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Thermodynamic and Economic Analysis of a High-efficiency System Integrating ORC Power Generation, CO_2 Capture, and CO_2 Storage Driven by Complementary LNG Cold Energy and Flue Gas Waste Heat.

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Abstract: Liquefied natural gas (LNG) is a clean primary energy source, and the large amount of cold energy stored in LNG provides an opportunity for sustainable technologies to recover and utilize this energy source. This can improve the energy efficiency of LNG regasification terminals and the economic viability of the LNG supply chain. In this paper, an efficient system integrating ORC power generation, CO_2 capture, and CO_2 storage driven by complementary LNG cold energy and flue gas waste heat is constructed. The exergy-efficiency of the system is 63.09%, the total round-trip efficiency η_(RTE-Overall) of the system was calculated to be 93.22% and the round-trip efficiency η_(RTE-LCES) of the LCES subsystem was 80.13%, and the total investment cost is 2.033 × 106, with a LCOS of 0.10 USD/ kW·h. Zero CO_2 emission is realized, which contributes significantly to environmental protection.

Keywords: LNG cold energy; ORC; CCS; LCES; Exergy.

1. Introduction

Natural gas combined cycle (NGCC) power plants currently account for more than 20% of global electricity generation. As global energy demand continues to grow, NGCC power plants will gain an increasing share of the global energy market. However, NGCC power plants emit large amounts of carbon dioxide, which contributes to global warming, and a large amount of heat energy contained within the flue gases is not efficiently utilized. LNG cold energy is a sustainable source of energy, and its effective use can have significant benefits.[1] LNG is a high-grade, low-temperature energy source, with regasification temperatures ranging from -162°C to 25°C. LNG cold energy and low-temperature heat energy are both sources of heat and cold, and for recovering the low-temperature heat and minimizing the loss of the cold energy[2], it would be beneficial to utilize both low-temperature heat energy and cold energy in the process of gasification of LNG, using LNG as the cold energy and the low-temperature heat as the heat. If we can use LNG as the cold source and low temperature heat energy as the heat source, and utilize low temperature heat energy in the process of gasification of LNG, and carry out the gradient utilization of cold energy of LNG at different temperatures, it can greatly reduce the waste of energy.[3]

In order to make efficient use of energy, this design combines LNG cold energy with low-temperature distillation to capture CO_2. and CO_2 energy storage technology is an energy storage technology that uses CO_2 as an energy storage medium. [4-7] This technology is characterized by high efficiency, environmental protection and renewability, and has been widely used in electric power, industry, construction and other fields. The working principle of carbon dioxide energy storage technology mainly stores and releases energy by absorbing and releasing carbon dioxide [8-9]. In the energy storage stage, carbon dioxide is absorbed from the emission source using a specific high temperature or chemical reaction and converted into a high energy density state. When energy is required to be released, the carbon dioxide is then released through the opposite process and converted to a low energy density state [10-12]. In this process, carbon dioxide serves as a carrier of energy, converting primary energy into secondary energy for energy storage and release.

2. System Modeling

2.1. Process description

As can be seen from the above, the system consists of three main parts: the first part is a two-stage ORC power generation system with LNG coupled with flue gas waste heat; the second part utilizes LNG cold energy to capture CO_2 from the flue gas components; and the third part is a CO_2 storage system constructed by utilizing the captured CO_2. The three parts are described in detail below.

The first part of the two-stage ORC power generation system is shown in Figure 2.1.

After being pressurized by pump 3 (state 35), the LNG enters the two condensers (Con1 and Con2) of the two-stage condensing ORC in turn to condense the TCORC working fluid. For a two-stage condensing ORC system, the working fluid from the outlets of the two turbines (Tur4 and Tur5) enters the two condensers (Con1 and Con2) to exchange heat with the LNG. As a result, these change from a vapor state to a liquid state (states 37 and 44). It then enters the two pumps (pump2 and pump4) for pressurization. The pressurized working fluids (states 38 and 45) are mixed (state 47) and enter the evaporator (Eva) to absorb heat from the flue gas. The working fluid in the evaporator changes from a liquid to a vapor (state 48). The working fluid (states 39 and 46) then enters two turbines (Tur4 and Tur5) to generate power. This is supplied to the compressor and pumps of the LCES system.

The second part of carbon capture is shown in Figure 2.2.

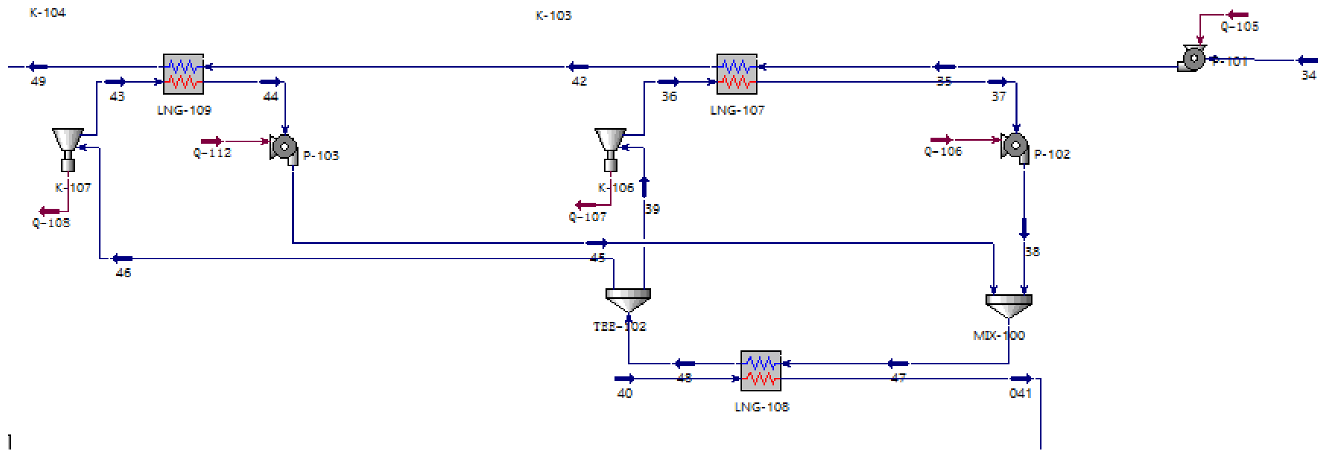

Figure 2.1 Two-stage ORC power generation system

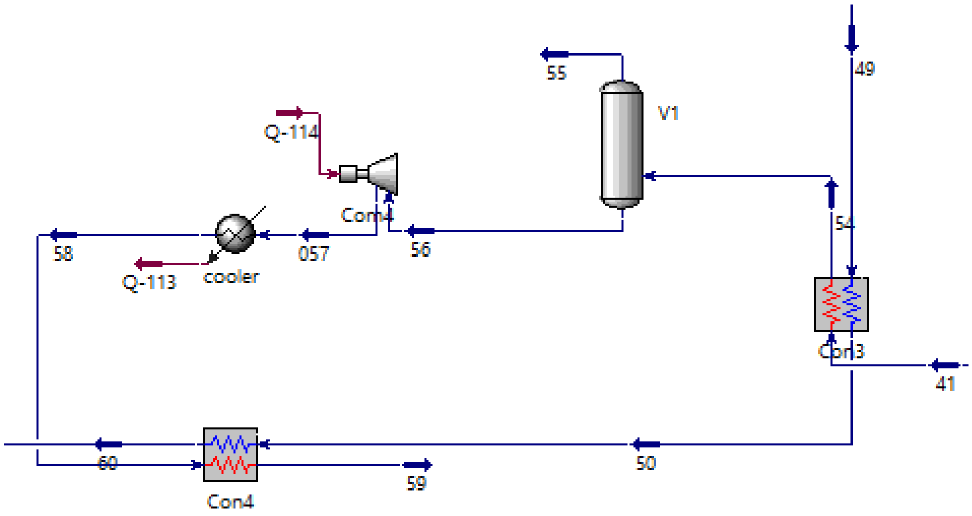

Figure 2.2 Low-temperature distillation carbon capture

After flowing through the two-stage ORC condenser, the LNG (state 49) enters the condenser (Con3) to condense the flue gas outflow from the two-stage ORC (state 41), so that the water vapor in the flue gas can be completely condensed, and enters the separator (V1) to remove the condensate in the flue gas (state 55), and the remaining flue gas is compressed by the compressor (Com4), and then enters the cooler (cooler) to cool down with seawater, and then cool down with the LNG (state 50) at the condenser (Con4). The remaining flue gas is compressed by the compressor (Com4), then enters the cooler (cooler) to cool down with seawater, and then exchanges heat and cools with LNG (state 50) in the condenser (Con4) to change the flue gas into liquid CO2, completing the carbon capture and realizing the zero carbon emission.

The third CO_2 energy storage section is shown in Figure 2.3.

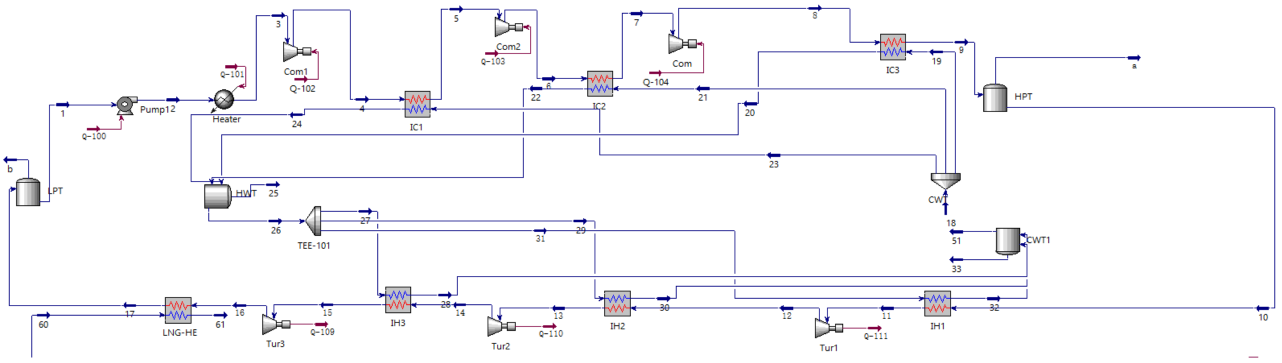

Figure 2.3 CO_2 energy storage section

For the charging phase, during off-peak hours, liquid CO_2 (state 1) at the outlet of the low pressure storage tank (LPT) is pressurized by pump 1 to (state 2). It then enters the heater. Here, the CO_2 undergoes a phase change from liquid to vapor (state 3). The CO_2 is then compressed by three compressors (Com1, Com2 and Com3) and cooled in three intercoolers (IC1, IC2 and IC3). After this, the high-pressure CO_2 turns into a liquid (state 9) and enters a high-pressure storage tank

(HPT) for storage. In this process, the cold water (state 18) at the outlet of the cold water tank (CWT) is split into three streams (states 19, 21 and 23) and enters the three intercoolers for heating. The cold water is heated into hot water, which is then mixed (state 25) and stored in the hot water tank (HWT), which stores the heat of compression.

For the discharge phase, during peak hours, liquid CO_2 (state 10) at the outlet of the high-pressure storage tank (HPT) enters three intermediate heaters (IH1, IH2, and IH3) to be heated up and expands into the corresponding turbines (Tur1, Tur2, and Tur3). It is then exchanged with carbon captured LNG (state 60) in a heat exchanger (LNG-HE) to be converted to low temperature and low pressure CO_2 (state 17).

The process flow of the LNG cold energy and flue gas waste heat complementary drive power generation, carbon capture, and CO2 storage system is shown in Figure 2.4:

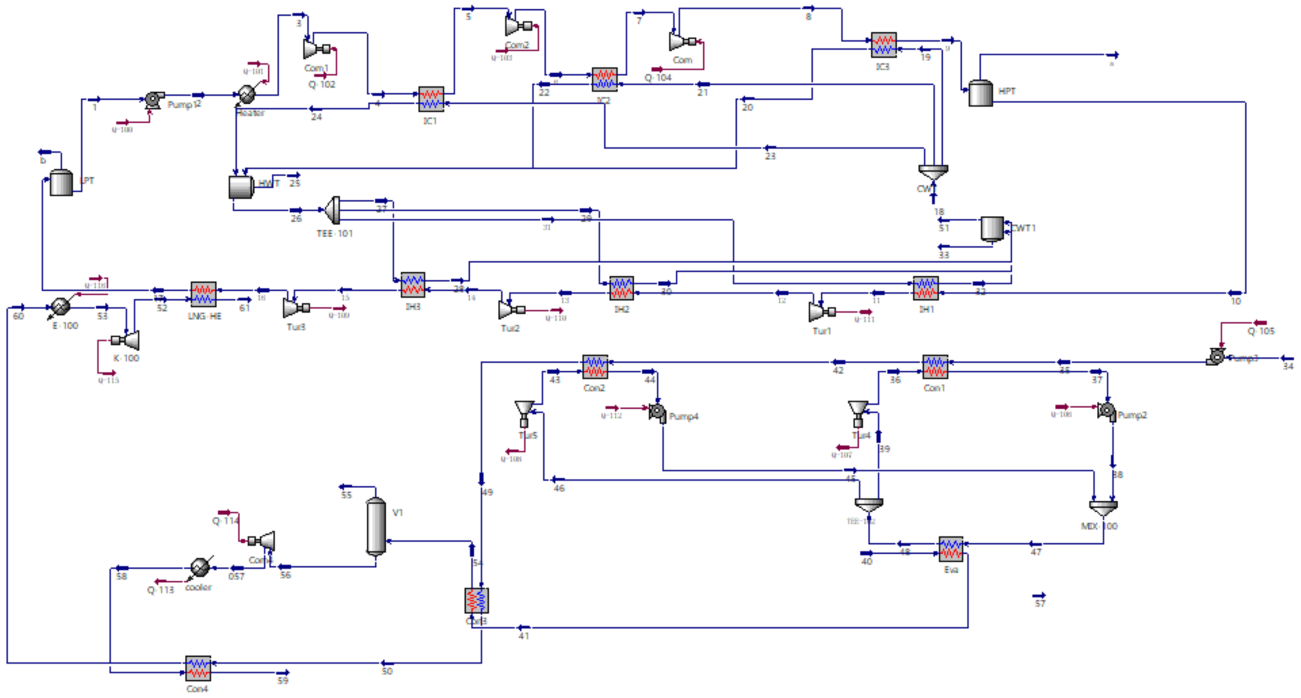

Figure 2.4 Process flow of LNG cold energy and flue gas waste heat complementary drive power generation, carbon capture, CO2 storage system

2.2. System assumptions

(1) All systems operate under steady-state conditions.

(2) The transfer of heat between the system and the surroundings is disregarded.

(3) Neglect variations in potential and kinetic energy.

(4) All mechanical energy is fully transformed into electrical energy.

(5) The isentropic efficiency of pumps, turbines, and compressors is constant.

3. Evaluation Methods

3.1. Thermodynamic calculations

The system was analyzed for energy according to the first law of thermodynamics. The compressor and pump constitute the main power consuming components of the system. Meanwhile, the turbine is the power output component.

The system exergy efficiency index measures the perfection of the energy in the conversion process or equipment utilization, provides a scientific evaluation standard for the equivalent energy or power, and reflects the utilization rate of the system for the available energy, which is defined as the ratio of the system benefit exergy to the cost of exergy: the exergy efficiency is introduced as the thermodynamic evaluation index of the system[13-15]:

$$\eta_{ex} = \frac{E_{gain}}{E_{pay}} \times 100\% \tag{1}$$

Ei is the value of exergy for the mass or flue gas at each state point as follows:

$$E_i = m_i[(h_i - h_0) - (T_0 + 273)(s_i - s_0)] \tag{2}$$

Egain is the system gain exergy and the system gain exergy satisfies the following relationship:

$$E_{gain} = W_{net} + E_{CO2} \tag{3}$$

Epay is the system payout exergy, which is the sum of the input exergy from the heat source flue gas and the LNG cold exergy:

$$E_{pay} = E_{fuel\ in} - E_{LNGin} \tag{4}$$

The simulation calculation by Aspen HYSYS engineering software gives the system's exergy efficiency as 63.09%.

3.2. Energy Storage System Round Trip Efficiency

Round-trip efficiency is the ratio of the power output during energy release to the net power consumption of the system during energy storage.The power consumption of the

LCES system during energy storage is provided by the net power output of the ORC system[16]:

$$\eta_{RTE-Overall} = \frac{W_{dischar,CO_2}}{W_{char,co_2} - W_{ORC} + W_{Pump}} \qquad (5)$$

$$\eta_{RTE-LCES} = \frac{W_{dischar,CO_2}}{W_{char,CO_2}} \qquad (6)$$

The total round-trip efficiency $\eta_{RTE-Overall}$ of the system was calculated to be 93.22% and the round-trip efficiency $\eta_{RTE-LCES}$ of the LCES subsystem was 80.13%.

3.3. Economic calculations

In this design, the levelized cost of ownership (LCOS) is chosen as the object of study, which is the ratio of the total system cost to the net power output during the annual operating time. Its equation is as follows[16]:

$$LCOS = \frac{Z_{TIC} \cdot CRF + Z_{OSM} + Z_{off-peokelectricity}}{N_1 \cdot W_{Tur,CO_2} + N_2 \cdot (W_{ORC} - W_{Pam,ING})} \qquad (7)$$

The formula for the capital recovery factor CRF is:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (8)$$

The equation for the equipment maintenance cost $Z_{O\delta M}$ is given below:

$$Z_{O\delta M} = Z_{TIC} \cdot CRF \cdot \varphi \qquad (9)$$

The total investment cost of the system's equipment was calculated to be 2.033×10^6 with a LCOS of 0.10USD/ kW · h.

4. Conclusions

(1) The joint utilization of LNG cold energy and flue gas waste heat not only provides sufficient and reliable heat source for the LNG regasification process, but also realizes the recovery of waste heat, and ultimately realizes the efficient and complementary utilization of LNG cold energy and flue gas waste heat, which achieves the dual goals of protecting the environment and conserving resources, and provides certain theoretical guidance and technical support for practical engineering applications.

(2) The whole system realizes the graded utilization of LNG cooling energy and carbon dioxide capture, utilization and storage (CCUS), achieving net-zero CO2 emissions. The net-zero emission will help to slow down the process of climate change, and also help to improve air quality and protect biodiversity.

(3) The exergy-efficiency of the system is 63.09%, the total round-trip efficiency $\eta_{RTE-Overall}$ of the system was calculated to be 93.22% and the round-trip efficiency $\eta_{RTE-LCES}$ of the LCES subsystem was 80.13%, and the total investment cost is 2.033 × 10^6, with a LCOS of 0.10 USD/ kW · h.

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