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Thermodynamic Analysis of Cold Energy Replenishment in Liquid Air Energy Storage System

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Abstract. Liquid air energy storage (LAES), as a promising large-scale energy storage technology, offers significant advantages due to its geographical independence and the ability to store energy at ambient pressure. It holds great potential for future applications. The cold storage unit is the core component of the LAES. During the energy storage phase, the unit supplies cold energy to compress the air, while in the energy release phase, it recovers cold energy from the liquid air. However, as the cold storage unit operates in a cryogenic environment, cold energy inevitably leaks from the unit into the surrounding environment. If this cold energy is not replenished in time, the temperature of the cold storage fluid will rise, eventually preventing the compressed air from liquefying and causing the LAES to fail. This study first investigates the impact of cold energy leakage on system performance. A strategy is then proposed to compensate for the cold loss by reducing the pressure of the expanding air, thereby supplying additional cold energy to the cold storage units. A thermodynamic analysis is conducted to compare the performance of the actual system with that of an ideal system. For a 10 MW/80 MWh LAES system, the daily cold energy loss is calculated to be 341.90 kWh, resulting in an exergy loss of 490.00 kWh. The actual system generates 80.56 MWh of electricity, representing a 0.78% decrease compared to the ideal system output of 81.19 MWh. Through these analyses, the paper aims to provide optimized solutions to mitigate cold energy leakage and ensure the efficient operation of the LAES, offering theoretical support and practical guidance for its actual application.

1. Introduction

The growing scarcity of fossil fuel has accelerated the adoption of renewable energy worldwide. However, the intermittent and fluctuating nature of renewable energy poses significant challenges for grid integration. Energy storage technologies offer a crucial solution to this issue. Currently, large-scale energy storage can be achieved through several technologies, including pumped hydro storage, battery energy storage, compressed air energy storage, and liquid air energy storage

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(LAES) [1]. Among these, LAES stands out for its advantages such as independence from geographical constraints, storage at atmospheric pressure, and relatively low storage costs [2]. In a typical LAES system, electricity is stored during off-peak periods in the form of liquid air and released during peak demand. During the charging process, air is compressed in multiple stages, cooled progressively, and then passed into a cold storage unit where it is further cooled to a liquid state. The liquid air is stored in cryogenic tanks. During the discharge process, the liquid air is pressurized and sent back through the cold storage unit, where its cold energy is recovered by cold storage fluids. The pressurized air is then reheated and expanded in multiple stages to generate power. The cold storage unit in LAES enables both the liquefaction and gasification of air, significantly improving energy density. However, cold energy losses from the cold storage unit to the environment are inevitable. Without timely replenishment of the lost cold energy, the temperature of the unit will gradually rise, ultimately leading to system failure. To address this issue, this paper proposes a method for replenishing the cold energy in the storage unit and conducts a thermodynamic analysis to evaluate the impact of cold energy leakage on overall system performance.

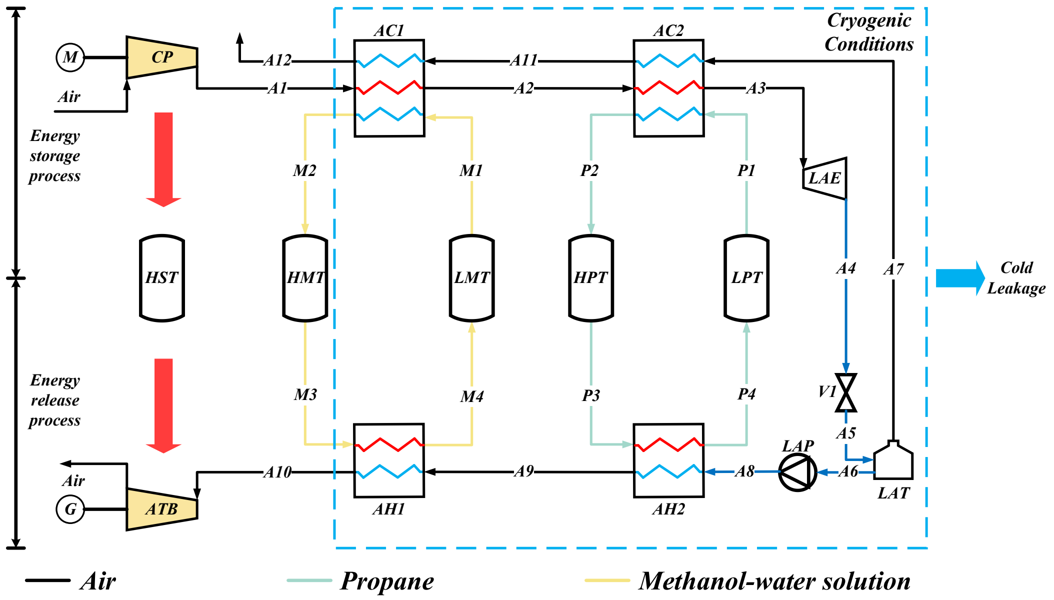

Figure 1. The operational diagram of the liquid air energy storage system.

2. System description

Figure 1 illustrates the operational diagram of a Liquid Air Energy Storage (LAES) system. During the charging process, ambient air is compressed by compressors, and the compression heat is stored in a heat storage tank (HST). The high-pressure air then enters the cold storage unit, where it is cooled to a liquid state by low-temperature methanol and low-temperature propane. The liquefied air is subsequently depressurized via a liquid air expander (LAE) and a throttle valve (V1), and stored at atmospheric pressure in the liquid air tank (LAT). During the discharge process, the liquid air is first pressurized by a liquid air pump (LAP) and then sequentially heated to ambient temperature by high-temperature propane and high-temperature methanol. The heated, high-pressure air recovers thermal energy from the HST before expanding through an air turbine (ATB), where it performs work as it is released to atmospheric pressure. In LAES systems, both the cold storage unit and the liquid air tank operate at cryogenic temperatures, which inevitably leads to cold energy losses to the surrounding environment. This study proposes a method to compensate for these cold energy losses by lowering the pressure of the liquid air at point A8 during the discharge process. In doing so, the total exergy of the liquid air remains nearly constant; however, a portion of the pressure exergy is converted into cold exergy, thereby enhancing the available cold energy within the system.

3. Mathematical model

The main content of this chapter is to present the thermodynamic performance index for evaluating system. The dynamic components involved in the system include compressors, expanders, and pumps. The energy consumption of the compressors and pumps can be calculated as follows [3]:

$$W_{CP} = m_{CP} \cdot (h_{out} - h_{in}) \tag{1}$$

$$W_{Pump} = m_{Pump} \cdot (h_{out} - h_{in}) \tag{2}$$

The output work of the expander can be calculated as follows [3]:

$$W_{TB} = m_{TB} \cdot (h_{in} - h_{out}) \tag{3}$$

where m is the mass flow rate through the device (kg/s), and h_{in} and h_{out} are the specific enthalpies of air at the inlet and outlet of the device, respectively (kJ/kg).

The power consumption during the charging process and the power output during the discharging process can be calculated as follows:

$$W_{ES} = \sum W_{CP} - W_{LAE} \tag{4}$$

$$W_{ER} = \sum W_{ATB} - W_{LAP} \tag{5}$$

The round-trip efficiency of the system can thus be calculated as:

$$RTE = \frac{W_{ER}}{W_{ES}} \tag{6}$$

The daily cold energy loss of the storage tank can be calculated as:

$$L_{tank} = m_{fluid} \cdot \gamma \cdot r_v \tag{7}$$

where m_{fluid} is the mass of the working fluid in the storage tank (kg), γ is the latent heat of vaporization of the fluid (kJ/kg), and r_v is the daily evaporation rate of the fluid, taken as 0.05% [3].

The exergy of a fluid stream can be calculated as:

$$E_t = (H - H_0) - T_0 \times (S - S_0) + n\left[\sum_{j=1}^{n} x_j e_j^0 + RT_0 \sum_{j=1}^{n} x_j \ln x_j\right] \tag{8}$$

where H and S are the enthalpy and entropy under specific operating conditions, respectively; H_0 and S_0 are the enthalpy and entropy under standard conditions, respectively; x_j and e_j^0 represent the mole fraction and the standard chemical exergy of the j-th component, respectively.

The exergy destruction of each component is calculated as the difference between the incoming and outgoing exergy, and can be expressed as:

$$E_{des} = \sum E_{t,in} - \sum E_{t,out} \tag{9}$$

4. Results and discussion

4.1 System simulation

To facilitate the analysis of deviations between the actual and ideal systems, the following assumptions are made:

(1) Air is considered as a mixture of nitrogen (78.12%), oxygen (20.96%), and argon (0.92%), with no other components present;

(2) Pressure drops in pipelines and heat exchangers are neglected;

(3) The isentropic efficiency of the compressor and high-temperature turbine is set to 85%, while the isentropic efficiency of the cryogenic liquid air turbine is set to 75%.

The system is designed with a rated capacity of 10 MW / 80 MWh.

4.2 Energy analysis

In a Liquid Air Energy Storage (LAES) system, all cold storage tanks—including the low-temperature methanol tank (LMT), high- temperature propane tank (HPT), low- temperature propane tank (LPT), and the liquid air tank (LAT)—operate in cryogenic conditions, leading to continuous cold energy loss to the environment. The cold leakage parameters of these tanks are summarized in Table 1. Among them, LMT and HPT operate at similar temperatures, while LAT has the lowest temperature. Based on calculations, LAT exhibits the smallest cold energy loss at 22.68 kWh/day, whereas LPT has the highest loss at 137.41 kWh/day. For a 10 MW / 80 MWh LAES plant, the total daily cold energy loss amounts to 341.90 kWh.

Table 1. The cold leakage parameters of tanks.

Tanks	LMT	HPT	LPT	LAT
Liquid storage capacity (t)	248.45	1474.44	1474.44	802.19
Temperature (°C)	-99.77	-97.58	-177.50	-193.34
cold loss (kWh/day)	72.18	109.63	137.41	22.68

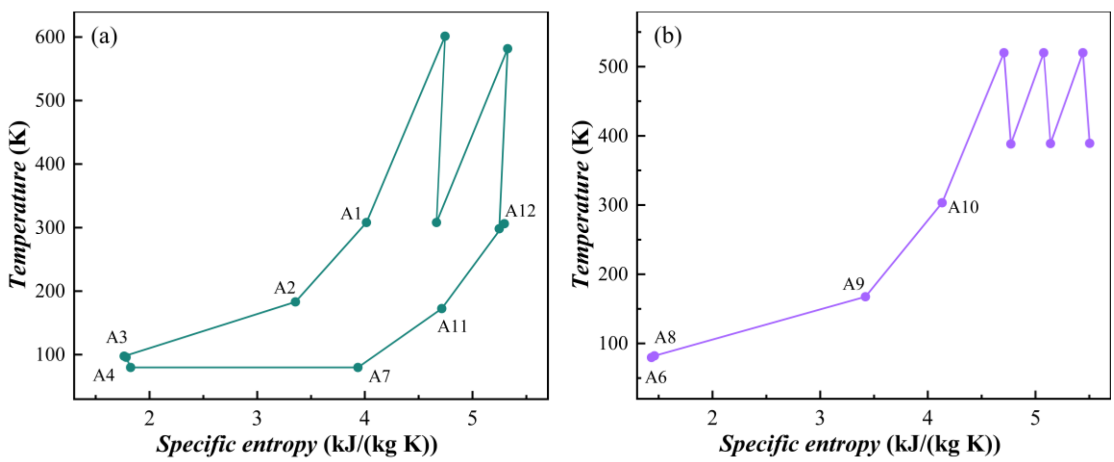

Figure 2. The T-s diagram of the cold storage unit. (a) energy storage process; (b) energy release process.

The T-s diagram of the cold storage unit is shown in Figure 2. The process node labels (A1-A12) in Figure 2 correspond to those in Figure 1. The process from A1 to A3 represents the cooling of air, during which entropy continuously decreases. The path A7–A11–A12 corresponds to the reheating of return air. The parameters for both the ideal and actual systems are presented in Table 2 and Table 3, respectively. A comparative analysis between the ideal and actual systems, based on calculations, is presented in Table 4. The power consumption during the charging process is identical for both systems. In the actual system, the liquid air tank (LAT) experiences cold energy loss, which is not accounted for in the ideal system. As a result, the amount of liquid air stored in the LAT is reduced by 0.05% compared to the ideal case. Additionally, to compensate for the cold energy loss in the cold storage unit, the actual system reduces the pressure after the liquid air pump to provide additional cold energy. The pressurization level in the actual system is 42.54 bar, which is 3.47% lower than the 44.07 bar used in the ideal system. Due to the reduction in total air mass, while the total amount of compression heat remains unchanged, the air temperature during the reheating stage of the discharge process increases. Although this higher temperature is beneficial for power generation, the combined effect of lower air pressure and reduced air mass leads to a 0.78% decrease in electricity output during the discharge process compared to the ideal system.

Table 2. The parameters for the ideal system.

Items	Temperature (℃)	Pressure (bar)	Flow rate (kg/s)
A1	35.00	70.00	33.01
A2	-85.00	70.00	33.01
A3	-175.50	70.00	33.01
A4	-177.28	6.00	33.01
A5	-193.34	1.10	33.01
A6	-193.34	1.10	27.85
A7	-193.34	1.10	5.16
A8	-191.04	44.07	27.85
A9	-101.77	44.07	27.85
A10	27.61	44.07	27.85
A11	-97.59	1.10	5.16
A12	33.00	1.10	5.16

Table 3. The parameters for the actual system.

Items	Temperature (℃)	Pressure (bar)	Flow rate (kg/s)
A1	35.00	70.00	33.01
A2	-85.00	70.00	33.01
A3	-175.50	70.00	33.01
A4	-177.28	6.00	33.01
A5	-193.34	1.10	33.01
A6	-193.34	1.10	27.84
A7	-193.34	1.10	5.17
A8	-191.12	42.54	27.84
A9	-102.05	42.54	27.84
A10	28.45	42.54	27.84
A11	-97.59	1.10	5.17
A12	33.00	1.10	5.17

Table 4. The performance analysis of the ideal and actual systems.

Items	Ideal system	Actual system	Change rate
Power consumption in the energy storage process (MWh)	140.52	140.52	-
Power generation in the energy release process (MWh)	81.19	80.56	-0.78%
Round-trip efficiency (%)	57.78	57.73	-0.09%
Pressure of the expanding air (bar)	44.07	42.54	-3.47%
Temperature of the expanding air (°C)	184.87	185.08	0.11%
Flow rate of the expanding air (Nm^3/h)	77315.83	77274.56	-0.05%

4.3 Exergy analysis

The exergy flow diagram of the cold storage unit is shown in Figure 3. The daily exergy destruction of the LMT, HPT, LPT, and LAT is 0.06 MWh/day, 0.08 MWh/day, 0.29 MWh/day, and 0.06 MWh/day, respectively. During the charging process, the total exergy entering the LAT is 167.51 MWh, of which 7.85 MWh exits the tank in the form of return gas. In the discharging process, when

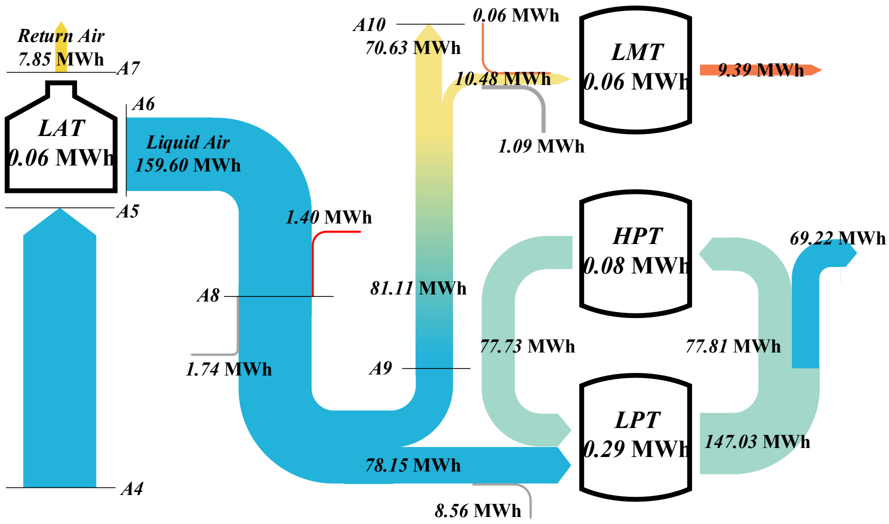

Figure 3. The exergy flow diagram of the cold storage unit.

liquid air exchanges heat with high-temperature propane, 78.15 MWh of exergy from the liquid air is transferred into the LPT, resulting in an exergy destruction of 8.56 MWh due to heat exchange. Similarly, during heat exchange between air and high-temperature methanol, 10.48 MWh of exergy from the air is transferred into the LMT, with an associated exergy destruction of 1.09 MWh. Ultimately, the exergy of the expanding air leaving the cold storage unit is 70.63 MWh.

5. Conclusion

Energy storage technologies are a key solution to current energy challenges. Among possible solutions, Liquid Air Energy Storage (LAES) stands out due to its low storage cost and independence from geographical constraints. In LAES systems, cold storage units are employed to liquefy air during the charging process and recover cold energy during the discharging process, significantly enhancing the system's energy density. However, since the cold storage units operate under cryogenic conditions, cold energy inevitably leaks to the environment. If not replenished in time, this leakage can lead to system failure. This study proposes a method to compensate for cold energy loss by reducing the pressurization pressure of liquid air, thereby enhancing cold energy supply to the cold storage units. A thermodynamic analysis of this strategy is conducted. Based on the analysis, for a 10 MW/80 MWh LAES system, the daily cold energy loss is calculated to be 341.90 kWh, corresponding to an exergy loss of 490.00 kWh. During operation, the actual system produces 0.78% less electricity and exhibits a 0.09% lower round-trip efficiency compared to the ideal system. This study aims to supply additional cold energy for LAES during actual operation, but it cannot provide cold energy replenishment when LAES has been shut down for a period of time.

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