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Multi-parameter optimization of cold energy recovery in cascade Rankine cycle for LNG regasification using genetic algorithm

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ABSTRACT

A large amount of energy is consumed in the liquefaction process of LNG and is normally disposed through heat exchange with seawater in the regasification process. In this study, a cascade Rankine cycle was optimized to recover the cold energy by applying a genetic algorithm.

Gene population composed of chromosomes with various process parameters as geno types was created. Randomly created and combined chromosomes were restricted to conditions without any violation of the integrity of thermodynamic modeling. The process conditions that resulted in the maximum net produced power could be found by varying the process parameters. Ethane (C2) and propane (C3) were applied and compared as working fluids. In application of a single fluid, the C2C2 cycle showed higher maximum value than the C3C3 cycle. The C2C3 cycle showed the highest power generation among all cycles. LNG at −162 °C, 100 kPa is regasified to 10 °C, 6000 kPa NG, while sea water used as heat source enters at 15 °C, 100 kPa and exits at 10 °C, 300 kPa. In the regasification of 1 kg/s LNG mass flow rate, power generation performance was 96.3 kW in the C2C3 cycle and the first law efficiency was 11.1% at this condition.

1. Introduction

LNG is supplied through a complicated process starting from the initial production to the final distribution to the users, including the liquefaction of natural gas (NG) and regasification of liquefied natural gas (LNG).

Large amount of energy is consumed in the liquefaction process of NG to make LNG. It is known that power energy up to 300 kWh is used to produce 1 ton of LNG when using the C3 MR (mixed refrigerant) cycle, which is one of the commonly used liquefaction processes in the field [1].

This LNG cannot be used by final users directly. A regasification process of LNG is required for final users to use. Heat source is required for regasification in which seawater is mainly used. In this regasification process, the energy is normally disposed to seawater without being recovered. Assuming that the air temperature is 20 °C, this wasted energy is known to reach up to 240 kWh per ton of LNG regasification [2].

Various studies have been carried out on the topic of recovering this wasted energy. The nature of LNG with ultra-low temperature can be directly used in various fields that require cold energy, such as in the liquefaction of carbon dioxide, liquefaction of hydrogen, various separation processes, freeze-drying, and etc.

Along with this direct use of ultra-low temperature, power can be produced by recovering cold energy. The method of recovering the energy stored in LNG to produce power can be classified into mechanical energy recovery and thermal energy recovery. The direct expansion cycle (DEC) which was proposed to recover mechanical energy uses LNG as working fluid in a turbine to produce power by the expansion energy of LNG evaporation [3] [4]. Various methods to produce power by recovering thermal energy in such as Rankine [5] [6], Brayton [7], Kalina [8] cycles, and combined forms of these cycles [9] [10] have been proposed [11].

There have been researches on the use and optimization of Organic Rankine cycle (ORC) applied in waste heat recovery. Andreasen et al. conducted a multi-objective optimization of the net power output and the component costs for ORC power plants using low-temperature heat. They evaluated the economic feasibility of zeotropic mixtures compared to pure fluids [12]. Lecompte et al. suggested a methodology for ORC systems design based on multi-objective thermo-economic optimization. They investigated and compared subcritical ORC and transcritical ORC by applying this methodology to waste heat recovery [13]. Oyewunmi et al.

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presented optimization of an ORC system utilizing a low-temperature geothermal heat with mixed working-fluid in consideration of thermodynamic and heat-transfer performance, component sizing and capital costs [14]. Heberle and Brüggemann presented a thermo-economic evaluation of ORC used in geothermal power generation with variance of zeotropic mixture concentration and heat source temperature [15].

After the genetic algorithm has been developed, engineering fields implemented this method to solve complicated problems and find optimum solutions. Genetic algorithms have been also diversely used in thermal engineering. Recent studies carried out in this field include the optimization of the supercritical CO_2 power cycle [16], gas-steam combined power cycle [17], ammonia-water power system [8], and low grade waste heat recovery [18].

ORC has been applied in LNG cold energy recovery where LNG is set as the heat sink with seawater as the heat source to produce power by using other organic solvents as working fluid. Lee and Kim conducted an energy and exergy analysis of a combined cycle consisting of an ORC and an LNG cycle for the recovery of low-grade heat source and LNG cold energy [19]. Xue et al. studied a two-stage ORC for the recovery of low-grade heat of exhaust flue gas and the cryogenic energy of LNG [20]. Sung and Kim suggested a dual loop ORC system for recovery of waste heats from engine exhaust, cooling water and LNG cold energy [21]. Choi et al. suggested and optimized a cascade Rankine cycle consists of multiple stages of the ORC in a layered structure to recover LNG cold energy [22]. Lee and Choi performed a thermodynamic assessment of sequential ORC for recovery of cold energy of LNG and the exhaust gas heat of a diesel generator [23]. Results of many of these researches presented a tendency which showed a significant improvement of performance in multi-cycles compared to single cycle when applied to ORC LNG cold energy recovery.

However, a comprehensive optimization considering multi-parameters in multi-cycles to maximize the total cycle simultaneously was not performed in these studies. The condition that partially maximizes one cycle by changing one parameter was found when all other parameter conditions are fixed. Then another parameter was changed while fixing this condition to maximize the selected cycle only. Then these parameters were fixed for the first cycle and a parameter for the next cycle was changed, and another parameter and so on.

To author's knowledge, there have been few studies conducting multi-parameter search on multiple cycle cold energy recovery of LNG regasification. In this study, a cascade Rankine cycle is analyzed to maximize power production by changing the working fluid and various thermodynamic parameters. The genetic algorithm was applied for the optimization.

2. Process analysis

2.1. LNG regasification Cascade Rankine cycle

The LNG regasification cycle applying the cascade Rankine cycle is shown in Fig. 1. In basic LNG regasification processes, heat is supplied from seawater. LNG, which is generally stored in −162 °C temperature, receives heat from seawater and is regasified to 10 °C NG. Only waste of energy occurs in this process without any recovery. The cascade Rankine cycle with a double loop arrangement of the Rankine cycle was added to recover cold energy in the regasification process. Ethane (C2) and propane (C3) were used as the working fluids. Physical and environmental properties of these working fluids are described in Table 1. C2 and C3 are flammable non-toxic and have low environmental impact with zero ODP and very low GWP. These are known to be suitable for use in very low temperature applications with good thermodynamic performance [22,23].

The same working fluids were applied both in the outer cycle and inner cycle, or different working fluids were applied in these cycles for comparison. Cycles are notated according to the sequence of working fluids used in outer cycle and inner cycle. For example, when C2 is applied to outer cycle and C3 is applied to inner cycle, then the cascade cycle is notated as C2C3 cycle, and vice versa. When the same fluid was applied to both cycles, the cascade cycle is notated as C2C2 or C3C3 cycle. As the cascade Rankine cycle was added, LNG passes through the LNG-100 and LNG-101 heat exchanger to receive heat from each organic working fluid. To correspond to the NG supply specification, deficient heat was supplied from seawater at the end of the cycle.

In the outer cycle, the working fluid OC2, pressurized through the P-101 pump, changes into OC3 through heat exchange between the LNG and inner cycle at LNG-101. OC3 becomes OC4 by receiving heat from seawater through E-100. OC4 produces turbine-work W100 at K-100 to become low pressure OC5, which then passes LNG-100 and becomes liquid phase OC1 from the condensation through heat exchange with LNG.

In the inner cycle, IC1 is pressurized through the P-102 pump to become IC2 which passes the E-101 heat exchanger and vaporizes in receiving heat from seawater. IC3 produces turbine-work W101 through the K-101 turbine to become low-pressure state IC4. Then, IC4 passes the LNG-101 heat exchanger to become liquid state IC1 through condensation. Fig. 2 illustrates a typical *T-s* diagram of cascade Rankine cycle applied in cold energy recovery.

In this study, the mass flow rate of LNG treated in the regasification system was set to 1 kg/s. The chemical composition of LNG is shown in Table 2 in mole fractions [23]. The temperature and pressure of LNG1 input in the P-100 LNG pump and regasified NG were set to −162 °C, 100 kPa and 10 °C, 6000 kPa, respectively. The temperature and pressure at the entrance and exit of seawater that supplies heat of gasification were fixed to 15 °C, 100 kPa and 10 °C, 300 kPa, respectively. For heat exchange between LNG and working fluids of ORC, the HYSYS LNG exchanger model was used, which performs energy and material balances for multi-layer plate-fin type heat exchanger [24]. Shell-tube type heat exchangers were used for seawater. Heat losses from the heat exchangers were ignored. Other assumptions that are generally applied in LNG process analysis were used in the process simulation as shown in Table 3.

The Peng-Robinson Equation of State, which is known to provide relatively accurate analysis on thermodynamic properties of hydrocarbons including LNG, was applied in the thermodynamic analysis of the process [25,26]. Aspen HYSYS (ver. 7.3) was used in process modeling and simulation [24].

2.2. Energy analysis and objective function

The net produced power of the power generation system, $\dot{W}_{net}$ is defined as the power produced subtracted the power consumed, as shown below in Eq. (1).

$$\dot{W}_{net} = \dot{W}_{output} - \dot{W}_{input} \quad (1)$$

The produced power, $\dot{W}_{output}$ which is produced by the turbines where pressure drop expansion of working fluids occur, is the sum of the powers of K-100 and K-101 turbines of the two cycles, as shown in Eq. (2).

$$\dot{W}_{output} = \dot{W}_{turbines} = \dot{W}_{K-100} + \dot{W}_{K-101} \quad (2)$$

The power consumption, $\dot{W}_{input}$, in the proposed system is the sum of the power consumed by the pumps that pressurize the LNG,