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Configuration optimization of stand-alone Liquid Air Energy Storage for efficiency improvement

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Abstract. Liquid Air Energy Storage (LAES) is one of the most potential large-scale energy storage technologies. At off-peak hours, electricity is stored in the form of liquid air at -196 ºC (charging process); at peak hours, electricity is recovered through expanding the liquid air (discharging process). It is found that there is excess heat of compression up to 40% in the LAES, which is directly exhausted. To solve the above problem, two configurations are proposed and compared: the first, denoted by Mode-1, is to use the excess heat to drive an Organic Rankine Cycle (ORC); the second, named as Mode-2, is to add two more expansion stages in the discharging process. Effects of different working parameters on the two configurations are studied. Simulation results show that both Mode-1 and Mode-2 have much higher round trip efficiencies than the baseline system, with the maximum improvement of 12% and 8.6%, respectively.

1. Introduction

In the past, power plants were mostly based on the burning of fossil fuels, which caused high carbon emissions. To relieve carbon emissions, one of the key strategies is using renewable energy, which is considered to be environmentally friendly. Over the period of 2007-2012, renewable generation grew at an average rate of 5.9% per year. However, renewable generation is unstable and intermittent. The supply of variable renewable generation does not match the demand for electricity during all hours of the year [1]. The generated electric energy may be wasted if it is not consumed in time. Therefore, it is necessary to build a bridge between the energy supply and demand chains, where energy storage stands out due to its ability to add flexibility, control intermittence and provide back-up generation for electrical networks [2].

Among the large-scale energy storage technologies, liquid air energy storage (LAES) attracts much attention. Compared with other large-scale energy storage technologies, such as compressed air and pumped hydro, LAES has the advantages of high energy densities, no geographical constraints, highly competitive capital, etc. [3]. However, its round trip efficiency, ~50%, is relatively lower than other technologies, ~70%. Hence, it is quite necessary to improve the LAES performance for widely application in the future.

Thermodynamics and performance improvement of the LAES were studied. The round trip efficiency of LAES could be greatly improved through the storage and utilization of cold energy of liquid air during air discharging and air compression heat during air charging. Morgan et al. [4] considered a conventional two-turbine Claude cycle for air charging. However, this cycle resulted in a large pinch in the cold box which limited the effective utilization of the cold energy. To solve this problem, a chain of three turbines was proposed to replace the single cold turbine [5], and a round trip efficiency of 47% rising to 57% was calculated. Sciacovelli et al. [6] developed a dynamic model for the packed bed cold store and addressed the dynamic performance of the LAES. Temperature gradient of the cold store filled with pebbles is generally large in the axial direction, which degrades the cold energy due to axial dispersion. To avoid the above issues, a combination of propane and methanol was proposed to work as both the cold storage medium and working fluid for heat transfer [7, 8], which gave good temperature gradient match during heat exchange and hence an efficient cold recovery. Guizzi et al. [7] presented a thermodynamic analysis of the LAES, aiming to assess the system efficiency and to identify if and how it can achieve an acceptable round trip efficiency (50-60%). Li et al. [9] proposed an optimization methodology for thermodynamic design, where exergy efficiency and genetic algorithm were chosen as an evaluation index and an evaluation criterion, respectively.

In the previous stand-alone LAES, all the air compression heat in the air charging is randomly used to improve the output power of the turbine in the air discharging. However, based on our sensitivity analyses, it was found that the air compression heat cannot be fully used in the air discharging, up to 40% of which was excess [10, 11]. To effectively make use of the excess air compression heat, a novel stand-alone LAES is proposed with two configurations. Comparisons are made between the two configurations with different charging and discharging pressure. Significant performance improvements of the stand-alone LAES could be expected.

2. The previous stand-alone LAES

Fig. 1 shows the configuration of the previous stand-alone LAES system, which includes a charging cycle and a discharging cycle. In the charging cycle, ambient air after purification (state 1) is compressed to high pressure (state 8) and meanwhile the heat of compression is stored in a heat storage tank; then, the high pressure air is cooled down by the cold energy recovered from the liquid air; finally, the cooled air (state 10) enters a cryo-turbine, in which it expands to ambient pressure (state 11) and part of the air is liquefied and stored in a liquid air tank. In the discharging cycle, the liquid air (state 24) is pumped to high pressure (state 25) and then releases cold energy to the energy storage medium; finally, the high pressure air (state 27) goes through a three-stage expansion, with pre-heating or inter-heating by the stored heat of compression in the charging cycle, to generate electricity.

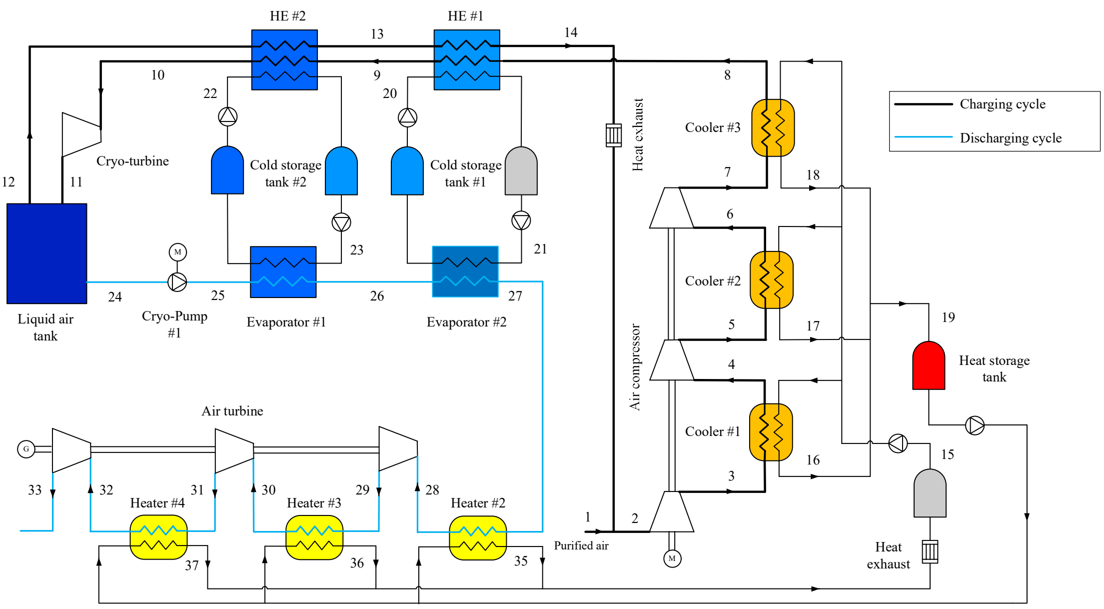

Fig. 1 Schematic diagram of the previous stand-alone LAES system.

For the working fluid in the stand-alone LAES, air is composed of nitrogen (78.12%), oxygen (20.96%) and argon (0.92%); pure propane and methanol are used as the cold storage media in the cold storage tank #2 and #1, respectively; Dowtherm G is used as the heat storage medium in the heat storage tank.

To analyze the system performance, mathematical models are made for each component:

- The system is working at a steady state; pressure loss through pipelines and thermal loss to environment are ignored;
- Power generation or consumption is calculated based on isentropic efficiency models; the isentropic efficiency of compressor, turbine and pump is 0.89, 0.9 and 0.7, respectively;
- Energy balance and pinch point limitation are applied to the heat exchangers; temperature difference at the pinch point is 2 °C in the Evaporators and 5 °C in other heat exchangers (HEs, Heaters and Coolers).

In the charging cycle, the net power input is given by:

$$W_{air,in} = m_{air,g} \cdot ((h_3 - h_2) + (h_5 - h_4) + (h_7 - h_6) - (h_{10} - h_{11})) \tag{1}$$

where $m_{air,g}$ is the air mass flow rate of the charging process, and h is the specific enthalpy

In the discharging cycle, the net power output is:

$$W_{air,out} = m_{air,l} \cdot ((h_{28} - h_{29}) + (h_{30} - h_{31}) + (h_{32} - h_{33}) - (h_{25} - h_{24})) \tag{2}$$

where $m_{air,l}$ is the mass flow rate of liquid air in the discharging process.

The round trip efficiency of the stand-alone LAES is defined as the ratio of net power output in the discharging process to the net power input in the charging process.

$$\eta_{RTE} = \frac{W_{air,out}}{W_{air,in}} \tag{3}$$

In the previous stand-alone LAES system, all the heat of compression stored in the charging cycle is used in the discharging cycle. However, based on our analyses, the supply of heat of compression exceeds the demand of the discharging cycle, and the excess heat of compression is directly exhausted which causes a waste of energy. As shown in Fig. 2, 30-40% of heat of compression is excess and wasted in the previous stand-alone LAES system.

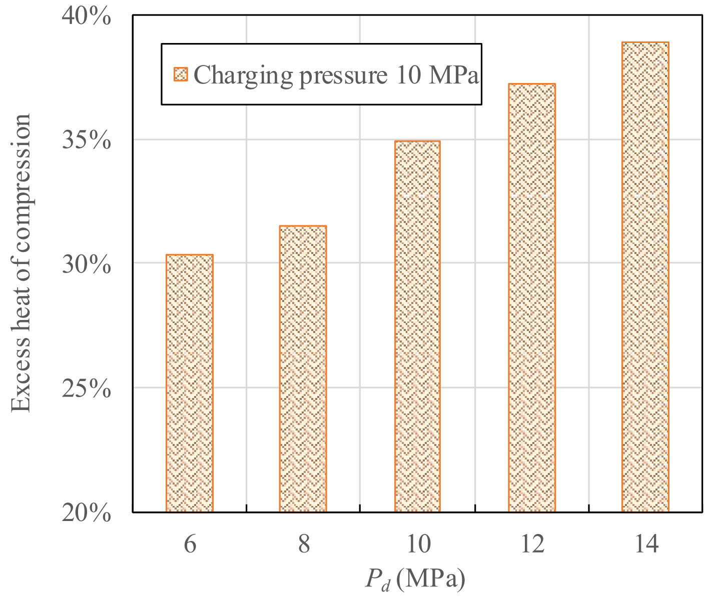

Fig. 2 Excess heat of compression in the previous stand-alone LAES system.

3. The novel stand-alone LAES

There is no doubt that the use of excess heat of compression will improve the system performance. Therefore, a novel stand-alone LAES system is proposed in this paper, as shown in Fig. 3. Two configurations, Mode-1 and Mode-2, are considered:

- Mode-1 is to use the excess heat of compression to drive an Organic Rankine Cycle (ORC) to generate more power, and R32 is chosen as the working medium in the ORC;
- Mode-2 is to add more expansion stages in the discharging cycle to generate more power; Fig. 4 shows the effect of expansion stages on the excess heat of compression; when two more stages are added, the heat of compression could be fully used in the discharging cycle.

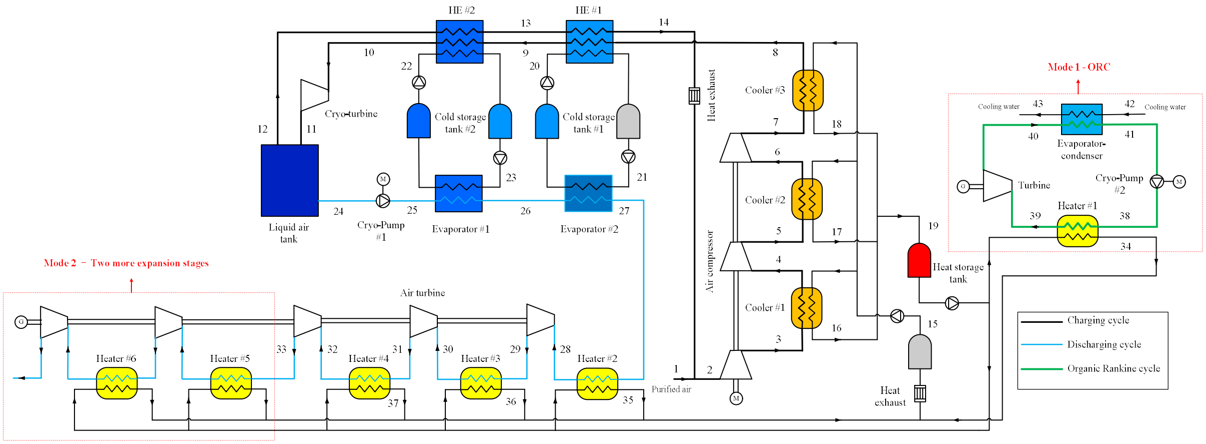

Fig. 3 Schematic diagram of the novel stand-alone LAES system.

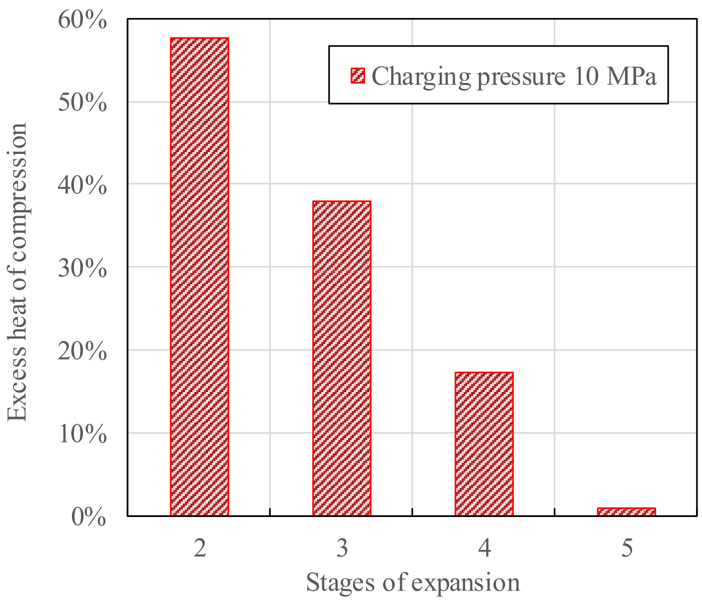

Fig. 4 Effect of expansion stages on the excess heat of compression (discharging pressure 12 MPa).

3.1. Effect of charging pressure on the stand-alone LAES

Fig. 5 shows the comparisons between the previous stand-alone LAES system and the novel stand-alone LAES system (Mode-1 and Mode-2) with various charging pressure (P_c), where discharging pressure (P_d) is set to 12 MPa. It is clear that both the Mode-1 and Mode-2 have much higher performances than the previous stand-alone LAES system, with the maximum improvement of 12% and 8%, respectively. In addition, Mode-1 prevails Mode-2 and is suggested.

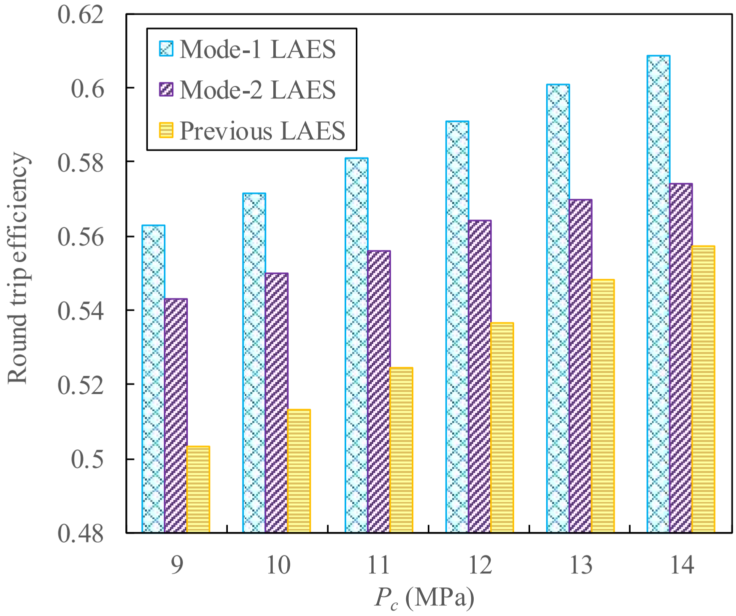

Fig. 5 Comparisons between the previous and the novel stand-alone LAES with different charging pressure (discharging pressure 12 MPa).

3.2. Effect of discharging pressure on the stand-alone LAES

Comparisons are also made between the previous stand-alone LAES system and the novel stand-alone LAES system (Mode-1 and Mode-2) with various discharging pressure (P_d), where charging pressure (P_c) is set to 12 MPa. As shown in Fig. 6, Both the Mode-1 and Mode-2 have much higher performances than the previous stand-alone LAES system, with the maximum improvement of 11% and 8.6%, respectively.

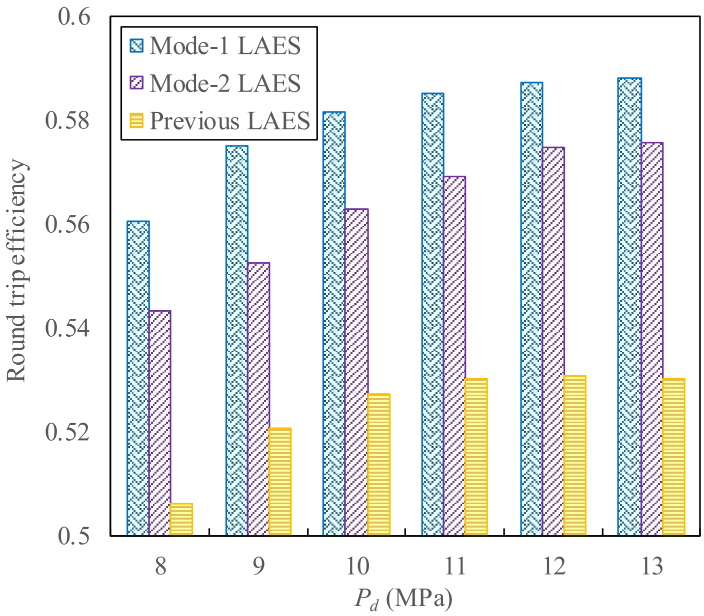

Fig. 6 Comparisons between the previous and the novel stand-alone LAES with different discharging pressure (charging pressure 12 MPa).

4. Conclusions

In the previous stand-alone LAES system, up to 40% of heat of compression is excess and directly exhausted which causes a waste of energy. To make use of the excess heat of compression, in this paper, two configurations of the stand-alone LAES, Mode-1 and Mode-2, are considered: Mode-1 is to use the excess heat to drive an organic Rankine cycle (ORC); Mode-2 is to add two more expansion stages in the discharging cycle. Comparisons are made among Mode-1, Mode-2 and the previous LAES system, with various charging and discharging pressure. Main conclusions are as follows:

- Both Mode-1 and Mode-2 show much higher performances than the previous stand-alone LAES system, with the maximum improvement of 12% and 8.6%, respectively.
- Mode-1, i.e. using the excess heat to drive an ORC, is suggested for improving the performance of the stand-alone LAES system, considering that Mode-1 has a higher round trip efficiency and is simpler than Mode-2.

Acknowledgments

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