Performance analysis of different ORC configurations for thermal energy and LNG cold energy hybrid power generation system

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Abstract. This paper presents a thermal energy and Liquefied natural gas (LNG) cold energy hybrid power generation system. Performances of four different Organic Rankine cycle (ORC) configurations (the basic, the regenerative, the reheat and the regenerative-reheat ORCs) are studied based on the first and the second law of thermodynamics. Dry organic fluid R245fa is selected as the typical working fluid. Parameter analysis is also conducted in this paper. The results show that regeneration could not increase the thermal efficiency of the thermal and cold energy hybrid power generation system. ORC with the reheat process could produce more specific net power output but it may also reduce the system thermal efficiency. The basic and the regenerative ORCs produce higher thermal efficiency while the regenerative-reheat ORC performs best in the exergy efficiency. A preheater is necessary for the thermal and cold energy hybrid power generation system. And due to the presence of the preheater, there will be a step change of the system performance as the turbine inlet pressure rises.

1. Introduction
In recent years, renewable energy utilization and industrial waste heat recovery have gained more and more attentions due to the energy structure and the environmental concerns. Since the temperatures of renewable energy sources and industrial waste heat are relatively lower than conventional fossil fuels, Organic Rankine Cycle (ORC) systems have been considered as a better solution than the water-steam Rankine cycle [1]. Many efforts have been made to improve the performance of ORC. Some researchers point out that reducing the condensing temperature of working fluid, for example, using Liquefied Natural Gas (LNG) as the cooling medium instead of water [2-3], could greatly increase the system thermal efficiency. Similarly, some LNG researchers figure out that increasing the evaporation temperature of working fluid, such as using solar energy or waste heat as the heat sources instead of seawater [4-6], could obviously improve the efficiency of LNG cold energy power generation system. Thermal energy and cold energy are two different types of energy. However, most of the studies focused on the efficiency improvement of one type of energy system achieved by the addition of the other type of energy, assuming the additional energy is offered free of charge. Few researches considered the thermal energy and the cold energy equally as the energy inputs. In this paper, we establish a low temperature thermal energy and LNG cold energy hybrid power generation system.
Low temperature thermal energy is adopted as the heat source of the steam generator (SG) and LNG is taken as the cooling media of the condenser.

The configuration of ORC is critical for achieving higher system efficiency. The basic ORC comprises four key components: the steam generator, the steam turbine or expander, the condenser and the pump. Nowadays, regeneration and reheat have been widely used to improve the Rankine cycle efficiency of large-scale power plants. Hence, some researchers have studied the effects of the addition of regenerator or reheater on the ORC efficiency. The addition of regenerator has been investigated by many researchers and the results show that regenerative ORC has a higher efficiency than the basic ORC [7-11]. Studies on reheat ORC shows that the addition of reheater could increase the net power output obviously but the efficiency improvement is little and even lower than the basic ORC [12-14]. However, most of the studies mentioned above focused on the ORCs utilizing low temperature thermal energy, little attention has been paid to the ORCs utilizing both thermal and cold energy. Moreover, according to the previous studies of the authors [15], a preheater, in which the working fluid is preheated to the nearly environmental temperature, is quite necessary for ORCs utilizing both thermal and cold energy. Thus, the basic ORC utilizing both thermal and cold energy is composed of five key components: the steam generator, the steam turbine or expander, the condenser, the pump and the additional preheater.

The purpose of this paper is to investigate the performance of different configurations of ORCs utilizing both thermal and cold energy. The paper is organized as follows. In Section 2, different configurations of ORCs are described. Section 3 presents the mathematical models and performance criteria. Section 4 is the results and discussion. Conclusions are shown in Section 5.

2. System description
In this paper, four ORC configurations, the basic ORC, the regenerative ORC, the reheat ORC and the regenerative-reheat ORC, were investigated. The schematic and T-s diagrams of the four configurations are shown in Figures 1-4 respectively.

2.1. Basic ORC
As observed in Figure 1, there are five processes in the basic ORC:
- Process 1-2: a non-isentropic compression process in the pump;
- Process 2-3: a constant pressure heat addition process in the preheater;
- Process 3-4: a constant pressure heat addition process in the steam generator;
- Process 4-5: a non-isentropic expansion process in the turbine;
- Process 5-1: a constant pressure heat rejection process in the condenser.

![Figure 1. Basic ORC system: (a) schematic, (b) T-s diagrams](image)
A preheater is added in the basic ORC compared to the traditional Rankine cycle. In the preheater, the working fluid is nearly preheated to the environmental temperature by water, which could save the thermal energy in the steam generator.

2.2. *Regenerative ORC*
For dry fluids, the exhaust vapor exiting the vapor turbine is still in superheated state. Hence, a regenerator is added to recover the remaining energy of the exhaust vapor to preheat the working fluid before it enters the preheater (Figure 2).

![Figure 2. Regenerative ORC system: (a) schematic, (b) T-s diagrams](image)

2.3. *Reheat ORC*
As shown in Figure 3, the working fluid first expands to an intermediate pressure in turbine I, and then flows into the reheater for temperature boost. The working fluid is heated to the same temperature as the new vapor and then enters turbine II for further expansion.

![Figure 3. Reheat ORC system: (a) schematic, (b) T-s diagrams](image)

2.4. *Regenerative-Reheat ORC*
The regenerative-reheat ORC is a combination of the regenerative ORC and the reheat ORC (Figure 4).
3. Mathematical models and performance criteria
The mathematical models of the devices are established based on the conservation of mass and energy [3]. The thermodynamic properties of working fluid are calculated by the Reference Fluid Thermodynamic and Transport Properties 9.0.

3.1. Performance criteria of the cogeneration system
Both the first and the second law of thermodynamics are employed as the performance criteria. The systems are simulated to compare the performance of the proposed cycle with those of the basic ORC.

The thermal and exergy efficiency can be determined by:

\[ \eta_{th} = \frac{\text{energy in products}}{\text{total energy inputs}} \]  

(1)

The exergy efficiency is:

\[ \eta_{ex} = \frac{\text{exergy in products}}{\text{total exergy inputs}} \]  

(2)

4. Results and discussion

| Term                           | Value | Unit   | Term                           | Value | Unit   |
|-------------------------------|-------|--------|-------------------------------|-------|--------|
| Environmental temperature     | 25    | °C     | LNG pressure                  | 0.6   | MPa    |
| Environmental pressure        | 0.1   | MPa    | Condensation temperature      | -75   | °C     |
| Heat source temperature       | 100   | °C     | Turbine efficiency            | 80    | %      |
| Heat source pressure          | 0.5   | MPa    | Pump isentropic efficiency    | 80    | %      |
| Mass flow rate of heat source | 0.8   | Kg·s⁻¹ | Reheater inlet temperature    | 100   | °C     |
| SG inlet temperature          | 20    | °C     | Reheater outlet temperature   | 75    | °C     |
| LNG inlet temperature         | -161.48 | °C     | Reheater pressure             | 0.5   | MPa    |

System simulation was performed in MATLAB. The dry fluid R245fa is usually selected as the working fluid in ORC due to different factors like lower critical temperature almost 154.01°C, critical pressure almost 3.651Mpa, ozone depression potential is 0 and global warming potential is 6300. Then, R245fa was chosen as the typical working fluid. Simulation conditions of the system are displayed in Table 1. Tables 2 show the thermodynamic parameters at each node of the four different configurations respectively.
Table 2. Simulation results of different ORC configurations

| State | Basic ORC | Regenerative ORC | Reheat ORC | Regenerative-Reheat ORC |
|-------|-----------|------------------|------------|------------------------|
|       | t (°C)   | p (MPa)          | t (°C)     | p (MPa)                | t (°C)     | p (MPa) |
| 1     | -75      | 0.0003           | -75        | 0.0003                 | -75        | 0.0003  |
| 2     | -74.87   | 0.4419           | -74.87     | 0.4419                 | -74.87     | 0.4419  |
| 3     | 20       | 0.4419           | 55.52      | 0.4419                 | 20         | 0.4419  |
| 4     | 85       | 0.4419           | 85         | 0.4419                 | 85         | 0.4419  |
| 5     | -37.15   | 0.0003           | 85         | 0.0003                 | 85         | 0.0003  |
| 6     | -161.48  | 0.6              | -37.15     | 0.0003                 | 85         | 0.0003  |
| 7     | -85      | 0.6              | -69.87     | 0.0003                 | -9.62      | 0.0003  |
| 8     | 100      | 0.5              | -161.48    | 0.6                    | -161.48    | 0.6     |
| 9     | 62.68    | 0.5              | 85         | 0.6                    | -85        | 0.6     |
| 10    | 25       | 0.5              | 100        | 0.5                    | 100        | 0.5     |
| 11    | 15       | 0.5              | 25         | 0.5                    | 100        | 0.5     |
| 12    | -        | -                | 25         | 0.5                    | 75         | 0.5     |
| 13    | -        | -                | -          | -                      | 25         | 0.5     |
| 14    | -        | -                | -          | -                      | -          | -       |
| 15    | -        | -                | -          | -                      | -          | -       |
| 16    | -        | -                | -          | -                      | -          | -       |
| 17    | -        | -                | -          | -                      | -          | -       |

Figure 5 shows the exergy loss distributions of the four ORC configurations. Other exergy losses indicate the sum of the exergy losses in pump, regenerator and reheater. The condenser occupies the largest portion of the total irreversible loss, which is due to the great temperature differences between the working fluid and the LNG. The reheat ORC has the biggest total exergy loss. This can be explained since the reheater boosts the condenser inlet temperature (turbine outlet temperature) of the working fluid from -37.15 °C (basic ORC) to -9.62 °C, which enlarges the temperature difference between the working fluid and the LNG. As to the regenerative-reheat ORC, the addition of the reheater does not lift the condenser inlet temperature since the regenerator cools down the turbine exhaust steam before it enters the condenser. Furthermore, the regenerator increases the preheater inlet temperature, which results in the decrease of preheater exergy loss. Hence, the regenerative-reheat ORC has the lowest total exergy loss.

It can be observed from Figure 6 that the specific net power outputs of the basic ORC and the regenerative ORC are identical, which could be explained by the same inlet and outlet parameters of the turbine and the pump as shown in Table 2. The specific net power outputs of the reheat ORC and the regenerative-reheat ORC are also identical because of the same reason. The specific net power outputs of ORCs with reheat are obviously greater than that of ORCs without reheat since the reheater
provides extra energy. It could also be noticed that the increases of net power outputs rise rapidly at first and then become more and more slowly. This is because the increase of turbine power output is becoming more and more smaller but the increase of pump power input is becoming more and more larger as the turbine inlet pressure rises.

Figure 7. Variation of the mass flow rate with the turbine inlet pressure

Figure 7 shows the variation of the mass flow rate with the turbine inlet pressure. There is a step change of the mass flow rate at the turbine inlet pressure of 0.123MPa (the saturation pressure of 20°C for R245fa). Since the preheater outlet temperature is set to 20°C, when the turbine inlet pressure is lower than 0.123MPa, the working fluid at the preheater outlet is superheated steam, which means the evaporation process of the working fluid is completed in the preheater. However, when the turbine inlet pressure is higher than 0.123MPa, the working fluid at the preheater outlet is subcooled liquid, which means the evaporation process of the working fluid is completed in the steam generator. Hence, the working fluid has a step decrease in the mass flow rate. Another interesting point is that the mass flow rate drops as the turbine inlet pressure rises. This is because the higher the turbine inlet pressure is, the higher the heat source outlet temperature is. That is, less energy provided by the heat source is utilized to heat the working fluid. Hence, the mass flow rate of the working fluid decreases.

Figure 8 illustrates the variation of the thermal efficiency with the turbine inlet pressure. It can be observed that the thermal efficiency is higher than 1 when the evaporation process occurs in the preheater (turbine inlet pressure <0.123MPa) since the cold energy input of LNG is not considered in the calculation of the thermal efficiency. Figure 8 also shows that the addition of regeneration cannot improve the thermal efficiency at all, which is quite different from the results of usual ORC utilizations. The reason for this is that this is a system that using both thermal and cold energy for power generation and a preheater is absolutely necessary as mentioned above. Due to the presence of the preheater, the working fluid will always be preheated to 20°C by environmental air before it enters the steam generator. Which means the regeneration cannot increase the steam generator inlet temperature since this temperature is kept constant of 20°C by the preheater. Moreover, it should also be noticed that the thermal efficiencies of ORCs without reheat is greater than that of ORCs with reheat. This is because the reheat process enlarges the specific net power outputs at the cost of more energy input in the re heater.

The variation of the exergy efficiency with the turbine inlet pressure is shown in Figure 9. It can be observed that the regenerative-reheat ORC has the best exergy efficiency since the total exergy loss of this ORC is the smallest as shown in Figure 5. It should also be pointed out that although there is a step decrease of exergy efficiency when the evaporation process is transferred from the preheater to the steam generator, the exergy efficiency after the turning point rises as the turbine inlet pressure increases and finally surpass the previous exergy efficiency peak. The reason for this is that the total exergy loss (especially the loss in condenser) drops more than the total net power output does as the turbine inlet pressure increases.
Figure 10 shows the effect of turbine inlet temperature on system exergy efficiency at a certain turbine inlet pressure (0.706 MPa). With the increase of the turbine inlet temperature, the temperature difference between working fluid and the heat source reduces, which results in the decrease of the exergy loss in the steam generator. Hence, the exergy efficiency rises with the increment of turbine inlet temperature for all the configurations.

5. Conclusions
This paper presents the performance analysis of different ORC configurations using dry fluid R245fa as the working fluid based on laws of thermodynamics. The following conclusions may be drawn:

- Reheat could increase the specific net power outputs obviously but it may also reduce the system thermal efficiency.
- As the turbine inlet pressure rises, there is a step change of system performance due to the transfer of the evaporation process from the preheater to the steam generator. The thermal efficiency drop greatly after the turning point while the exergy efficiency rises gradually and finally surpasses the previous peak.
- Condenser accounts for the largest part of the total exergy loss. Utilizing lower condensing temperature could greatly reduce the exergy loss in the condenser.

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