Cascaded Organic Rankine Cycles (ORCs) for simultaneous utilization of Liquified Natural Gas (LNG) cold energy and low-temperature waste heat

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Abstract: Liquified Natural Gas (LNG) is a good way to transport natural gas from suppliers to end consumers. LNG contains a huge amount of cold energy due to the energy consumed in the liquefaction process. Generally, the LNG cold energy is lost during the regasification process at the receiving terminal. Power generation with LNG as the heat sink is an energy-efficient and environment-friendly way to regasify LNG. Among different kinds of power generation technologies, Organic Rankine Cycle (ORC) is the most promising power cycle to recover LNG cold energy. ORC has been widely used to convert low-temperature heat into electricity. If low-temperature waste heat and LNG cold energy utilization are utilized simultaneously, the efficiency of the whole system can be improved significantly. However, due to the large temperature difference between the low-temperature waste heat source and LNG, one stage ORC cannot exploit the waste heat and LNG cold energy efficiently. Therefore, a cascaded ORC system is proposed in this study. The optimization of the integrated system is challenging due to the non-convexity and non-linearity of flowsheet and the thermodynamic properties of the working fluids. A simulation-based optimization framework with Particle Swarm Optimization algorithm is adopted to determine the optimal operating conditions of the integrated system. The maximum unit net power output of the integrated system can reach 0.096 kWh per kilogram LNG based on the optimal results.

Key words: Organic Rankine Cycles, LNG cold energy, waste heat, process optimization

1. Introduction

Due to the increasing attention to the environmental effects of human activities, improving energy efficiency and reducing the CO_2 emission is more and more important for the conventional energy industry. Natural gas plays an increasingly important role in the global energy market. Due to the low energy density of natural

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gas compared with oil, natural gas has to be liquified to Liquified Natural Gas (LNG) for global trade. LNG contains huge amounts of cold energy, which is obtained at the cost of considerable mechanical work during the liquefaction process. One ton of LNG consumes about 850 kWh electricity [1]. However, the cold energy of LNG is generally discarded to seawater or air directly without reutilization. If the cold energy of LNG can be recovered properly, the energy efficiency and profit of LNG industry can be improved substantially. Due to the cryogenic temperature level of LNG, it is an ideal heat sink for Organic Rankine Cycle (ORC). Therefore, ORC could be a promising technology to recover LNG cold energy [2]. ORC has been widely investigated for the applications in solar energy [3], engine waste heat recovery [4] , biomass energy [5], industrial waste heat recovery [6], etc. However, there are limited studies focusing on the ORC system for the LNG cold energy recovery. Yu et al. [7] investigated 22 working fluids for the ORC recovering LNG cold energy. Lin et al. [8] proposed a transcritical CO_2 cycle to recover LNG cold energy and waste heat from the gas turbine exhaust. However, only one stage power cycle is considered in these studies. To improve the utilization efficiency of both waste heat and LNG cold energy, the flowsheet of the system should be more integrated to avoid too large temperature approach in the heat exchanger. Cascaded cycles can improve the efficiency of the system to some extent. However, the process synthesis and optimization of the system become more complex. Therefore, this study proposes to use an evolutionary optimization algorithm to optimize the cascaded ORC system for simultaneous utilization of low-temperature waste heat and LNG cold energy.

2. Process Description

The layout of the proposed cascaded ORC system is illustrated in Fig. 1. The higher temperature cycle converting waste heat into electricity is called Top Cycle (TC) and the lower temperature cycle utilizing LNG cold energy is called Bottom Cycle (BC). Low-temperature waste heat acts as the heat source in the top ORC, and the condensation heat is the heat source of the bottom ORC. LNG is pumped to the evaporation pressure, which is a key variable in the system. And then the LNG evaporates in the condenser of the bottom ORC acting as the heat sink. Since the temperature of LNG is still below ambient temperature after evaporation, LNG is heated up by seawater. It is assumed that the LNG is heated up to 10°C by the seawater in this study. To improve the utilization efficiency of low-temperature waste heat, natural gas superheater is set between the waste heat and LNG as shown in Fig. 1. Therefore, the top cycle mainly focuses on recovering the low-temperature waste heat and the bottom cycle aims at recovering the LNG cold energy. In this study, the LNG is assumed to be used for power plant, and the waste heat is assumed to be the treated flue gas at 150°C. Since the LNG mass flowrate is assumed to be 1620 kg/h, the molar flowrate of flue gas (mostly CO_2) should be 9509 kg/h based on the combustion of natural gas. The composition of LNG is the same as that in [7]. Due to the different operating temperature ranges of the top cycle and bottom cycle, working fluid should be chosen carefully for the top and bottom cycle, respectively. The top cycle is like a conventional ORC for low-temperature waste heat recovery. Based on a new pinch based working fluid selection study [9] and the waste heat conditions, R600 is chosen as the working fluid for the top cycle in this work. For the bottom cycle, the condensation temperature of the working fluid should be as close as possible to the temperature of LNG. Based on the saturation temperature at 1 bar, R1150 has the lowest saturation temperature among 22 working fluids investigated by Yu et al. [7]. Therefore, R1150 is chosen as the working fluid for the bottom cycle. The integrated process is simulated in Aspen HYSYS, and Peng-Robinson equation of state is chosen for the thermodynamic property's calculation of working fluids and LNG.

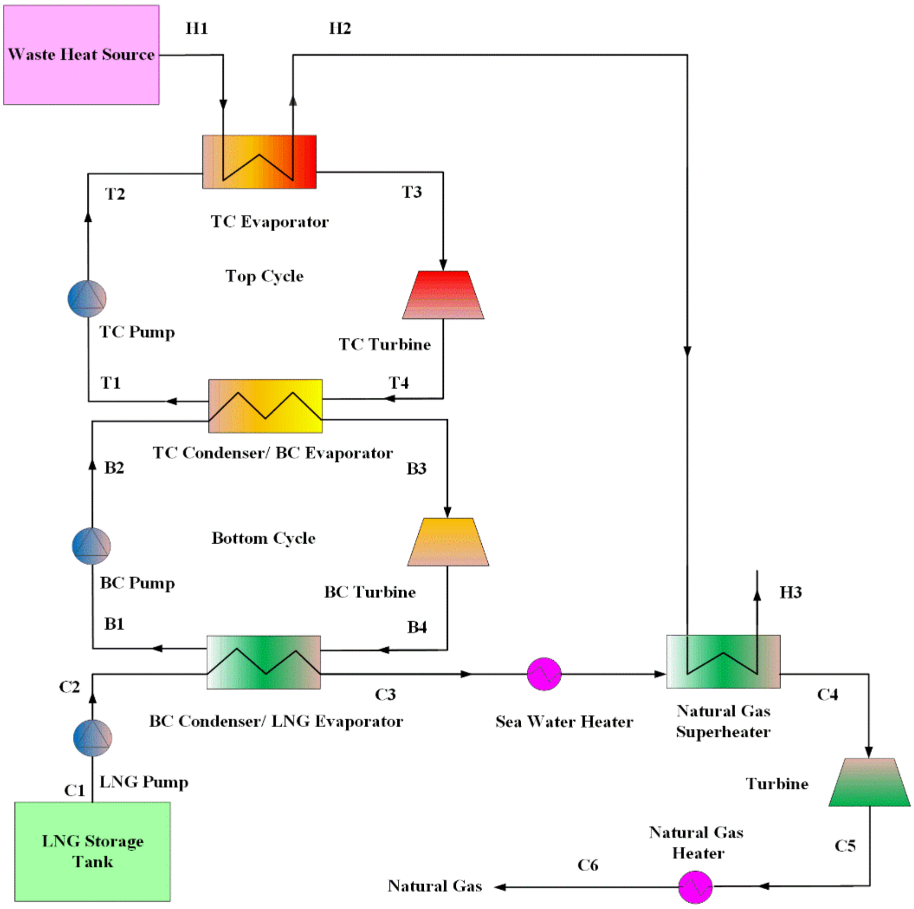

Fig.1 Flowsheet of the cascaded ORC system

3. Process Optimization

Due to highly non-linearity and non-convexity of the problem, a derivative-based optimization algorithm is inappropriate in this case. The evolutionary algorithm is more suitable for solving this problem. In this study, we adopt the Particle Swarm Optimization (PSO) algorithm, which was originally developed by Eberhart and Kennedy [10], to optimize the integrated system. PSO is a population-based optimization technique inspired by the social behavior of bird flocking or fish schooling. This optimization algorithm has been successfully applied in energy system, such as heat exchanger network design [11], distillation column design [12], and ORC system for engine waste heat recovery [13]. Therefore, it can be adopted in this study to optimize the cascaded ORC system. Based on the analysis of the degree of freedom, there are 7 independent variables for the integrated system as listed in Table 1. The lower and upper bounds of these variables are given in Table 1 as well. The upper bound of the evaporation pressure of both top and bottom ORC is set as the 90% of the critical pressure of the working fluids to guarantee the stable operation of subcritical ORC system [14]. To avoid too high capital cost and guarantee the stable operation of the system, the following constraints should be added in the optimization model. (1) The minimum temperature approach of TC evaporator and natural gas superheater should be greater than 5°C. (2) The minimum temperature approach of TC condenser/BC evaporator and LNG evaporator/BC condenser should be greater than 3°C. (3) The vapor fraction of TC pump and BC pump inlet streams must be 0. (4) The vapor fraction of TC turbine and BC turbine outlet streams must be greater than 95%. Once these constraints are violated during the optimization, a large penalty number will be added to the objective function to drive the search direction within the feasible region.

Table 1. The lower and upper bounds and optimal values of independent variables

Variables	Lower bound	Upper bound	Optimal value
Condensation pressure of TC (bar)	1	5	1.37
Evaporation pressure of TC (bar)	5	34.1	14.69
Working fluid flowrate of TC (kmol/h)	5	50	18.43
Condensation pressure of BC (bar)	1	5	3.24
Evaporation pressure of BC (bar)	10	45.5	38.96
Working fluid flowrate of BC (kmol/h)	10	50	32.17
LNG evaporation pressure (bar)	5	150	79.52
Heat load of TC evaporator (kW)	50	400	181.69
Heat load of natural gas superheater (kW)	0	150	77.20

4. Results and discussion

The optimal values of the independent variables are listed in Table 1. The maximum power output of the integrated system is 155.5 kW. Since the mass flowrate of LNG is assumed as 1620 kg/h, the unit power output is 345.6 kW with the LNG flowrate being

1kg/s. Therefore, the power output is 0.096 kWh/kg (LNG based metrics). Compared with the electricity consumed during the liquefaction process, the power output of the system is still quite low. The Logarithmic Mean Temperature Difference (LMTD) of top cycle evaporator, top cycle condenser, bottom cycle condenser, and natural gas superheater are 20.44°C, 11.85°C, 19.72°C, and 15.67°C respectively. The LMTD of the top cycle evaporator is larger than other heat exchangers. The final temperature of waste heat is 44.17°C, which means that the waste heat recovery ratio is very high. The top cycle power output, bottom cycle power output and natural gas expander power output are 29.56 kW, 36.88 kW and 102.30 kW respectively. It is clear that the expansion of natural gas generates 61% of the total power output. However, the LNG pump consumes 10.07 kW pumping work. The direct expansion of natural gas is an effective way to recover the LNG cold energy as well. These are the optimal operating conditions obtained from the PSO algorithm with a maximum of 100 generations. If the population size and the iteration numbers are increased, better results could be obtained. There is still space to improve the efficiency of the system. Other than the cascaded ORC system, series ORC system could probably result in higher efficiency. However, series ORC system is out of the scope of this paper but will be investigated in the future work.

5. Conclusion

In this study, a cascaded ORC system to recover low-temperature waste heat and LNG cold energy is simulated and optimized. Cascaded ORC system can improve LNG cold energy recovery efficiency. R600 and R1150 are chosen as the working fluids for the top and bottom cycle respectively since they have appropriate critical properties in their corresponding operating temperature range. Process optimization is performed based on a simulation-based optimization framework, which adopts PSO as the optimization algorithm. The optimal operation conditions of the system are derived based on this optimization framework. The maximum netpower output is 343.2 kW with the LNG flowrate being 1 kg/s, which is equivalent to 0.096 kWh/kg. The rigorous techno-economic optimization of the integrated energy system and series ORC system will be investigated in future work.

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