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Study on thermodynamic parameters of Liquid Air Energy Storage System coupled with LNG

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ABSTRACT

With the increasing proportion of renewable energy generation in the power system, its intermittence and volatility promote the development of Energy Storage systems. Liquid Air Energy Storage (LAES) has attracted wide attention due to its many unique advantages including high energy density, geographical-constraint free and a highly competitive capital cost. However, its efficiency is not high, mainly due to the lack of cold energy to cool the air, and the system's liquid rate is low (about 70%). On the other hand, liquified natural gas (LNG) is an efficient and well-developed technology to store and transport natural gas after purification and liquefaction, which has a lot of cold energy that can be used to help cool the air. In this study, LNG is directly involved in the air-cooling process. According to the LNG inlet temperature, the recoverable energy cold in the discharging air is stored in different tanks. The thermodynamic model of the system is established, and the optimal mass flow rate of propane and LNG is studied. Performance of the system under different working conditions with or without LNG is analyzed. The result shows that it should increase the mass flow rate of propane on the premise of ensuring the temperature of the cold storage tank; The efficiency of the independent LAES system is still less than 51%, ignoring the disadvantages of high heat storage temperature under high energy storage pressure. However, under the optimal LNG supply mass flow rate, the recommended charging pressure is 8MPa, the energy release pressure is 16MPa, the liquid rate is up to 89.35%, and the system efficiency is 68.83%. In addition, optimal LNG flow rates under various operating pressures are provided to guide engineering practice.

Keywords: Energy storage, Liquid air, LNG cold energy, Cycle efficiency

1. INTRODUCTION

Renewable energy plays an indispensable role in modern energy structure, and promoting the development of renewable energy is an important way to achieve carbon neutrality [1]. According to Renewable Energy Policy Network for the 21st Century (REN21), an international non-governmental organization, 256 GW of new installed Renewable Energy power generation capacity will be added in 2020, accounting for more than 80% of the world's total new installed capacity [2]. However, renewable energy is intermittent and volatile, as well as the mismatch between the demand and supply of the power system, Energy storage technology can not only solve these problems [3] but also convert the low-value valley energy into high-value peak energy, thus bringing huge social and economic benefits. Liquid air energy storage (LAES) is proposed based on compressed air energy storage (CAES), a new technology that can realize large-scale energy storage. In addition to many advantages of CAES, this technology does not rely on a large high-pressure gas storage chamber and gets rid of geographical location, geomorphic conditions and other restrictions on site selection. Therefore, the LAES power station can be established in any location and has the advantages of high energy density, atmospheric storage, long life, strong capital competitiveness, low operation and maintenance costs and other advantages, which have attracted wide attention in recent years [4-6].

However, the efficiency of the independent LAES system is low, because the cold energy recovered from the released liquid air is not enough to cool the compressed air to the lowest temperature, which is less than 18%. The ratio of liquid air does not reach the maximum value in the charging process, resulting in inadequate absorption and utilization of the compressed heat in the process of energy release [7]. On the other hand, natural gas, as the most abundant and cleanest fossil fuel, plays an increasingly important role in the energy supply system [8]. Natural gas is often transported over long distances, which requires the gas to be cooled to minus 155 degrees Celsius and liquefied. When liquefied natural gas (LNG) is transported to users in a natural gas plant, it is usually restored to the ambient temperature through heat exchange with the environment, which has a large amount of available cold energy [9]. Therefore, the high-quality cold capacity of LNG can be used in the liquefaction process of LAES to improve the liquefaction rate, thus improving the defects of insufficient utilization of compression heat and thus improving the system efficiency.

Some research has been done on LNG coupled with the LAES system (LAES-LNG). Peng et al. [10] designed an LNG refrigeration process, in which the cold energy of LNG is absorbed and stored by pressurized propane, and used to improve the air liquefaction process in LAES. QI M et al. [11] established an LNG-LAES system, which uses LNG to cool the air before entering the compressor to realize low-temperature compression, thus reducing the compression work and improving the system cycle efficiency. SHE X H et al. [12] proposed an LNG-Brayton-LAES system, which solved the incomplete utilization of compressed heat in the LAES system, but the system did not analyze the amount of LNG, and additional Brayton cycle systems were needed in the existing LAES system. Kim et al. [13] used LNG cold energy to cool compressed air and natural gas combustion to heat expanded air, thus the circulation efficiency reached 64.2%. Zhang et al. [14] In the process of air liquefaction, the cold energy of LNG is directly recovered and the energy-releasing air is heated by other heat sources, and the energy storage efficiency reaches 70%. However, all the above studies add LNG into the system as waste energy, without considering the mass flow rate of LNG, and the system circulation efficiency is bound to improve. In fact, the Rankine cycle [15] is one of the most common utilization methods for LNG. When LNG is added to the system, its potential power generation capacity in other systems should be taken into account. In addition, in terms of the cold energy recovery of the released liquid air, the cold energy in the lower temperature range that the LNG cold energy cannot reach has not been recovered to the maximum extent.

In view of the shortcomings of the above research, in this study, we establish a thermodynamic model of the LAES-LNG system and store the part of cold energy that is lower than the LNG inlet temperature during the energy release process separately to achieve maximum recovery. at the same time introduce a comprehensive efficiency evaluation index, and analyze the performance of the system with or without LNG, as well as the optimal mass flow rate of LNG and cold storage medium.

2. THE LAES-LNG SYSTEM

2.1 System descriptions

Fig 1 shows the process of the LAES-LNG system, which consists of an air compressing process, an air heating and expending process, and an LNG regasification process.

When storing energy, the multistage compressor uses the excess electric energy to compress the air to a high-pressure state. At the same time, the compression heat is absorbed by the cold water, and the water after absorbing the compression heat is stored in the hot water tank. Then the high-pressure air enters the air cooler where it is cooled by the recycling air, the low-temperature LNG, and the propane from the cold store. finally, the high-pressure air expands in the cryo-turbine and then the liquefied air is stored in the liquid air tank.

When releasing energy, the liquid air is pressurized by a cryo-pump, which first releases cold energy to propane until the temperature is 120K (the lowest temperature that LNG can reach, graded storage to make full use of cold energy), other cold energy is absorbed by compressed propane and stored in cold store2, finally enters the heater and heated by hot water, and enters the expander for power generation.

The LNG is pressurized to 7Mpa by a cryo-pump before it releases cold energy to help the liquefaction process in the air cooler. then, it is further heated by the ambient heater and enters the natural gas transportation pipeline to supply to the users.

2.2 system model

compressor model can be described as follow:

$$W_c = m_{air,c}(h_{out,c} - h_{in,c})$$

$$\eta_c = \frac{h_{out,s,c} - h_{in,c}}{h_{out,c} - h_{in,c}}$$

Where W_c is the power consumption of each compressor, m is the mass flow rate of compressed air, η_c is the Isentropic efficiency of the compressor, $h_{in,c}$ and $h_{out,c}$ represent the inlet and outlet specific enthalpy of the air, $h_{out,s,c}$is the outlet specific enthalpy when isentropic expansion to the same pressure.

Expander model can be described as follow:

$$W_t = m_{air,t}(h_{in,t} - h_{out,t})$$

$$\eta_t = \frac{h_{in,t} - h_{out,t}}{h_{in,t} - h_{out,s,t}}$$

The characters' meaning is similar to those of the compressor, just change compressor to turbine.

The potential generating capacity of cold energy in LNG when used in other common systems such as the Organic Rankine Cycle system can be described as,

$$W_{LNG} = m_{LNG}\, w_{LNG}$$

We consider W_{LNG} as part of the consumption of the system and the value of w_{LNG} is 91.52 kJ/kg here according to previous research.

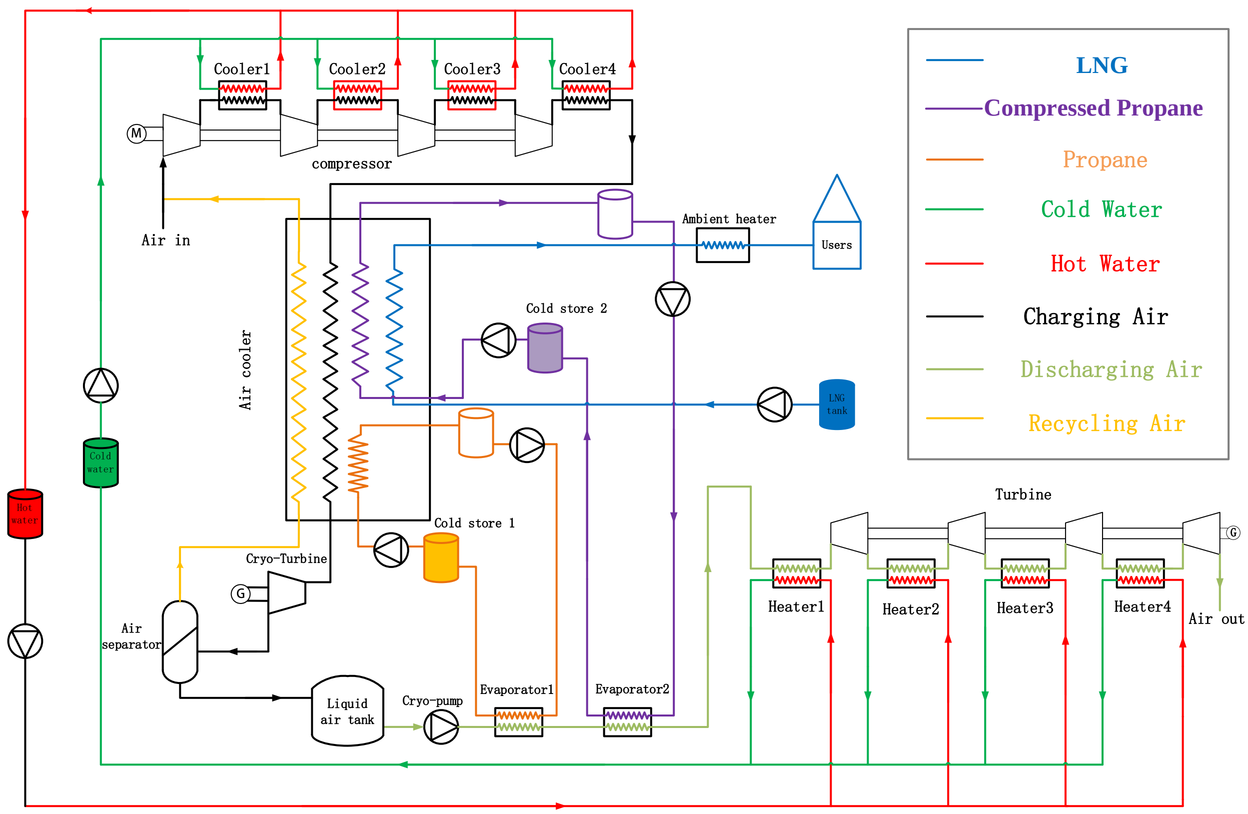


Fig. 1 Schematic diagram of the LAES-LNG-CS system.

The comprehensive efficiency of the round trip can be defined as,

$$\eta_{RTE} = \frac{W_{air,t}}{W_{air,c} + W_{LNG}}$$

$$Y = \frac{m_{air,t}}{m_{air,c}}$$

where $W_{air,c}$ is the value of the total consumed power of all compressors minus the power generated by the cryo-turbine, $W_{air,t}$ represents the difference between the value of all power generated by turbines and the power consumed by the cryo-pump. Y is the Liquefied rate of the system.

3. RESULTS AND DISCUSSIONS

3.1 Assumptions and parameters

The following assumptions are adopted in the calculation of the proposed system:

- The thermal properties of air are evaluated by REFPROP 10.0, consisting of nitrogen (78.12%), oxygen (20.96%) and argon (0.92%).
- the temperature of the feed LNG, consisting of methane（90.38%）, ethane（5.37%）propane（4.25%）， is 120K.
- The system is in a steady state.
- Ignore the energy loss in the pipeline, storage tank and heat storage tank.

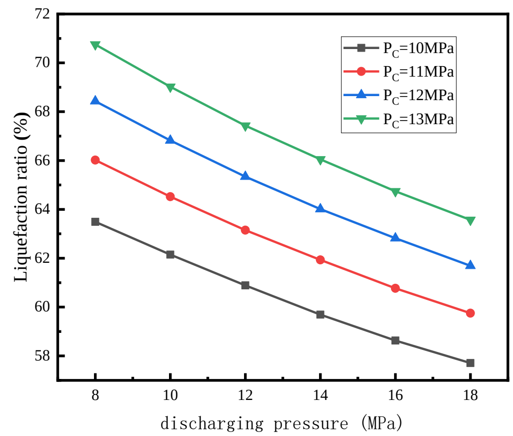
The calculation was done in the MATLAB environment, using fluid physical parameters from REFPROP 10.0. The values of key simulation parameters are listed in table 1.

parameter	value
environment temperature	293K
environment pressure	0.1MPa
Charging pressure	8 MPa
Pinch point in air cooler and evaporators	2K
Discharging pressure	16 MPa
Pinch point in coolers and heaters	10K
Pressure of compressed propane	1MPa
Isentropic efficiency of compressor	0.86
Isentropic efficiency of turbine	0.90
Isentropic efficiency of cryo-turbine	0.82
Isentropic efficiency of cryo-pump	0.75
LNG transportation pressure	7 MPa
LNG feed temperature	120K

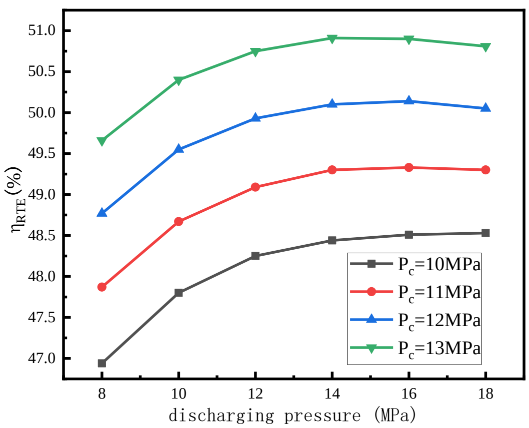
Table.1 parameters of the LAES-LNG system

3.2 The performance of the system without LNG

For the LAES, the liquefaction rate will affect the air mass flow in the discharging process, thus affecting the system efficiency. In the case of other conditions unchanged, it is mainly affected by the charging and discharging pressure, this paper studies the performance difference of its work under various pressure conditions.



(a)



(b)

Fig. 2 The liquefaction ratio and the efficiency of LAES under different working pressure

As shown in fig 2(a), when the charging pressure is constant, the liquefaction rate decreases with the increase of discharging pressure. the liquefaction rate increases with the increase of charging pressure under constant discharging pressure. This is mainly because the higher discharging pressure, the higher the temperature after the cryo-pump, and the recoverable cold energy is less. So, the temperature before the cryo-turbine increases, and the liquefaction rate decreases. As the charging pressure increases, the pressure before the cryo-turbine increases, and less cooling is required to cool the higher-pressure air due to smaller specific heat capacity, so the liquefaction rate increases.

For the overall system efficiency shown in fig 2(b), when the energy storage pressure is constant, the system efficiency will increase first with the increase of the discharging pressure and then decrease. With the increase of the discharging pressure, the mass flow involved in the expanding process will decrease due to less liquefaction rate, but the power generated by the air per unit mass will increase, at the beginning the latter accounts for the main influencing factors, and the system efficiency is improved. after reaching a certain extent, the former accounts for the main factor, and the system efficiency decreases. With the increase of energy storage pressure, the efficiency of the system increases, which is mainly because as the charging pressure rises, although the compression process consumes more power, it can not only improve the mass but also the heating temperature of the expanding air, and the system efficiency is improved.

According to the above analysis, higher energy storage pressure is needed to improve the efficiency of the independent LAES system, but its efficiency is still less than 51% despite the disadvantage of high heat storage temperature required by high temperature compression heat.

3.3 The influence of compressed propane mass flow rates on the performance of the LAES-LNG system

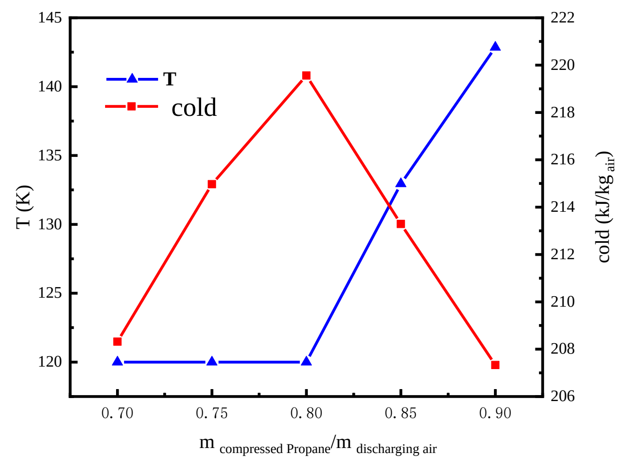


Fig. 3 Influence of compressed propane mass flow rates on LAES-LNG system

Since cold propane is stored in cold store 1 for recovering cold energy in the discharge air below the LNG feed temperature (120K), the specific heat of the discharging air and methane in this temperature range is basically the same and nearly does not change with temperature, the propane flow rate is easily controlled.

This article explores the effect of pressurized propane mass flow rate from cold store 2 on system performance. In figure 3, the abscissa represents the mass ratio of pressurized propane to the discharging air, and the longitudinal axis represents the temperature in cold store 2 and the amount of cold energy that can be provided to cool compressed air per unit mass. in the beginning, with the increase of the mass flow of pressurized propane, the pinch point is still on the outlet side of propane in evaporator 2, the temperature of the cold store 2 is unchanged, and the recoverable cold energy gradually increases. When the propane flow rate is further increased, the pinch point becomes the inlet side of the propane in evaporator 2, although the total amount of propane absorbed in evaporator 2 increases, the temperature in the cold store rises, and the quality of the cold energy can be used to decrease, resulting in a decrease in the recovery of cold in the entire cycle. In this studied condition, the optimal value is about 0.8 kg per unit of discharging air.

Therefore, in the actual process, under the premise of ensuring that the temperature of the cold store 2 is not higher than 120K, the pressured propane flow should be increased as much as possible to ensure the recovery of the cold energy.

3.4 The mass flow rate of LNG on LAES-LNG performance

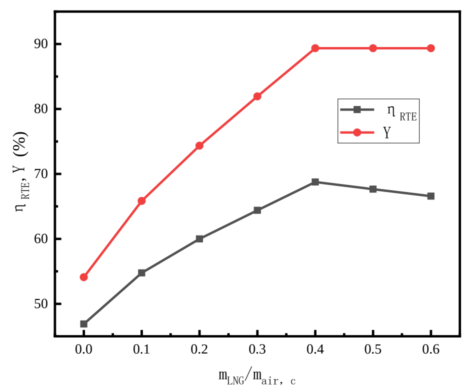


Fig. 4 Influence of LNG mass flow rates on the LAES-LNG system performance

When considering the potential power generation capacity of LNG use in other systems, the mass flow rate of LNG becomes part of the energy consumed by the charging process, and it is particularly important to choose the optimum LNG mass flow according to the operating conditions.

Fig.4 illustrates the impact of the mass flow of LNG on the system when the charging pressure is 8MPa and the discharge pressure is 16MPa, and the optimum ratio is about 0.4. In the beginning, with the increase of the mass flow ratio of LNG to compressed air, more LNG can provide more cold energy lacking in the air cooler, and the liquefaction rate gradually increases. only a part of the LNG with low power generation potential is used, which improves the liquefaction rate, increases a large amount of expansion power, and significantly improves the system efficiency. However, when the mass flow rate of LNG is further increased, the liquefaction rate of the system remains unchanged, which is due to the feed temperature of LNG being 120K, limited by the pinch point, the cold energy for the compressed air cooling to 122K has been saturated, and the recoverable cold energy in cold store 1 limits the liquefaction rate to be further improved, the expansion work will not increase. However, it leads to an increase in the W_{LNG} in the efficiency calculation, resulting in a decrease in system efficiency.

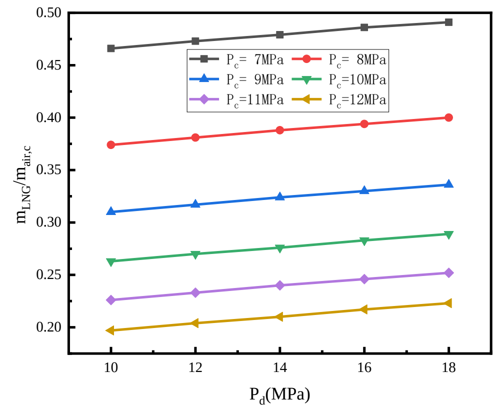


Fig. 5 The optimum LNG mass flow rate under different charging and discharging pressure

When the charging pressure and discharging pressure of the system change, each status point corresponds to an optimal LNG mass flow rate and the corresponding optimal system efficiency. As shown in fig. 5, When the energy storage pressure is fixed, with the increase of the energy release pressure, the increase in the optimal LNG mass flow rate is very small, and for every 1MPa increase in the energy release pressure, only 0.003 kg of LNG per unit of mass air is provided. When the discharging pressure is timed, as the charging increases, the optimal LNG flow rate significantly decreases, mainly because the specific heat capacity of the high-pressure air is small, especially at low temperatures, and the amount of lacking cold energy for liquefaction is less. It can be seen that the required supply of LNG is mainly affected by energy storage pressure.

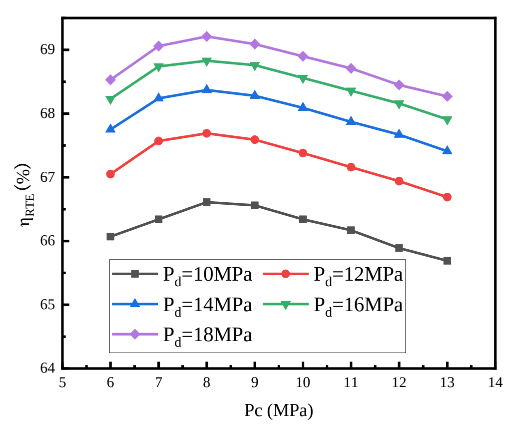


Fig. 6 The efficiency of different working pressure under optimum LNG mass flow rate

Fig.6 illustrates the trend of the overall efficiency of the system of different working pressures, under the condition of providing the optimal amount of LNG. When the discharging is fixed, the system efficiency increases first with the increase of the energy storage pressure and then decreases, and the optimal energy storage pressure is about 8MPa.When the charging pressure is fixed, the system efficiency increases with the increase of the discharging pressure. Therefore, in order to increase the efficiency of the system, it is recommended that the energy storage pressure of the system be set to 8 MPa, to maximize the discharging pressure under the pressure required by the heat exchanger and other components. When the discharging reaches 16 MPa, the efficiency of the LAES-LNG system is up to 68.83%, which is much bigger than that of the LAES system.

4. CONCLUSION

The standalone LAES system is not efficient due to the lack of cooling energy for cooling air. In this paper, LNG is directly involved in cooling air, the thermodynamic model of the system is established, and the impact of key parameters on system performance is analyzed with or without LNG, and the main conclusions are as follows:

(1) When no LNG is added, the efficiency of the high charging pressure system is high, but the heat storage temperature is too high to be easily met, and the system efficiency is generally less than 51%;

(2) The study of the mass flow rate of propane for the system shows that as long as the temperature in cold store 2 is not higher than 120K, the propane flow rate can be increased as much as possible for higher system efficiency. the mass flow ratio of the optimum compressed propane to the discharge air under the default parameters is about 0.8.

(3) The optimal energy storage pressure of the LAES-LNG system is 8MPa, and when the discharging pressure reaches 16 MPa, the efficiency can reach 68.83%;

(4) When the charging pressure is 8MPa and the discharge pressure is 16MPa, the optimal supply of LNG is 0.4Kg per kilogram of compressed air. The optimum LNG mass flow rate under other conditions is mainly affected by the energy storage pressure, and the influence of energy release pressure is very small.

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