Thermodynamic Multi-Objective Optimization of an ORC-LNG Combined Cycle System

Zhaokuo Yuan\(^1\), Lijun Wu\(^1\) and Ping Zhang\(^1\)

1 School of Mechanical Engineering, Tongji University, Shanghai 201804, PR China
E-mail: ljwu@tongji.edu.cn

Abstract: A thermodynamic model of a dual loop organic Rankine cycle (ORC) combined with liquefied natural gas (LNG) expansion system has been developed to analyze the thermodynamic performance for the purpose of recovering LNG cold energy and blast furnace slag water waste heat. Furthermore, a multi-objective genetic algorithm (GA) is employed to solve the optimal solutions from the viewpoints of maximizing thermal efficiency and exergy efficiency simultaneously over the whole operating range of the combined cycle system. The results show that the optimal evaporation temperature and the intermediate condensation temperature of the first ORC (cycle A) are 83 °C and 19 °C separately. The optimal condensation temperature of the second ORC (cycle B) is -63 °C. The optimal gasification pressure and the supply pressure of the LNG expansion are 3.92 MPa and 0.20 MPa. At the rated condition, the ORC-LNG combined cycle system has the maximum thermal efficiency of 46.12% and exergy efficiency of 51.67%, with a 4.39 MW total net power output.

Keywords: LNG; Blast furnace slag water; Dual loop organic Rankine cycle; multi-objective optimization; Genetic algorithm

1. Introduction
As a clean and efficient energy source, liquefied natural gas (LNG) must be gasified before being supplied to users. The utilization of LNG cold energy mainly includes air separation, seawater desalination, cold storage refrigeration, and power generation. At present, the Rankine cycle, gas cycle, and LNG direct expansion cycle are most commonly used for recovering LNG cold energy\([1]\). Because coastal development has the characteristics of low cost and low consumption, the general trend of steel industry shifting to the sea has been formed in recent years. Establishing ORC to recover the waste heat of the blast furnace slag water, which temperature is about 65~95 °C, has been researched widely\([2-4]\). Parameters and structure have an important influence on the thermal performance of the ORC system\([5-8]\). This study established the ORC-LNG combined cycle system for the purpose of recovering LNG cold energy and blast furnace slag water waste heat.

2. ORC-LNG combined cycle system

2.1 System description
The schematic diagram of the ORC-LNG combined cycle system is shown in Figure 1. The condenser A is the joint between Cycle A and Cycle B because it also plays a role of evaporator B. The LNG in the storage tank is raised to the gasification pressure by the booster pump C, and pumped into the condenser B to absorb heat from the working fluid in Cycle B. Figure 2 shows the temperature-entropy diagram of the ORC-LNG combined cycle system.
2.2 Thermodynamic modeling

When the rated power of the Expander A has been determined, the mass flow rate of the working medium in Cycle A can be expressed as:

\[ m_{Af} = \frac{W_{EA}}{h_5 - h_2} \]  

(1)

The condenser A plays an evaporator role in Cycle B simultaneously, and the working fluid in Cycle B absorbs heat from that in Cycle A. The mass flow rate of the working medium in Cycle B is given by:

\[ m_{Bf} = \frac{m_{Af} (h_2 - h_4)}{(h_8 - h_{12})} \]  

(2)

The power consumption of the Pump A can be expressed as:

\[ W_{pA} = m_{Af} (h_8 - h_1) \]  

(3)

The heat transfer rate of the Evaporator A and the mass flow rate of the blast furnace slag water can be expressed as:

\[ Q_{eva} = m_{Af} (h_7 - h_6) \]  

(4)

\[ m_{bfsw} = \frac{Q_{eva}}{C_p (T_{sw1} - T_{sw2})} \]  

(5)

The power output of the Expander A can be expressed as:

\[ W_{EB} = m_{Bf} (h_5 - h_6) \]  

(6)

LNG acts as cold fluid in Condenser B, and its mass flow rate is given by:

\[ m_{Lf} = \frac{m_{Bf} (h_8 - h_{11})}{(h_{L5} - h_{L2})} \]  

(7)

The power consumption of the Pump B can be expressed as:

\[ W_{pB} = m_{Bf} (h_{12} - h_{11}) \]  

(8)

The power consumption of the Pump C is given by:

\[ W_{pC} = m_{Lf} (h_{L2} - h_{L3}) \]  

(9)

The power output of the Expander C is given by:

\[ W_{EC} = m_{Lf} (h_{L5} - h_{L6}) \]  

(10)

For the entire ORC-LNG combined cycle system, the thermal efficiency is defined as the net output
power divided by absorbed heat and given by:

$$\eta_{th} = \frac{W_{net}}{Q_{evaA}} \quad (11)$$

Where the net output power is equal to:

$$W_{net} = (W_{EA} - W_{AP}) + (W_{EB} - W_{BP}) + (W_{EC} - W_{CP}) \quad (12)$$

The exergy efficiency can be defined as the ratio of net output power and net input enthalpy exergy:

$$\eta_{ex} = \frac{W_{net}}{(E_{sw1} - E_{sw2}) + (E_{L1} - E_{L2})} \quad (13)$$

### 2.3 Operation condition

The operation conditions of the system are shown in Table 1. The values in brackets are the range of parameter variation.

| Parameters                                      | Units | Values   |
|-------------------------------------------------|-------|----------|
| Working mediums of Cycle A and Cycle B          | /     | R152a    |
| Temperature of blast furnace slag water         | °C    | 90       |
| Evaporation temperature                         | °C    | 75 (17–83) |
| Condensation temperature                        | °C    | -60 (-66–0) |
| Intermediate condensation temperature           | °C    | 15 (~45–73) |
| LNG gasification pressure                       | MPa   | 3 (0.8–5) |
| LNG supply pressure                             | MPa   | 0.6 (0.2–2.9) |
| Rated power of the Expander A                   | kW    | 1000     |
| Pinch points temperature difference            | °C    | 5        |
| Isentropic efficiency of expanders              | /     | 0.85     |
| Isentropic efficiency of pumps                   | /     | 0.8      |

### 3. Multi-objective optimization

A multi-objective genetic algorithm is employed to solve the optimal solutions from the viewpoints of maximizing thermal efficiency and exergy efficiency over the whole operating range of the combined cycle system. Figure 3 presents a diagram of the GA methodology.

**Figure 3.** The working principle of GA method.

In this study, two objectives of maximizing thermal efficiency and exergy efficiency over the whole operating range of the combined cycle system are considered in the proposed multi-objective optimization framework. Five decision parameters are selected for the thermodynamic optimization of
the combined system:

- $T_1$: Evaporation temperature of Cycle A (°C)
- $T_{10}$: Condensation temperature of Cycle B (°C)
- $T_3$: Intermediate condensation temperature of Cycle A (°C)
- $P_{L3}$: LNG gasification pressure (MPa)
- $P_{L6}$: LNG supply pressure (MPa)

4. Results and discussion

4.1 Effects of single parameter

Multi-objective optimization problems involve multiple objective functions and multiple decision parameters. Firstly, the effects of single decision parameter on the thermodynamic performances of the combined system are investigated in this study.

4.1.1 Effect of the evaporation temperature of Cycle A

The variations in the thermodynamic performances of the ORC-LNG combined cycle system with the evaporation temperature of Cycle A ($T_1$) are shown in Figure 4. It can be seen from the figure that the thermal efficiency and exergy efficiency of the combined system increase with the increase of evaporation temperature. When the evaporation temperature is 83 °C, the thermal efficiency and the exergy efficiency have maximum values of 36.99% and 45.32%, respectively.

4.1.2 Effect of the condensation temperature of Cycle B

Figure 5 shows the variations in the thermodynamic performances of the ORC-LNG combined cycle system with the condensation temperature of Cycle B ($T_{10}$). It can be seen that the thermal efficiency and exergy efficiency decrease with the increase of condensation temperature, which obeys the second law of thermodynamics. When the condensation temperature is -66 °C, the thermal efficiency and the exergy efficiency have maximum values of 37.38% and 46.68%, respectively.

4.1.3 Effect of the intermediate condensation temperature of Cycle A

Figure 6 shows the variations in the thermodynamic performances of the ORC-LNG combined cycle system with the intermediate condensation temperature of Cycle A ($T_3$). From the figure we can see that in the growth process of intermediate condensation temperature, both the thermal efficiency and the exergy efficiency have a tendency to increase first and then decrease. The curves have extreme points at different intermediate condensation temperatures. When the intermediate condensation temperature is 23 °C, the thermal efficiency has the maximum value of 36.42% and when the intermediate condensation temperature is 21 °C, the exergy efficiency has the maximum value of 44.93%.

![Figure 4. Effect of evaporation temperature on the thermodynamic performance of the combined system.](image1)

![Figure 5. Effect of evaporation temperature on the thermodynamic performance of the combined system.](image2)
4.1.4 Effect of the LNG gasification pressure. Figure 7 and Figure 8 show the variations in the thermodynamic performances of the ORC-LNG combined cycle system and its compositions with the LNG gasification pressure ($P_{Lg}$). From the figure we can see that there is an extreme value of the total thermal efficiency exists under the combined effects. When the LNG gasification pressure is 4.4 MPa, the thermal efficiency has the maximum value of 37.39%. Under the combined influences, the exergy efficiency of the ORC-LNG combined cycle system increases first and then decreases as shown in Figure 8. When the LNG gasification pressure is 4.2 MPa, the exergy efficiency has the maximum value of 46%.

4.1.5 Effect of the LNG supply pressure. Figure 9 and Figure 10 show the variations in the thermodynamic performances of the ORC-LNG combined cycle system and its compositions with the LNG supply pressure ($P_{L6}$). For the ORC-LNG combined cycle, as the LNG supply pressure increases, the output power of the Expander C decreases, which reduces the net output work of the combined system. Meanwhile, the heat absorption of the system does not change. As a consequence, the thermal efficiency of ORC-LNG combined system decreases as the LNG supply pressure increases. When the LNG supply pressure is 0.2 MPa, the thermal efficiency has the maximum value of 44.52%. As the LNG supply pressure increases, the output power of the Expander C decreases, which reduces the net output work of the combined system. Meanwhile, the input enthalpy exergy of heat absorption keeps stationary. So the thermal efficiency of ORC-LNG combined system decreases as the LNG supply pressure increases.
pressure increases. When the LNG supply pressure is 0.2 MPa, the exergy efficiency has the maximum value of 49.92%.

**Figure 9.** Effect of LNG supply pressure on the thermal efficiency of all cycle systems.

**Figure 10.** Effect of LNG supply pressure on the exergy efficiency of all cycle systems.

### 4.2 Multi-objective Optimization of the ORC-LNG Combined Cycle System

The multi-objective optimization of the ORC-LNG combined cycle system is to maximize the thermal efficiency and the exergy efficiency over the whole operating range. The weight coefficient of each objective function in GA is 0.5. The results show that the iteration convergence is achieved when the number of iteration is 313. The optimization results are shown in Table 2.

| Parameter | T₁ (°C) | T₁₀ (°C) | T₃ (°C) | P₁₃ (MPa) | P₆ (MPa) | Thermal Efficiency (%) | Exergy Efficiency (%) |
|-----------|---------|----------|---------|-----------|----------|------------------------|-----------------------|
| Optimization | 83.00   | 19.48    | 63.00   | 3.92      | 0.20     | 46.12                  | 51.67                 |

### 5. Conclusions

In this paper, a thermodynamic model of a dual loop organic Rankine cycle (ORC) combined with liquefied natural gas (LNG) expansion system has been developed to analyze the thermodynamic performance for the purpose of recovering LNG cold energy and blast furnace slag water waste heat. The effects of five key parameters on the thermodynamic indicators of the ORC-LNG combined cycle system are investigated. Furthermore, a multi-objective genetic algorithm (GA) is employed to solve the optimal solutions from the viewpoints of maximizing thermal efficiency and exergy efficiency simultaneously over the whole operating range of the combined cycle system. The main conclusions can be summarized as follows:

- In the growth process of intermediate condensation temperature and LNG gasification pressure, there is a tendency to increase first and then decrease and the extreme point on the curve does not appear in the same condition.
- With the increase of LNG supply pressure, the thermal efficiency and efficiency of the system showed a downward trend.
- The optimal evaporation temperature and the intermediate condensation temperature of the first ORC (cycle A) are 83 °C and 19 °C separately. The optimal condensation temperature of the secondary ORC (cycle B) is -63 °C. The optimal gasification pressure and the supply pressure of the LNG expansion are 3.92 MPa and 0.20 MPa.
- At the rated condition, the ORC-LNG combined cycle system has the maximum thermal efficiency of 46.12% and exergy efficiency of 51.67%, with a 4.39 MW total net power output.

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