Design and analysis of a cascade energy storage system based on LNG-LAES

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Abstract—Faced with increasingly serious energy and environmental problems, LNG and renewable energy have gradually entered the public eye and become the key to solving these problems. However, if the large amount of cold energy contained in LNG and the energy storage technology that regulates the volatility of renewable energy are not properly utilized, energy loss will result. In this study, by combining LNG cold energy cascade utilization and liquid air energy storage technology, a cascade energy storage system based on LNG-LAES is proposed. According to the different electricity demand of end users at different times, the system is divided into three operation modes and respectively The heat transfer, energy, exergy and other aspects were analyzed. The analysis results show that the LNG-LAES cascade energy storage system designed in this research has certain advantages in terms of energy efficiency, exergy efficiency and practical economy.

1. Introduction

With the further development of the economies of various countries in the world and the continuous growth of the population, the demand for energy worldwide is also increasing[1]. From the past 2015 to the predictable future 2040, global energy demand will grow at an annual rate of 0.6%-1.5%, which will definitely bring more energy consumption. At present, in the world, fossil fuel energy still accounts for the vast majority of energy consumption, and the greenhouse gases produced during its combustion have led to global environmental problems such as global warming and global climate deterioration.

As one of the cleanest fossil fuels, natural gas has become a key way to alleviate energy and environmental problems. Due to the inconsistency of where natural gas is produced and where it is used, it is more common to convert it into liquefied natural gas and then transport it. Liquefied natural gas is produced by cooling natural gas to -162°C under atmospheric pressure, and each cubic meter of liquefied natural gas contains about 625 cubic meters of natural gas, which also makes the energy density of liquefied natural gas significantly higher than that of natural gas[2]. After the liquefied natural gas is transported to the final use site, it needs to be re-gasified into natural gas before it can be transported into the transportation pipeline and transported to the user's location for use. During this process, about 830kJ/kg of cold energy will be released[3]. Therefore, rational use of this part of cold energy can not only recover the energy consumed in the natural gas liquefaction process, improve the energy efficiency of the LNG supply chain, but also have positive significance for improving environmental problems.

Like natural gas, renewable energy is also used to solve energy and environmental problems. In 2019, renewable energy generated 2,588GW, accounting for 26.4% of the global total[4]. It is predicted that by 2050, the penetration rate of renewable energy will reach 70%-85% of global electricity[5]. However, due to the volatility and instability of renewable energy, there is a supply-demand mismatch between its power generation and real power demand, so energy storage technology has emerged as the times require. Among them, liquid air energy storage technology has the advantages of low cost, high energy storage efficiency, long service life of the system and easy expansion.

To sum up, how to effectively utilize the cold energy of LNG and rationally set up LAES for energy storage have become two important solutions to energy and environmental problems in the future. Therefore, this study integrates the two, adding processes such as organic Rankine cycle, direct heat exchange, and direct expansion work to fully utilize the cold energy of LNG in cascades. And based on this system, the concept of cascade energy storage is innovatively proposed, and different energy demand levels are divided according to different periods of time, and different operation modes are designed to achieve the effect of cascade energy storage.

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2. Description of the system

2.1. Off-peak/medium-peak time

In off-peak and medium-peak time, the power in the grid can basically meet the needs of users. At this time, the power grid does not need or seldom needs this process to supply power. The system operation mode is shown in the figure below. First of all, the cold energy of LNG is first used in the LAES system. The LNG flow passes through multiple heat exchangers to exchange heat with the air. When the LNG heats up, the cold energy is transferred to the air to realize the liquefaction of the air, and the liquid air is stored in the tank. Then LNG exchanges heat with the working medium discharged from the expander, and the mixed working medium absorbs the cold energy of LNG to be liquefied again, and then undergoes pressurization by the pump and heating of seawater to generate electricity again, completing the Rankine cycle. Then the LNG and the refrigerant ethylene glycol exchange heat directly in the heat exchanger, and the cooled ethylene glycol can be transported to the data center as a coolant. Finally, LNG recovers the remaining cold energy through multi-stage direct expansion power generation. At the same time, the pressure will be reduced, and it will be turned into natural gas and passed into the pipeline for residents to use. In off-peak time, the electric energy generated by the system will be connected to the electrolyzed water hydrogen production device and converted into hydrogen energy for further energy storage. LAES, refrigerant cold storage, and electrolyzed water hydrogen production device simultaneously constitute the first level of cascade energy storage, which is also the level with the most energy storage. And in the medium-peak time, as the end-use power demand increases, the process needs to feed more power into the grid. At this time, the power generated by the system is not used for hydrogen production. Instead, it is connected to the grid to meet the power demand of users. At this time, the LAES system and refrigerant storage form the second level of cascade energy storage.

2.2. On-peak time

At the time of peak electricity consumption, the electricity demand of users reaches the maximum, and the power supply pressure of the grid reaches the peak. At this time, the process needs to generate electricity and supply it to the grid. The specific process operation is shown in the figure, and the cold energy of LNG will no longer be used in the LAES system. Instead, it is plugged into a new LNG-ORC power generation cycle. Make the LNG parameters at both ends consistent with the other two operating modes, so that convenient switching of operating modes can be realized. At the same time, the liquid air originally stored in the tank will also be released. After being pressurized by the pump and heated by seawater, it will expand and generate electricity, and finally become air and be discharged into the atmosphere. In this mode of operation, the focus is on the release of energy, so only the refrigerant is stored for subsequent use. This is also the third level of the cascade energy storage system and the level with the least energy storage.

2.3. Process simulation

In order to evaluate the specific performance of the LNG-LAES cascade energy storage system designed in this paper, the mature process simulation software Aspen Hysys V11 is used for simulation, and the Peng-Robinson state equation is selected for calculation of relevant values. This equation is the most commonly used equation in the field of petrochemical and natural gas processing, and has the advantages of simplicity and accuracy[6]. In order to simplify the simulation calculation process and make the result analysis clearer, the following assumptions are put forward:

(1) The whole process system runs in a steady state;

(2) During the whole process, the change of kinetic energy and potential energy is ignored;

(3) Ignore the flow pressure drop and heat loss of the fluid in the heat exchanger, heater and pipeline;

(4) The ambient temperature and pressure are set to 25°C and 101.325kPa respectively;

(5) In order to avoid setting the heat exchanger area too large, set the minimum temperature difference of all heat exchangers at 3°C;

(6) Ignore the loss of liquid air in the storage tank and the heat loss of other equipment to the surrounding environment;

(7) The air is purified in advance to remove moisture, carbon dioxide and hydrocarbons before entering the process;

(8) Use the isentropic efficiency model to calculate compressors, pumps and expanders;

(9) In order to make the thermodynamic analysis more intuitive and convenient, use LNG with an inlet pressure of 130.00kPa and a flow rate of 1kg/s;

(10) In order to make better use of the cold energy of LNG and keep close to the exothermic curve of LNG, a mixed working fluid is selected in ORC. The working fluid is composed of 40% Ethane, 40% Propane, 10% i-Butane and 10% n-Butane.

3. System analysis

3.1. Off-peak/medium-peak time

3.1.1. Heat transfer performance

Heat transfer composite curves are often used to evaluate and check the feasibility of heat exchangers[7]. The distance between the hot and cold flows on the load curve can indicate the irreversibility of heat exchangers. In this time, the heat transfer curve is shown in Fig.1. It can be seen from the image that there is no temperature crossover in the heat exchange process that occurs in each heat exchanger, which also ensures the feasibility of the process flow. In many cases, the pinch point is the lowest temperature difference between the hot and cold streams, usually at the inlet or outlet of the heat exchanger. After calculation, the minimum temperature difference in this process flow appears in the heat exchanger HEX-3, which is also the outlet of the LNG stream 4 and the inlet of the EG stream 1. The minimum temperature difference is 3°C, which meets the requirements of the heat exchanger and meets the Safety performance of the heat exchanger. The heat transfer temperature difference in other places is greater than this value.

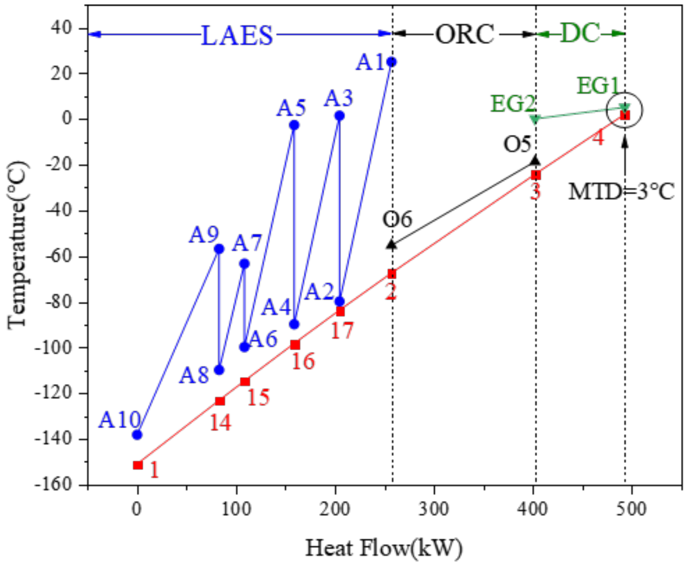

Fig.1 Heat transfer curve of the off-peak/medium-peak time

3.1.2. Cold energy utilization

It is the key to improve the overall thermodynamic efficiency to use appropriate technology to utilize cold energy in different temperature ranges of LNG. In this time, LNG releases a total of 492.8kW of cold energy. The proportion of cold energy used is shown in Fig.2. Due to the use of high-quality low-temperature cold energy, more than half of the cold energy is absorbed by the air, thus participating in the energy storage process.

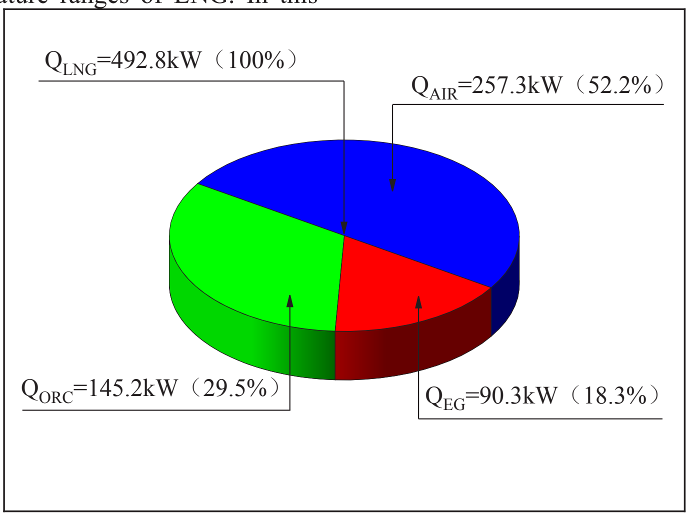

Fig.2 Utilization rate of LNG cold energy of the off-peak/medium-peak time

3.1.3. Energy analysis

After calculation, in the off-peak/medium-peak time, the system generates a total of 137.91kW of electric energy and consumes 218.26kW of electric energy. However, due to the low demand at this time, the electricity price is at a low price, which will not cause a large loss to the system economy. Under the premise, a large amount of liquid air is produced at the same time. Among them, LNG direct expansion power generation accounts for the vast majority, accounting for as high as 88.82%, indicating that under this mode, the electricity generated during the LNG regasification process is still the mainstream. At the same time, the net power generation of the ORC subsystem is 15.19kW, which is 9.4% and 24.82% higher than the research by He et al. in 2020 (13.89kW) and the research by Lee et al. in 2019 (12.17kW), which shows that although the ORC subsystem is added to the LNG regasification process, the LNG temperature range and the working fluid used have a greater impact on the performance of the ORC system. In the off-peak time, 5°C ethylene glycol with a molar flow rate of 459.68kmol/h is used to absorb cold energy by reducing the temperature to 0°C, thereby bringing a cooling capacity of 58.41kW to the data center, which not only realizes LNG The recovery of cold energy also meets the cooling needs of the data center.

The energy efficiency of the LNG regasification subsystem is 14.52%, the reason for the low efficiency is that the heat transfer efficiency between each heat flow and LNG is insufficient. Secondly, the efficiency of the air liquefaction subsystem is as high as 63.89%, which also shows that the purpose of energy storage is better achieved in this mode.

3.1.4. Exergy analysis

In the off-peak/medium-peak time, the net exergy value entering the system is 1194.08kW, while the net exergy value flowing out of the system is 972.35kW, and the exergy efficiency of the system reaches 81.43%. The total exergy loss of the system is 221.73kW, which includes exergy loss due to irreversibility in the energy system and exergy destruction caused by unused exergy discharged into the environment. From the analysis of specific equipment, the specific equipment classification and their respective proportions in the overall exergy loss are shown in Fig.3. Among them, the compressor only contributes 6.78% of the total exergy loss, which is because the suction temperature of each compressor is very low, resulting in a small exergy loss. Due to the reasonable setting of the working conditions of the inlet and outlet of the working medium, the exergy loss of the steam turbine is also relatively small, only 6.19%, and the pump generates more contribution to the exergy loss in this process because it compresses the fluid to a high pressure value, while The equipment that causes the most exergy loss in this mode is the LNG heat exchanger, which is due to the large number of LNG heat exchangers used in the process and the large temperature difference between the hot and cold fluids in the heat exchanger, resulting in a large Exergy loss.

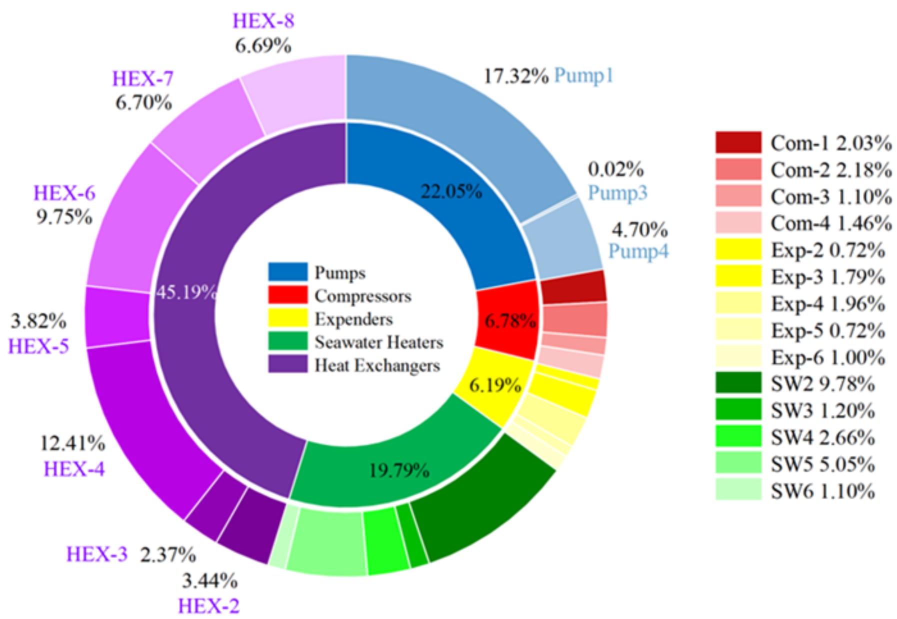

Fig.3 Energy loss of the device in the off-peak/medium-peak time

3.2. On-peak time

3.2.1. Heat transfer performance

In on-peak time, LNG exchanges heat with the mixed working fluid in ORC-1 and ORC-2 successively, and then exchanges heat with EG. The system heat exchange curve in this operating mode is shown in Fig.4. It can be seen from the figure that, the same as the other two operating modes, the minimum heat exchange temperature difference of the system in the overall process flow still appears in the heat exchanger HEX-3. In addition, in the newly added ORC-1 subsystem, in In heat exchanger HEX-1, the temperature difference between LNG stream 2 and mixed working fluid O1 reaches a minimum of 3.87°C, which is the smallest temperature difference in the heat exchanger, all of these ensure the heat exchange efficiency of the overall process and the safety performance of the heat exchanger. However, it can also be seen from the figure that the heat exchange between the two streams in the ORC-1 subsystem is not good. The reason may be that the mixed working fluid is more suitable for absorbing the cold energy of LNG in the LNG medium temperature zone, while in the low temperature zone Its heat transfer performance is not very good, and the performance of the ORC-1 subsystem can also be improved by optimizing the working fluid ratio in the future.

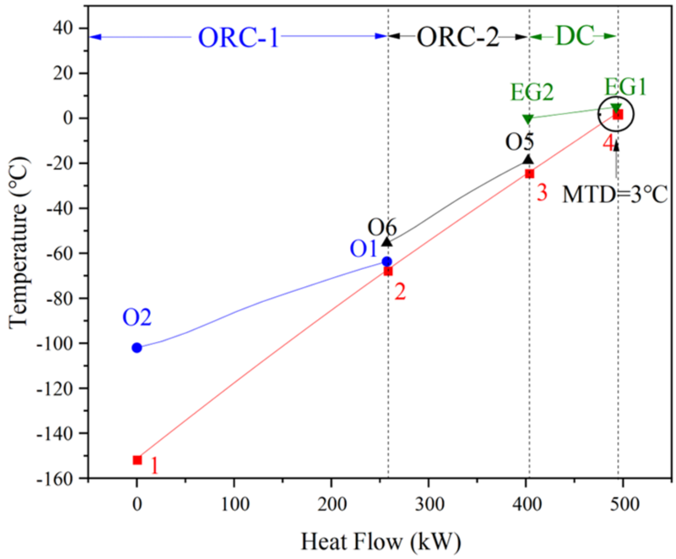

Fig.4 Heat transfer curve of the on-peak time

3.2.2. Cold energy utilization

Except for the ORC-1 subsystem, the process flow of the other subsystems and the specific parameters of the LNG flow participating in each heat exchanger have not changed. The proportion of cold energy utilized is the same as that of off/medium-peak mode.

3.2.3. Energy analysis

In on-peak time when end users' electricity demand rises sharply, the power generation of the overall system is as high as 360.01kW, while the power consumption is only 72.75kW, and the net power generation is as high as 287.26kW. This can make up for the situation that the other two operating modes consume more power than the system does work. In addition, during this period, the electricity price is also at a high level, which also makes this system more industrially feasible and economical. At this time, the power production and power consumption of each subsystem are shown in Fig.5. The liquid air that was originally stored is released when the power demand peaks, and the power generated is greater than the power generated by the direct expansion of LNG. It is the main contributor to the electricity production in this mode. Due to the utilization of LNG's low-temperature, high-quality cooling energy and the increase in the flow rate of the working medium, although the same working medium is used in this mode, the power output of the ORC-1 subsystem is higher than that of the ORC-2. There is a significant improvement.

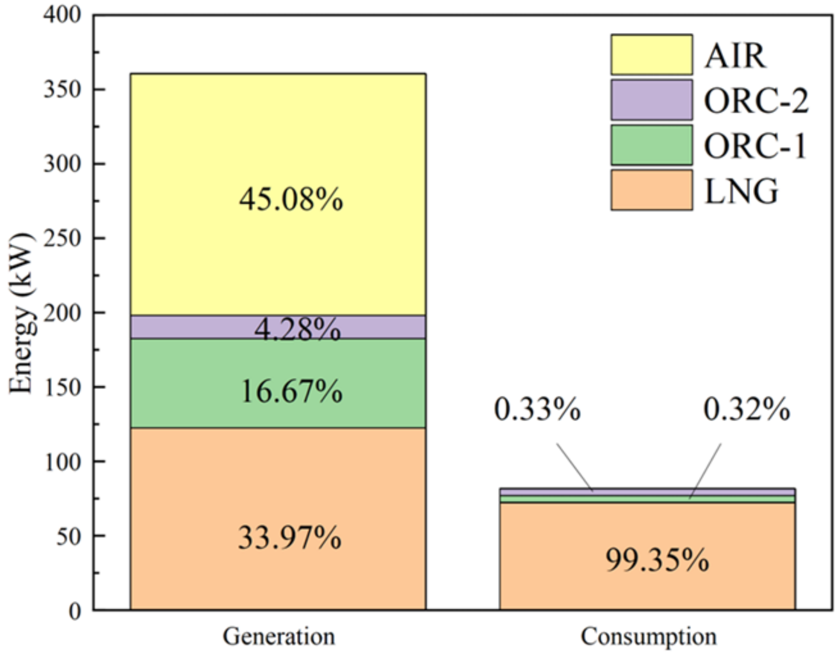

Fig.5 System power generation and power consumption in on-peak time

Except that the energy efficiency of the original subsystem remains unchanged, the efficiency of liquid air direct expansion power generation is as high as 55.84%. The high efficiency is due to the simple setting of the process flow, and the multi-stage expansion power generation designed according to the working conditions of liquid air improves the utilization efficiency of liquid air, and the generated electric energy is also the part that contributes the most in this mode. In addition, compared with ORC-2, the energy efficiency of the ORC-1 subsystem is significantly improved, because higher-quality LNG cold energy is used as a cold source, thereby further increasing the temperature difference between the cold source and the heat source , thus nearly doubling the energy efficiency.

3.2.4. Exergy analysis

In the on-peak time, the exergy value entering the system is 1302.69kW, while the exergy value flowing out of the system reaches 949.87kW. Liquid air is counted as the raw material flowing into the system, and the corresponding product flowing out of the system is gaseous air that is closer to the atmospheric environment. Therefore, although the use of compressors is missing in the process at this time, it still cannot make up for the change of liquid air into The exergy change value produced by raw materials. These reasons are also leading to the increase of exergy entering the system and the decrease of exergy flowing out of the system. Similarly, the exergy loss value of the process under this operating mode increases to 352.82kW, and the system exergy efficiency decreases to 72.92%. The specific equipment classification and their contribution to the overall exergy loss are shown in Fig.6. The seawater heat exchanger produced the most exergy loss contribution value, as high as more than half, significantly increased compared with the other two operating modes. The reasons are as follows. First, more seawater heat exchange is required in the process of this operating mode. The seawater heat exchanger heat the liquid air for subsequent expansion and work. In addition, there is a large temperature difference between liquid air and the mixed working fluid used in ORC-1 and normal temperature seawater, which increases the exergy loss generated in the seawater heat exchanger. Compared with the other two operating modes, the exergy loss generated by the LNG heat exchanger is relatively reduced. This is because the original LAES subsystem is replaced by the ORC-1 subsystem, which reduces the heat transfer in terms of quantity. The use of the device, thereby reducing the exergy loss value. In this mode, the exergy loss generated by steam turbines and pumps is relatively less than that of other equipment. This is because although the number of steam turbines has increased, the specific pressure of the expansion work is set reasonably, and the step-by-step expansion work is adopted, compared with other equipment, the exergy loss generated by the steam turbine is still relatively small. At the same time, the pump work required to press the air into the liquid air storage tank is reduced, so the exergy loss from the pump is also reduced.

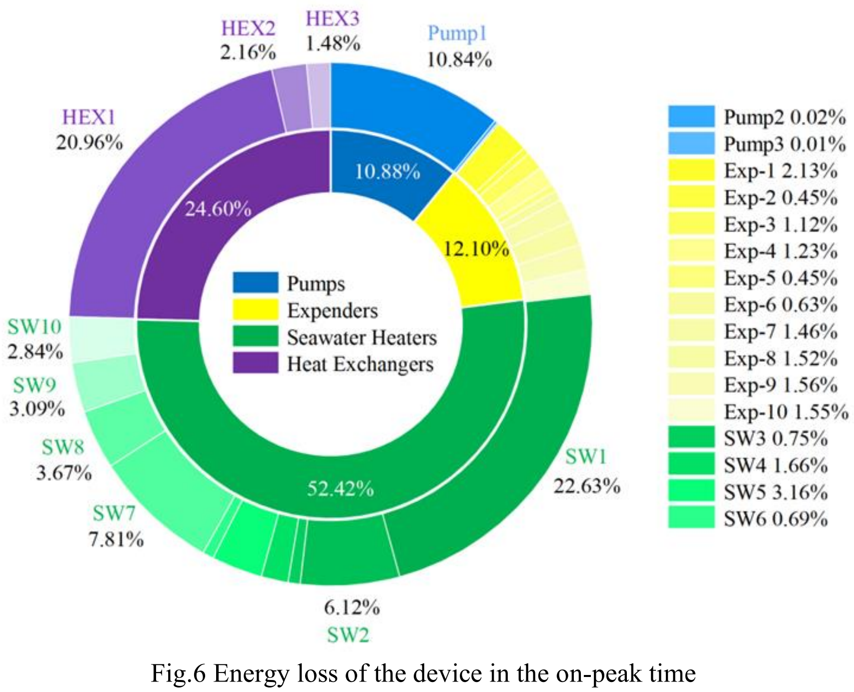

Fig.6 Energy loss of the device in the on-peak time

Comparing the exergy loss of the system designed in this research with the references in the same field, the results are shown in Fig.7. The exergy loss caused by low power consumption/mid-peak hours is relatively less, and the reduced exergy loss is mainly concentrated on the equipment steam turbine and seawater heat exchanger, which is due to the more reasonable process design and working fluid collocation of. However, the exergy loss generated under the peak power consumption mode is relatively more, and the increased part is mainly concentrated on the seawater heat exchanger, mainly the seawater heat exchanger used when ORC-1 and liquid air directly expand to do work due to. However, at the cost of generating relatively more exergy losses that increase within an acceptable range, the steam turbine unit obtains more usable electric energy.

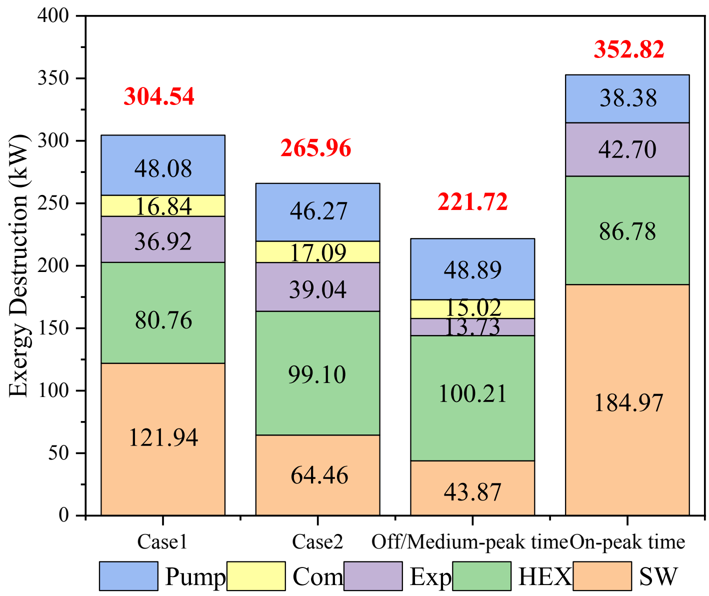

Fig.7 Comparison of exergy loss of this system with other cases

3.3. Dynamic running analysis

In order to meet the different electricity demand in various places and make full use of the liquid air prepared by the system, the system designed by this research institute maintains the working state of running for 12 hours in on-peak mode and 12 hours in off-peak mode and medium-peak mode during operation.

In this study, follow-up calculations are carried out based on the conversion ratio of electricity to hydrogen of 54.6kWh/kg H2 studied by scholars in literature[8]. According to the running time of the medium-peak mode, the daily output of the system is shown in Fig.8. Under the condition of the LNG inlet flow rate of 1kg/s, the production capacity of the whole system increased from 4320.12kWh to 5975.04kWh per day, and the adjustment range reached 38.31%. However, as the power generation increases, the corresponding hydrogen production of the system will decrease, from 30.31kg hydrogen production to zero. The system designed in this research is to match the power generation by adjusting the time of the medium-peak mode and the off-peak mode in the scenario where the end-use electricity demand is slightly lower, and to generate by-product hydrogen, thereby making the system to have better flexibility and energy reserve.

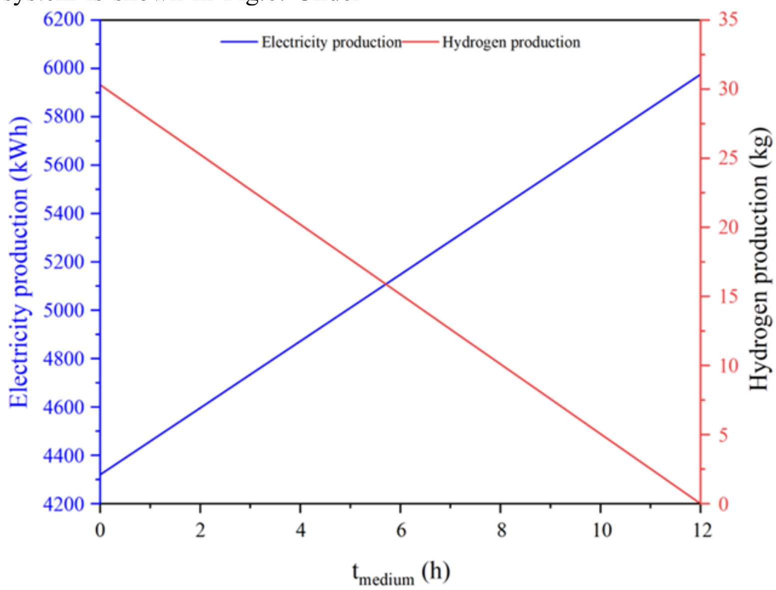

Fig.8 The output product of the system varies with the t_{medium}

If the system energy consumption is included, the feasibility and energy economy of the system can be judged more intuitively through the net power. The net power of the system varies with the operating time of the medium-peak mode as shown in Fig.9. The overall net power of the system tends to increase gradually with the increase of the operating time of the medium-peak mode. This is because the electricity generated is used to prepare hydrogen under the off-peak mode of operation, so it can be considered that the useful work at this time is 0, but the energy consumption of equipment such as pumps and compressors still exists, so in this mode there is only energy consumption, and the net power is a negative value. Under the extreme conditions of LNG flow rate of 1kg/s and medium-peak mode operating time of 12h, the net output power of the system is the highest, reaching 103.46kW. Compared with the research literature[6, 9] of the same energy storage system, respectively, An increase of 22.67% and 0.15%. At the same time, under another extreme condition, the net output power of the system can still maintain a positive value and be at the middle level of the industry. This also shows that the technological process designed in this study has both feasibility and energy economy on the basis of flexible storage and release of energy.

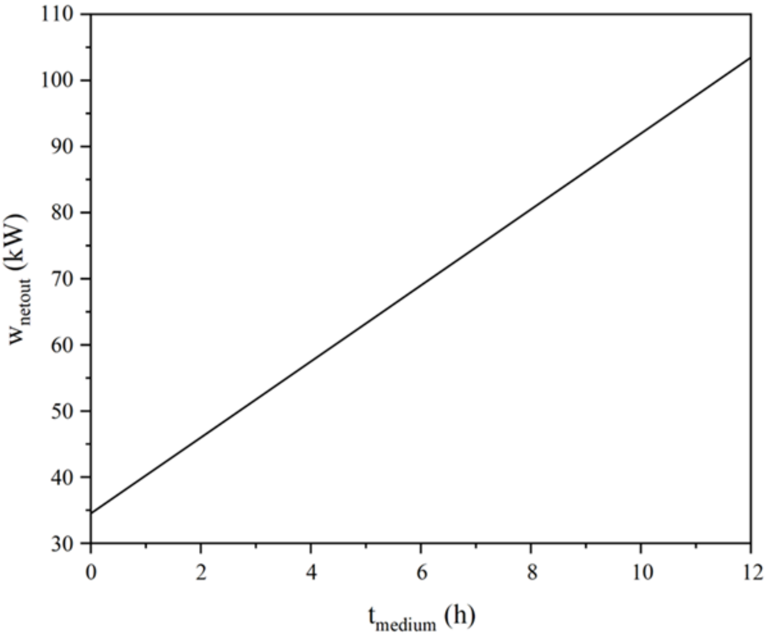

Fig.9 The net output power of the system varies with the t_{medium}

The round-trip efficiency is a key indicator used to evaluate the thermodynamic performance of the LAES system, which is defined as the ratio of the difference between the net output power generated by the energy storage system in the energy release mode and the output power in the conventional mode to the power consumed in the energy storage mode [36]. The calculated round-trip efficiency of the system is 111.55%. Since the system works by switching operation modes at different times, the on-peak operation mode of the system is regarded as the energy release process, and the off-peak and medium-peak operation modes are regarded as the energy storage process. At the same time, due to the full use of the heat energy of seawater in the process, the round-trip efficiency exceeds 100%, which is why this process is superior to the traditional LAES system.

4. Conclusion

Combined with the above analysis of the cascaded energy storage system based on LNG-LAES designed in this research, the following conclusions are drawn:

(1) Under low power consumption and mid-peak operating modes, the system generates a total of 137.91kW of electric energy and consumes 218.26kW of electric energy. 52.20% of the LNG cold energy is used for air liquefaction to store energy, and the exergy efficiency is as high as 81.43%. Compared with the previous system, the exergy loss is reduced by 27.20% and 16.63% respectively;

(2) Under the peak power consumption mode, the net power of the system is as high as 287.26kW to meet the power demand. At the same time, the efficiency of liquid air direct expansion power generation is as high as 55.84%, and the overall exergy efficiency is 72.92%, realizing the release of energy;

(3) In terms of dynamic operation, when the LNG flow rate is 1kg/s, the system realizes the adjustment effect of the daily production capacity from 4320.12kWh to 5975.04kWh, and produces up to 30.31kg of hydrogen. The net power of the system It can be raised up to 103.46kW, and the overall round-trip efficiency of the system has reached 111.55%.

In summary, the LNG-LAES cascade energy storage system designed in this research has certain advantages in terms of energy efficiency, exergy efficiency and practical economy. By switching between the three operating modes, energy storage and release can be better realized.

Acknowledgments

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