
	LNG (typical)	Working fluid (base)
Nitrogen	0.0052	0.0000
Methane	0.9539	0.3631
Ethane	0.0408	0.2817
Propane	0.0001	0.3552
i-Butane	1.0000	1.0000

METHODOLOGY

1. The Power Generation Cycle

The cold energy from LNG can be used to generate power using ORC, which is an implementation following the principle of the Clausius-Rankine steam cycle. In this system, the LNG cold energy is employed as a heat sink together with an organic working fluid of a low boiling point. It usually shows a high thermal efficiency allowing effective utilization of the available low-grade temperature heat source, such as the seawater. Furthermore, ORC combined with a direct expansion unit (Combined ORC) can lead to higher performance. Although a pure organic fluid or a mixture can be of use, the type and composition of the working fluid dictates a close and direct relation to the required mass flowrate of the working fluid and the amount of thermal energy needed for vaporization.

In the combined ORC (Fig. 1), ORC and the direct expansion cycle are properly annexed to improve power production. In addition to the direct expansion, a multi-stream cryogenic heat exchanger (MSCHE), a pump (P-100), evaporators (E-100, 101, 102, and 103) and turbines (K-100, 101, 102) are arranged in the ORC section. Recycle function (RCY-1) repeats this process until the two streams match within specified tolerances.

LNG enters MSCHE, wherein LNG is heated and evaporated to about −79 °C. During the regasification of LNG in MSCHE, a large amount of the so-called cold energy is released and transferred to the working fluid for its condensation. The highly pressurized natural gas resulting from LNG in MSCHE can be utilized to produce work through a turbine in the direct expansion cycle. Therefore, a higher power productivity can be expected comparing to either of the direct expansion cycle or ORC because the combined cycle recovers the pressure exergy of LNG from the direct expansion cycle and the thermal exergy from ORC.

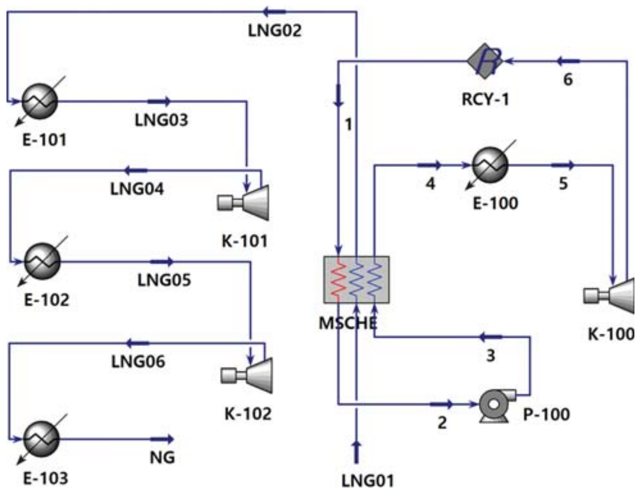

Fig. 1. Process flow diagram of the organic rankine cycle.

2. A Thermodynamic Model

Liquefied natural gas consists of a mixture of hydrocarbons that forms a clear, colorless, and odorless liquid. Although the actual composition of LNG varies depending on its source and liquefaction process, the dominant constituent is methane along with small percentage of hydrocarbons such as ethane, propane, butane, pentane, in addition to nitrogen. The working fluid of the combined ORC being considered in this work is also a mixture of light hydrocarbons. The working fluid of the optimized composition from the previous study was used as the base case and listed in Table 1 [15].

To control the processes and design applications for natural gas, the phase behavior and thermodynamic properties in the LNG systems are essential parameters. In particular, the composition of the working fluid determines its thermodynamic properties and thus the performance of the power generation cycle. Since both the working fluid and LNG are hydrocarbon mixtures, it may be natural to expect that a single model can predict the thermodynamic properties of both mixtures equally well. The Peng-Robinson equation of state (PR EOS) has been widely and successfully used to determine the state of hydrocarbon mixtures [20]. PR EOS shows superior performance in estimating the thermodynamic properties over other equations of state, and it has become admitted most confidently for natural gas systems in petroleum industries [see, for example, 19, 21-24].

3. Optimization Procedure

Fig. 1 presents the schematic of the combined ORC considered in this work where a mixture of light hydrocarbons ranging from C1 to C4 is adopted as a working fluid.

By using a mixture of hydrocarbons in the combined ORC, it is possible to draw a close match between the hot and the cold composite curves, with small temperature driving forces over the whole temperature range for active recovery of the cold energy from LNG. The composition of the working fluid can be adjusted to optimize the combined ORC driven by the LNG cold energy. Table 2 presents the operating condition, which is referred to as the base case, for the combined ORC quoted from Jeong et al. [24]. Later on in this article, this base case plays a role of a criterion to assess the performance of the cycle.

Table 2. The operating condition of the combined ORC used in this work [24]

Items		Value
Stream		
• LNG01 [33]	Mass flow rate	4,167 kg/h
	Temperature	−150 °C
	Pressure	3,700 kPa
Turbine	Isentropic efficiency	75%
• K-100	Exit pressure	350 kPa
• K-101		2,050 kPa
• K-102		500 kPa
Pump	Isentropic efficiency	75%
• P-100	Exit pressure	1,550 kPa
• MSCHE	Minimum approach temperature	3-5 °C
	Pressure drop	100 kPa
Evaporator	Pressure drop	50 kPa

Table 3. The typical GA tuning parameters [16]

Tuning parameters	Value
Population size	20×number of design variables
Reproduction count	50% of the population size
Maximum number of generations	100
Crossover fraction	0.8
Selection method	Tournament
Tournament size	8
Fitness scaling method	Top
Number of crossover points	1
Mutation method	Adaptive feasible

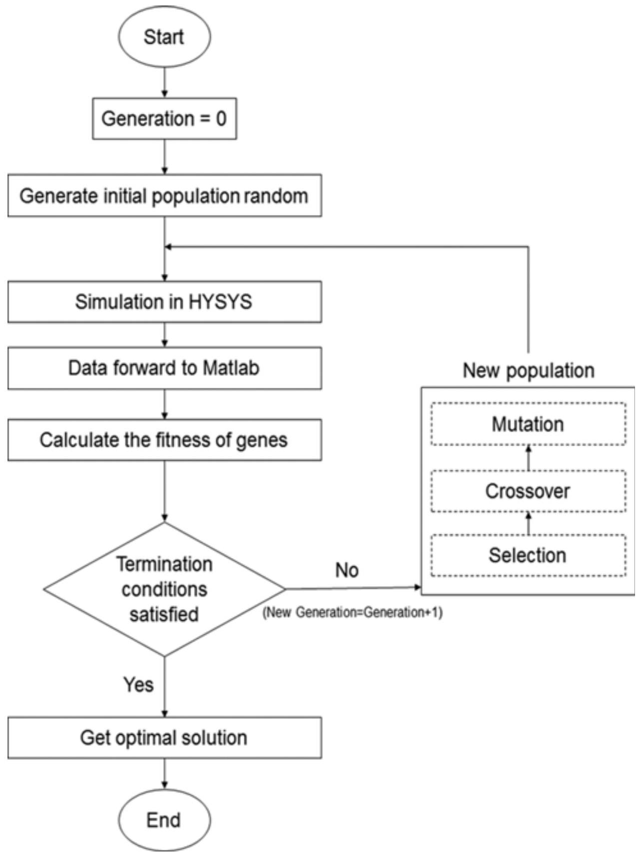

Fig. 2. The optimization procedure used in this study.

The process simulator Aspen HYSYS includes an optimization tool in itself; the optimization of the working fluid composition is difficult within the simulator due to the highly nonlinear characteristics of optimization problem with many local optimal solutions.

The genetic algorithm (GA) applies stochastic optimization to randomly generate a population of potential variables within the given bounds. Moreover, GA updates variables based on evolutionary strategies using inheritance, mutation, selection, and crossover, which are repeated until the optimal variables have been determined [25-29]. When the simulator receives candidate solutions generated from the GA solver, an objective function is evaluated from a process simulator, which is passed on to the optimization solver. The objective function, typically known as a fitness function in GA, is

Table 4. Heat and material balances of the organic rankine cycle

Name	LNG01	LNG02	LNG03	LNG04	LNG05	LNG06	NG
Vapor fraction	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Temperature [°C]	−150.00	−78.85	0.00	−29.31	0.00	−62.60	0.00
Pressure [kPa]	3,700	3,600	3,550	2,050	2,000	500	450
Mole flow [kmol/h]	249.80	249.80	249.80	249.80	249.80	249.80	249.80
Mass flow [kg/h]	4,167	4,167	4,167	4,167	4,167	4,167	4,167
Heat flow [kJ/h]	−2.23E+7	−2.01E+7	−1.91E+7	−1.93E+7	−1.91E+7	−1.95E+7	−1.90E+7
Name	1	2	3	4	5	6	
Vapor fraction	0.9651	0.0000	0.0000	0.2730	1.0000	0.9652	
Temperature [°C]	−36.70	−134.92	−134.29	−58.81	1.96	−36.70	
Pressure [kPa]	350	250	1,500	1,400	1,350	350	
Mole flow [kmol/h]	195.01	195.01	195.01	195.01	195.01	195.01	
Mass flow [kg/h]	5,842	5,842	5,842	5,842	5,842	5,842	
Heat flow [kJ/h]	−1.79E+7	−2.15E+7	−2.15E+7	−2.01E+7	−1.76E+7	−1.79E+7	

used to generate new sets of variables and check for the termination criteria [27]. The GA algorithm is described in detail in the literature [28].

In this study, Aspen HYSYS was linked with the optimizer from Matlab to determine the optimal composition of the working fluid in the cycle. The typical GA tuning parameters used in this study are listed in Table 3 [16]. Fig. 2 shows a flowchart of the optimization procedure taken in this study. The objective function from Aspen HYSYS was created in Matlab code. It maximizes the power output and is expressed as:

$$f_{max}=\max(W_{max})=\max(W_{max}-W_{pump}) \quad (1)$$

$$f_{min}=\min(-W_{min})=\min(W_{pump}-W_{comp}) \quad (2)$$

Here, the composition of the working fluid is the optimization variable that achieves the best performance of the combined ORC. The only constraint imposed on the optimization is that the minimum temperature approach in MSCHE ranges from 3 °C to 5 °C [30].

RESULTS AND DISCUSSION

The heat and material balances were calculated by using PR EOS in favor of Aspen HYSYS and the results are listed in Table 4.

To analyze the MSCHE unit graphically, the composite curves in the T-H diagram are plotted in Fig. 3. In the unit, the high-pressure working fluid and LNG are cold streams, while the low-pressure working fluid delivered from turbine is a hot stream. Fig. 3 shows the heat transfer curves in MSCHE for the ORC system of the base case and the optimized cases. The results show closer and more parallelized heat transfer curves in the optimized cases in Fig. 3(b) and (c) compared to the base case in Fig. 3(a), which indicates that with optimization of the working fluid composition, the heat transfer in MSCHE becomes more efficient. The GA-optimized case in Fig. 3(c) has a smaller area between the hot composite curves and cold composite curves than the HYSYS-optimized case in Fig. 3(b). This means that the optimization model via GA is more economically applaudable.

The optimization results starting from the base case listed in Table 5 show that the cycle with the optimized composition requires a higher working fluid flow rate. The combined ORC with the optimized composition has an exergy utilization efficiency of 18.9% in the HYSYS-optimized case and 25.0% in the GA-optimized case, whereas only 15.8% of an exergy utilization efficiency was attained in the base case. Here, the exergy utilization efficiency is defined as

$$\eta=\frac{W_{net}}{H_{NG}-H_{LNG}}=\frac{W_{comp}-W_{pump}}{H_{NG}-H_{LNG}} \quad (3)$$

The flowrate was adjusted to meet the constraint of the minimum temperature approach ranging from 3 °C to 5 °C. The optimizer using GA in Matlab has shown a performance superior to the optimizer in Aspen HYSYS, as shown in the optimization study starting from the base case where 115.9 kW of maximum net power was obtained with the Aspen HYSYS optimizer whereas the GA-based optimizer led to 153.5 kW. With the optimized composition by using the GA solver, the power cycle generates 58.4% higher than the initial net power of 96.9 kW. The results showed

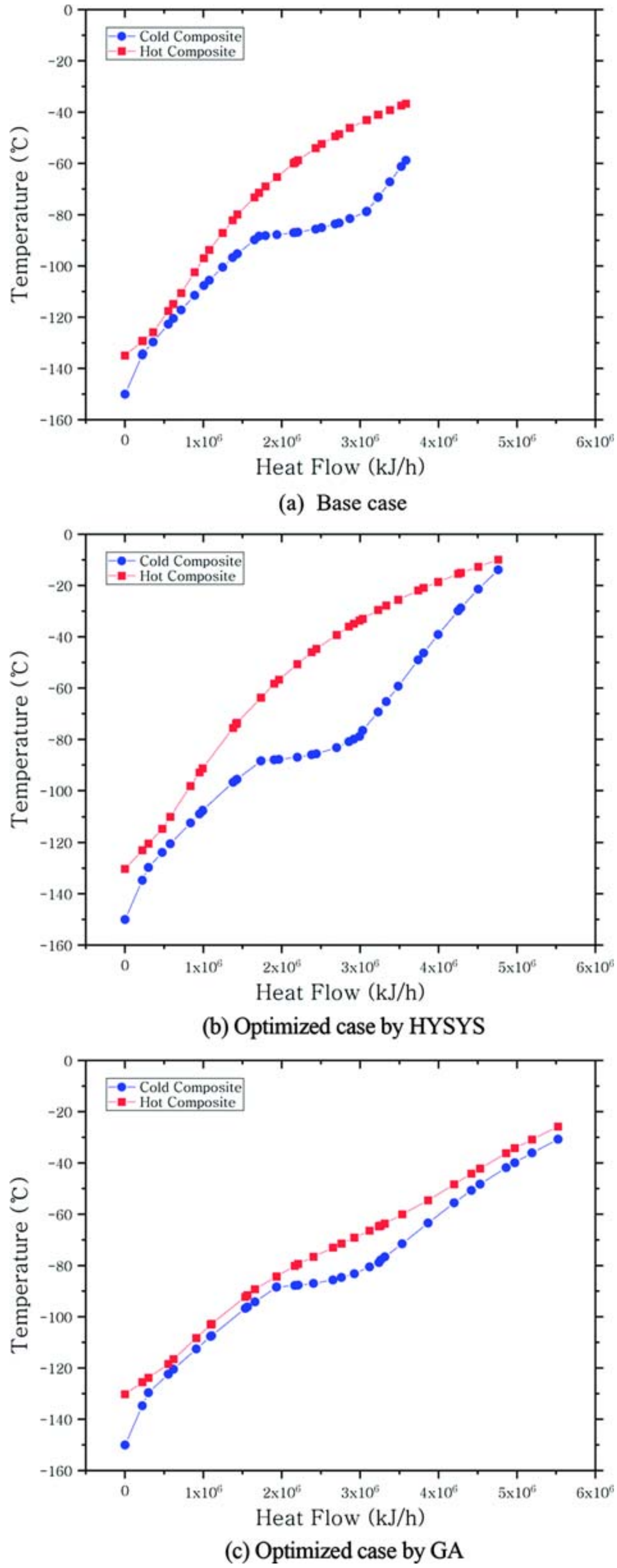

Fig. 3. The heat transfer curve in MSCHE for the cycle.

that the mole fractions of ethane and butane increased while those of methane and propane decreased.

Fig. 4 presents the T-S diagrams for the thermodynamic processes of the cycle with the working fluid of base case and the GA-

Table 5. The optimization results for ORC

Working fluid	Flow rate [kgmole/h]	W_{net} [kW]	Minimum temperature approach [°C]	Mole fraction			
				Methane	Ethane	Propane	i-Butane
Base	195.01	96.95	3.82	0.3631	0.2817	0.3552	0
Optimized (HYSYS)	208.64	115.9	3.90	0.2793	0.2167	0.2732	0.2308
Optimized (GA)	292.71	153.5	3.97	0.2905	0.5268	0.0214	0.1613

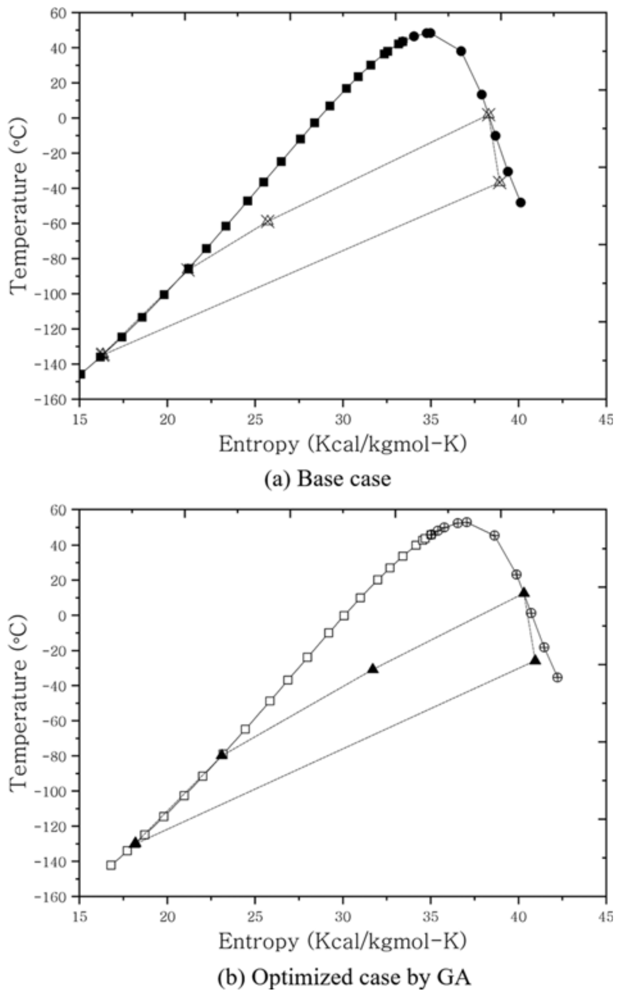

Fig. 4. T-S diagrams of the combined ORC.

optimized working fluid. Referring to Fig. 1, path (5→1) denotes the expansion process and lies in the two-phase region. The condensation process of the working fluid in MSCHE (1→2) is followed by compression (2→3), while the evaporation process starts (3→4) ahead of isobaric heating in MSCHE. The working fluids are multi-component mixtures, so the condensation and evaporation processes of the ORC system represent a non-isothermal phase transition and hence effectively match the temperature change of the heat source and heat sink.

An essential feature of the descriptions stems from the entropy difference between the saturated liquid and the vapor lines. Comparing to the base composition case, the optimized working fluid shows a more pronounced entropy change. This result indicates that the optimized working fluid exhibits a higher heat efficiency that is equivalent to a higher net work. This finding also implies that the optimized case (when the composition of the working fluid was optimized) needs a lower mass flowrate than the base case to absorb the same amount of thermal power from the heat source.

The LNG stream only exists between T_1 (−150 °C) and T_2 (−134.3 °C) and the available heat in this interval with a constant heat capacity is evaluated as:

$$Q_{(1\text{-}2)}=C_{p,LNG}\,(T_2-T_1) \tag{4}$$

However, for the stream between T_2 (−134.3 °C) and T_3 (−78.9 °C), the available heat in this interval is calculated as:

$$Q_{(2\text{-}3)}=(C_{p,LNG}+C_{p,working\ fluid})(T_3-T_1) \tag{5}$$

The 3-4 stream only exists between T_3 (−78.9 °C) and T_4 (−58.8 °C), and the available heat in this interval is given as:

$$Q_{3\text{-}4}=C_{p,working\ fluid}\,(T_4-T_3) \tag{6}$$

A series of heat values can be obtained in this way, and the results against the heat load are plotted in Fig. 3. A complete cold composite curve consists of a series of connected straight lines with each change in slope representing an overall change in the cold stream heat capacity and flow rate.

In this study, an economic analysis was also performed for the combined ORC by using Aspen process economic analyzer (APEA). The simulation model from Aspen HYSYS was mapped with the real time industrial equipment in the software library. The equipment size is prerequisite for costing and the results of size calculations performed during process simulation are loaded automatically by APEA.

In the economic analysis by using APEA, the cost of raw materials and the electricity production were not considered. The additional cost calculations were performed to include produced power cost. The cost of electricity was 0.13 $/kWh following the system marginal price (SMP) provided by the Korea Power Exchange. The investment parameters bring about effects on the design and cost estimation.

Table 6 shows the results of economic analysis. The total capital cost was increased by $14,986, while the annual product sales also increased by $67,252 when the working fluid was optimized by GA. The capital cost is the total cost of equipment, labor for setting equipment, piping, and design. The utility cost is for the power required for the pump and the heat for the heaters is provided by seawater.

This work presents an optimization strategy for the LNG cold energy recovery through a thermodynamic analysis based upon the process simulation combined with GA. The usage of GA was

Table 6. Economic analysis result

	Unit	Base	Optimized (GA)
Total capital cost	US$	1,737,952	1,752,938
Total utilities cost	US$/year	5,253	8,070
Total product sales	US$/year	326,659	393,911

proven to be substantial to improve the net power generation by 58.4% compared to 19.5% improvement through Aspen HYSYS default optimizer. The economic analysis was also performed to give a clear perspective on the optimization feasibility.

CONCLUSIONS

The combined ORC utilizing the LNG cold energy was modeled to understand the inherent irreversibility and improve the thermal efficiency for maximum produced work. For the cycle, a mixture of light hydrocarbons was selected as the working fluid because its thermodynamic properties can be easily tuned by changing the composition.

The working fluid composition was optimized with the aid of a solver based on GA to improve the performance by maximizing the produced work. In this effort, we linked the Aspen HYSYS simulator to a Matlab optimization solver to determine the optimal composition of the working fluid. In addition, the Peng-Robinson equation was implemented to calculate the physical properties of LNG and the working fluid, both of which are hydrocarbon mixtures.

The optimizer based on GA from Matlab showed a superior performance to the optimizer of Aspen HYSYS in the optimization study starting from the base case. The Aspen HYSYS optimizer increased the net power generation by 19.5%, while the optimizer based on the GA solver increased the net power generation by 58.4% compared to the base case. It appears that the irreversible loss might be reduced by optimizing the working fluid composition and thus relocating the saturation entropy curves closer to each other.

Scrutiny of the composite curves sheds a light on the insight that the combined ORC with the optimized working fluid shows a more efficient heat transfer in MSCHE than in the base case. Actually, the optimized working fluid shows closer and more parallelized heat transfer curves compared to the base case, indicating that heat transfer in MSCHE occurs more efficiently.

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