Optimization and Analyses of an Organic Rankine Cycle System Utilizing Cold Energy of Liquefied Argon

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Abstract. In order to study the feasibility of liquefied argon cold energy recovery by organic rankine cycle (ORC), an ORC system cooling by liquefied argon was proposed and the mathematical model was established in this paper. The thermophysical properties of several organic working substances were compared, and R218 demonstrates the best circulating performance under working condition. The operating characteristics of the ORC system under various parameters were analyzed and optimized. When the condensing pressure is 13.6kPa, the system output power reaches the peak value of 1.003kW. With the raising of the evaporation pressure, the net output power and the thermal efficiency of the ORC both increase. The raising of ambient temperature can effectively promote the circulating working substance in the evaporator to absorb heat from the air. The working substance at the exit of condenser under saturated state is propitious to the net output power of the system.

1. Introduction

Argon is widely used as shielding gas in metal welding in order to ensure quality [1]. Large amount of argon will be consumed to prevent the metal such as titanium alloy from being oxidized at high temperature during welding process [2]. Argon is usually stored in a dewar tank in the form of liquid phase. It is flown into the vaporizer from the dewar tank with temperature rise and pressure decrease before being used as welding shielding gas. In this process, the liquefied argon directly absorbs heat from the ambient environment, and large amount of cold exergy is not effectively utilized, which results in a massive energy waste.

The Organic Rankine Cycle (ORC) has attracted extensive interest because of its advantage in low-grade energy recovery [3]–[5]. ORC system with different working substances could utilize heat sources in various temperature ranges to perform work, and has already been used to recover geothermal energy [6], solar energy [7], [8], garbage incineration heat [9], and industrial flue gas waste heat [10]. Cold energy recovery is another important application of ORC.
Considerable research has been done on cold energy recovery by ORC. Wang et.al [11] analyzed power output of ORC utilizing cold energy of liquefied nature gas. Moghimi et.al [12] proposed a combined system consisting of a rankine cycle and a stirling cycle to utilize cold energy of liquefied natural gas (LNG). Zhang et.al developed a tripartite ORC system to improve cold energy recovery. However, the recent research about cold energy utilization by ORC technology was mainly focused on LNG gasification process, and few literatures on liquefied argon cold energy utilization were released. In fact, the global annual consumption of liquefied argon is large, and the benefits of liquefied argon cooling energy recovery are considerable. Since liquefied argon have completely different thermophysical properties than LNG, its ORC cold energy recovery system also has discrepant operating characteristics. In order to thoroughly study the feasibility of liquefied argon cold energy utilization by ORC, we designed a novel ORC cold energy utilization system for the liquefied argon gasification process and established its mathematical model in this paper. The operating characteristics of the system under various working conditions were analyzed and optimized.

2. System arrangement and mathematic model

2.1. ORC system description
The left diagram in Figure 1 shows the ORC system consists of a working substance pump, an air-bath evaporator, an expansion turbine, and a liquefied argon cooled condenser. Liquefied argon is drawn from the dewar tank, decompressed by the pressure reducing valve, and then flows into the condenser. Liquefied argon exchanges heat with organic working substance to raise temperature in condenser. At the same time organic working medium also transfers heat to the liquefied argon and then turns to the supercooled state. After being boosted to evaporating temperature by the working medium pump, it enters the air-bath evaporator to absorb heat from ambient air, and then performs work in the expansion turbine to generate electricity. Turbine exhaust steam continues to enter the condenser to heat liquefied argon.

Figure 1 indicates the thermal process of the ORC system. The four processes of adiabatic compression, constant pressure heat absorption, adiabatic expansion and constant pressure heat release are managed in the organic working substance recirculation. Point 1 to point 2 represents the adiabatic compression of the organic working fluid in pump. Point 2 to 4 via 3 represents the heat absorption process under a constant pressure, the organic working fluid absorbs heat from the ambient air in the evaporator to a superheated state. Point 5 to point 6 represents the adiabatic expansion process, thus the organic steam performs adiabatic expansion in the turbine to perform work. Point 6 to point 1 represents the heat release process in condenser, and the organic working fluid at the outlet of the expander will be converted into a low-temperature and low-pressure supercooled state and release heat to liquefied argon under a constant pressure.

![Figure 1. Schematic diagram and T-S diagram of liquefied argon cold energy recovering ORC system](image-url)
2.2. Mathematical Model Description

In order to simplify the calculation, the system model is created with the following assumptions: Due to the small size of the overall system, the heat dissipation loss of the system is ignored in the calculation, and the along-path resistance loss and local resistance loss caused by the evaporator, condenser and system pipeline are ignored. Since the constant pressure heat absorption process involves an air-bath evaporator with better heat exchange performance, the outlet temperature of the evaporator is determined to be 2 degree Celsius lower than the ambient temperature.

The physical properties of the working fluid and argon are obtained from the working fluid physical property calculation software REFPROP 9.0 developed by the National Institute of Standards and Technology (NIST).

The pinch temperature difference method and the first law of thermodynamics are used to model and analyze the ORC system performance of different organic working substances under various working conditions.

The heat balance process in the evaporator can be described as:

\[
Q_{he}=m(h_e-h_2)
\]  
(1)

Power output of the turbine can be expressed as:

\[
W=m(h_e-h_3)=m(h_{is}-h_{s})\eta_t
\]  
(2)

The heat exchange in condenser is rated as:

\[
Q_{co}=m(h_e-h_1)=c_w m_w \Delta T
\]  
(3)

\[
Q_{co}=U_A \frac{\Delta T_{max} - \Delta T_{min}}{\ln \frac{\Delta T_{max}}{\Delta T_{min}}}
\]  
(4)

The energy consumption of the working substance pump can be obtained by:

\[
W_{pump} = \frac{m \int_{P_{max}}^{P_{min}} v dp}{\eta_p} = \frac{m(h_{2s}-h_1)}{\eta_p}
\]  
(5)

Here pump coefficient is defined as:

\[
\eta_p = (h_{2s}-h_1)/(h_2-h_1)
\]  
(6)

The net power output can be deduced as:

\[
P_{net} = W-W_{pump}
\]  
(7)

The thermal efficiency of the ORC is calculated as:
According to the second law of thermodynamics, the cold exergy induced into the system by liquefied argon is calculated as:

$$E_{in} = \int_{T_{in}}^{T_{ev}} (1 - \frac{T_{0}}{T_{in}}) c_p m_{ar} dT = m_{ar} [T_{0} (s_{0} - s_{in}) - (h_{0} - h_{in})]$$

Thus the exergy efficiency of the system can be obtained by:

$$\eta_{ex} = \frac{W_{net}}{E_{in} - E_{out}}$$

An in-house MATLAB code was developed to calculate the specific performance of the system under various conditions. The flow chart of the calculating procedure is showed in figure 2.
3. Results and discussion

3.1. Selection of working substance

Table 1. Comparison of three working substances

| Substance | Type | Standard boiling temperature (℃) | Critical temperature (℃) | Critical pressure (MPa) | ODP |
|-----------|------|----------------------------------|---------------------------|-------------------------|-----|
| R115      | Dry  | -39.51                           | 79.95                     | 3.129                   | 0.4 |
| R218      | Dry  | -37.08                           | 71.87                     | 2.64                    | 0   |
| R245fa    | Dry  | 14.9                             | 154.05                    | 3.64                    | 0   |

In order to implement the effective utilization of liquefied argon cold energy, several organic working substances were screened and compared. The ideal organic working fluid should have the following features:

1) Excellent thermodynamic properties: the working fluid shall satisfy the requirements on specified working temperature range;

2) Environmental friendliness: the working substance with low Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) causes less damage to the ozone layer and contributes less to the greenhouse effect;

3) Safety in use: the circulating working fluid is required to be non-toxic or low in toxicity.

According to the above criteria, this paper screened three cyclic working substances of R115, R218 and R245fa as candidate working substances. The main performance parameters are shown in Table 1.

In order to further investigate the operating characteristics of the candidate working substances in the current system, the net output power of the three working substances under different condensing pressures and evaporating pressures were compared, and the results are shown in Figures 2 and 3. When the condenser liquid argon inlet temperature is 129.74K, the maximum net power that can be output by the three circulating working substances of R115, R218, and R245fa are 0.979kW, 1.003kW, and 0.962kW respectively. The condensing pressures at corresponding maximum output powers are 16.374kPa, 13.606kPa and 0.385kPa respectively. With the variety of evaporation pressure, the maximum net power output by the three circulating working substance of R115, R218 and R245fa are 0.996kW, 1.021kW and 0.989kW respectively. The evaporation pressures to reach the corresponding maximum output powers are 834.62kPa, 799.44kPa and 132.47kPa respectively.

Figure 3. Net power output of different work substances varying with condensing pressure

Comprehensive comparison of the operating characteristics of the three working substances under different condensation pressures illustrates that R245fa has the lowest evaporation pressure, thus less consumption of pump work in the circulation. However, the best condensing pressure of R245fa requires high vacuum in condenser with high quality sealing, thus it will increase the equipment cost of the ORC
system. R218 and R115 have similar optimum evaporation pressure and condensation pressure, but R218 delivers a higher maximum net output power than R218 within the whole working range. At the same time, R218 has a lower ODP value than R115, indicating less damage to ozone. Considering the above factors, it is suggested to choose R218 as the best working substance of the ORC system.

![Image](image-url)

**Figure 4.** Net power output of different work substances varying with evaporating pressure

### 3.2. Optimization of operating parameters

#### 3.2.1. Analysis of condensing pressure

The change trend of the main performance parameters of the ORC system under different condensing pressures is shown in Figure 5. The thermal efficiency of the ORC system continues decreasing as the system condensing pressure increasing. When the condensing pressure rises from 0.11kPa to 75kPa, the cycle efficiency drops from 29.38% to 12.44%. This can be attributed to the increase in the condensing pressure which causes the increase in the average exothermic temperature of the cycle. However, the rise of the condensing temperature will also facilitate the heat exchange in the condenser. As the argon inlet temperature and flow rate remain constant, when the condensing pressure rises from 0.11kPa to 75kPa, the heat exchange power in the condenser rises from 1.078kW to 6.078kW. This can be attributed to the increase in the condensation temperature, which leads to an increase in the average logarithmic temperature difference between the hot and cold fluids on both sides of the condenser. It can be seen that the increase in condensing pressure can effectively increase the heat transfer of the working fluid to liquefied argon, but it will also cause a decrease in cycle efficiency. Therefore, the net output power of the system shows a trend of rising at the early stage.
and falling at a later time. At the condensing pressure of 13.6kPa, the system output power reaches the maximum value of 1.003kW.

Figure 6. ORC performance varying with evaporating pressure.

3.2.2. Analysis of evaporating pressure. Figure 6 shows the operating characteristics of the ORC cold energy utilization system under different evaporation pressures. The net power output and the cycle efficiency both increase with the increase of the evaporation pressure. When the evaporation pressure rises from 566.36kPa to 799.44kPa, the cycle net output power rises from 0.978kW to 1.021kW, and the cycle efficiency rises from 12.44% to 27.09%. This can be attributed to the increase in the average endothermic temperature due to the increase in the evaporation pressure. The cycle efficiency is also improved. Further increase of the evaporation pressure makes the corresponding evaporation temperature rise. As a result, the cycle efficiency get further improved. However, if the corresponding evaporation temperature is too close to the ambient temperature, the heat transfer in the evaporator will sharply deteriorate and the heat absorption of the circulation from the surrounding air is also reduced. Under a high evaporating pressure, the working fluid in circulation is hard to be heated and turned into an overheated state at the corresponding evaporating temperature, which results in excessively high moisture content of the working substance at the inlet of the expansion turbine and severe reduction in net output power.

Figure 7. ORC performance varying with ambient temperatures.
3.2.3. Analysis of ambient temperature. Figure 7 illustrates the influence of ambient temperature on the operating characteristics of the system. Since the working substance in circulation directly absorbs heat in air-bathed evaporator, the ambient temperature has a significant impact on system performance. When the ambient temperature rises from 298.15K to 308.15K, the net output power of the system increases from 1.003kw to 1.052kw, which is a result of ambient temperature rise contributing to working substance in circulation absorption of heat from the environment in the evaporator. By contrast, the increase in system cycle efficiency due to the ambient temperature rise in this range is very limited. As the ambient temperature rises, the cycle efficiency of the system remains about 18.43%. The data reveal that, although the increase of ambient temperature can facilitate the heat exchange in the evaporator, the evaporation temperatures of the subheated section and the evaporating section of the system remain constant. As the average evaporating temperature of the cycle increases limitedly, the improvement of cycle efficiency is not significant.

However, it should be noticed that when the ambient temperature is lower than the circulating evaporation temperature corresponding to the circulating pressure, the heat transfer in the evaporator will be deteriorated. The circulating working substance cannot be heated to a superheated state, which leads to excessively high moisture content at the turbine inlet and affecting the normal operation of turbine. As a result, the net output power of the ORC drops significantly. Figure 7 shows that when the evaporation pressure drops to 291.15k, the net output power of the system drops rapidly from 1.003kw to 0.377kw. Therefore attention should be paid to reducing the evaporation pressure when the ambient temperature drops.

![Figure 8. ORC performance varying with subcooling degree of working substance](image)

3.2.4. Analysis of subcooling degree. The subcooling degree of the circulating working substance in condensing process is also an important parameter that affects the operation of the ORC system. When the subcooling degree increases from 0k to 6k, the net output power of the cycle drops from 1.041kw to 0.996kw, and the cycle efficiency decreases from 18.90% to 18.34%. With the increase of the subcooling degree, it will consume extra cold energy for cooling the circulating working fluid. Since the cold energy of the system is limited, the increase in the degree of subcooling reduces the circulation of the working fluid of the system, which indirectly reduces the output power of the circulation. It can be deduced that the net output power of the system reaches the highest when the subcooling degree of working substance at the exit of condenser is 0. However, if the system is unable to condense the working substance to subcooling state, the working medium at the inlet of the working substance pump will reach a two-phase state of gas-liquid, which will cause unstable operation of the circulating pump and affect the circulation efficiency.
4. Conclusion
In this paper, an organic rankine cycle (ORC) system cooling by liquefied argon was described and the mathematic model was established in order to study the feasibility of liquefied argon cold energy recovery. The thermophysical properties of three kinds of organic working substances were compared, and R218 was chosen to be suitable for the system. The operating characteristics of the ORC system under various working conditions were analyzed to find the optimized parameters.

The net output power of the system shows a trend of rising at the early stage and falling at a later time with condensing pressure increasing. When the condensing pressure is 13.6 kPa, the system output power reaches the maximum value of 1.003 kW. The net output power of the cycle and the cycle efficiency both increase with the increase of the evaporation pressure. The increase in ambient temperature can effectively facilitate the circulating working substance absorption of heat in the evaporator. The net output power of the system will be the highest when the subcooling degree of working substance at the exit of condenser is 0.

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