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Thermodynamic analysis of Liquid Air Energy Storage integrated with a serial system of Organic Rankine and Absorption Refrigeration Cycles driven by compression heat

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Abstract

The rapid increase in application of intermittent renewable energy generation has stimulated the development of energy storage system to guarantee a stable supply in electricity grid. As a large-scale storage technology, Liquid Air Energy Storage (LAES) technology has attracted many attractions in recent years due to it offers many unique advantages including high energy density, mature technologies based and geographical-constraint free. However, current LAES has relatively low round trip efficiency (less than 60%) and still needs improvement.

In the LAES system, a large amount of compression heat is recovered and stored over 470 K during air liquefaction, and then is used to heat high pressure air before turbines to increase output power when electricity is needed. The effective use of compression heat is a key method to increase the total net output and round trip efficiency of LAES. Currently, only 58-78% of compression heat can reheat the high-pressure air while the rest is idle and wasted. Thus, taking advantage of the excessive compression heat to generate extra electricity has enormous potential to enhance net output and round trip efficiency of the LAES.

This paper proposes an innovative liquid air energy storage system integrated with a serial system of Organic Rankine Cycles (ORC) and Absorption Refrigeration Cycles (ARC). In the proposed system, excessive compression heat can be to drive the ARC to create a low temperature environment for the ORC, meanwhile, it works as the heat source of the ORC. Through the serial system, more electricity is generated. Results show that relatively higher round trip efficiency could be obtained, with 3-9% enhancement compared with the current LAES.

Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.

Keywords: Liqulid Air Energy Storage; Compression heat; Aborption Refrigention Cycle; Organic Rankine Cycle

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1. Introduction

In the past decade, the penetration of intermittent renewable energy technologies and low carbon emissions requirements has promoted the development of energy storage technologies. The world power generation capacity from renewable source has rapidly risen from 6% in 2007 to 27.7% at the end of 2014 [1]. Energy storage technologies can overcome the intermittent electricity production from renewable sources, in addition, it contributes to resolve the mismatch between power demand and supply by shifting the peak-load [2].

Among all innovative energy storage technologies, Liquid Air Energy Storage (LAES) is gradually attracting more attention. LAES presents a high energy storage density, geographical flexibility, a relatively low capital cost and is based on a mature technology [3]. LAES uses intermittent renewable sources or off-peak time power to produce liquid air and store the energy in liquid air form. The liquid air is pumped to high pressure, evaporated and heated then drives turbines to generate electricity when electrical energy is needed. The principle of LAES was first proposed by University of Newcastle in 1977 [4], and the world first pilot plant (350 kW/2.5 MWh) was established and tested by Highview Power Storage, UK in Greater London at 2010. It was relocated at University of Birmingham for further testing and academic research in 2014. Meanwhile a commercial scale of LAES 5 MW/15 MW/h) is under construction in Manchester UK [5].

However, the development of LAES is gravely limited by its low roundtrip efficiency since then, the system is under studied to improve the roundtrip efficiency through system structure optimization or device performance optimization. For a standalone LAES, roundtrip efficiency can be improved significantly using energy storage units to recovery and reuse the heat from air compression and the cold energy from liquid air evaporation [6-10]. Morgan et al. [7-8] optimized the air liquefaction process by adding a Claude cycle in a cold box, obtaining an efficiency of 57%. Sciacovelli et al. [9] designed an optimized a direct-contact cold store using pebbles and rocks as cryogenic energy carriers to improve the operation efficiency of the cold recovery unit. The system was optimized by a dynamic cold store model to improve the performance of LAES. Guizzi et al. [10] performed a thermodynamic analysis of a standalone LAES with an energy recovery unit and an energy reuse unit. The study showed how the system performance was affected by the isentropic efficiency of turbine, the pressure losses and the pinch-point temperature of heat exchanger. It was concluded that a 54-55% roundtrip efficiency could be achieved. Other researchers claimed that the performance of LAES could be improved through the integration of LAES with waste heat sources coming from industries [11-12]. Li et al. [11] presented a LAES integrated with nuclear power generation that a highly efficient time shift of electrical power output and LAES can achieve a higher roundtrip efficiency of 70%. Antonelli et al. [12] presented a compression between hybrid LAES system with and that without fuel combustion. It was found that the use of heat coming from fuel combustion LAES could achieve roundtrip efficiency over 80%.

In this study, an innovative liquid air energy storage system is proposed to enhance the roundtrip efficiency by using the excessive heat generated during the air compression process. According to the sensitivity analysis of the LAES system, it was found that the heat recovered during compression cannot be fully used in the air superheating before the air flows into turbines, because between the 22% to 40% of the compression heat is idle. Thereby, Organic Rankine Cycles (ORC) and Absorption Refrigeration Cycles (ARC) were integrated to LAES to consume the compression heat excess and optimize the system performance. Comparisons are made between the LAES and LAES-ARC-ORC with different operating conditions. It was found that a significant round trip efficiency improvement could be achieved.

2. Description of cycle

The new system is based on a traditional LAES integrated with an ammonia-water Absorption Refrigeration Cycle and an Organic Rankine Cycle (LAES-ARC-ORC). The excessive heat, stored in form of thermal oil, can drive the ARC and create an extra relative low-temperature environment for cooling working medium of ORC, then the rest part of heat can heat the working medium in ORC to provide an auxiliary electricity generation respectively. The layout of LAES-ARC-RC system is described in Fig. 1.

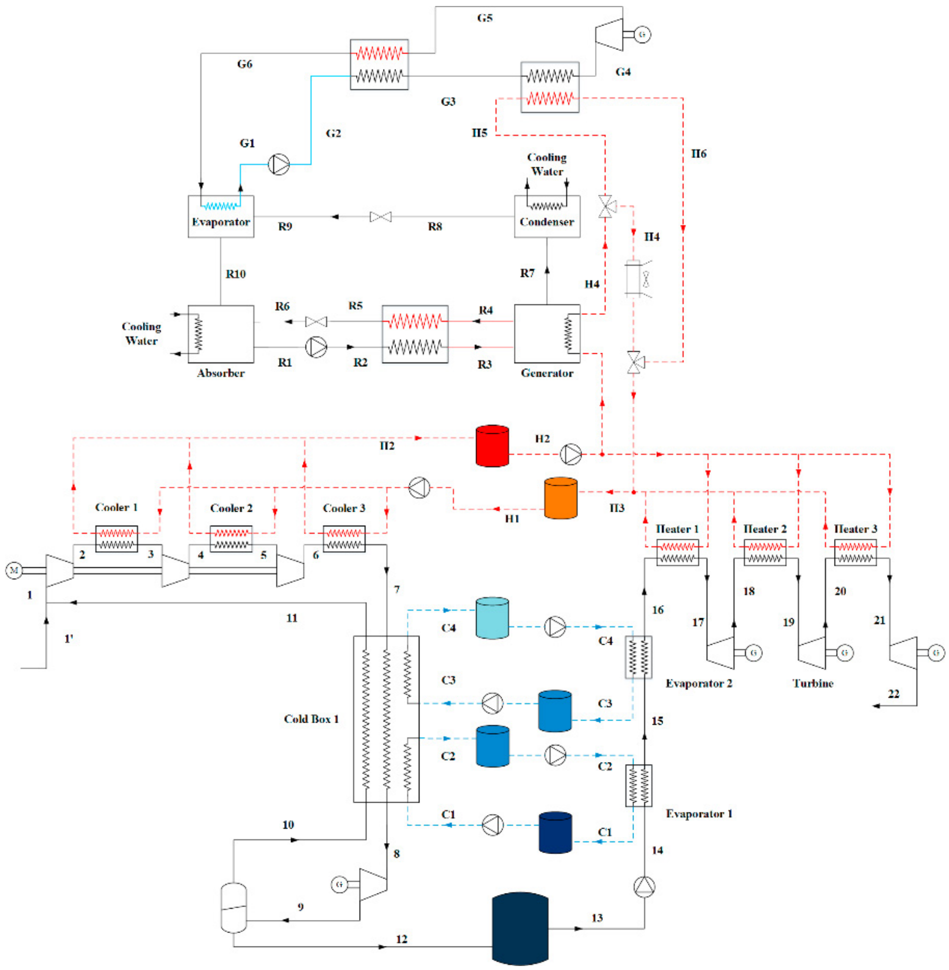

Fig. 1. Layout of LAES-ARC-ORC.

The air liquefaction unit runs at off-peak load time. The clean dry air is first compressed into a high pressure through multistage compressors and multistage intercoolers. Compared with a single stage compressor, multistage compressors significantly assist to decrease the energy consumption. Compression heat is recovered by thermal oil which is then stored in a high-temperature thermal store tank. The thermal oil temperature is determined by the compression ratio, being a higher store temperature a positively effects to the work capacity of the air in the power recovery unit. However, it significantly increases the electricity consumption of the air compressor. The high-pressure air is then cooled in the cold box by recycling air and cold fluids, then the air is expanded and liquefied by a cryogenic expander or an expansion value. Using a cryogenic expander can slightly decrease the energy consumption of the compressors but its maintenance cost and shorter operation life represents a drawback. The vapour-liquid mixed air is separated. The liquid air is stored in a tank at approximately 77 K and ambient pressure while the vapour which plays a refrigerant role carrying high-quality cold energy cooling the high-pressure air at the cold box.

When grid is at high load demand, the power recovery unit can be operated by liquid air flowing out of tank and pumping it over its critical pressure. Pumped air is then heated up in the evaporator. In the evaporator, the cold energy is also recovered from the cold fluids using propane and methanol as thermal energy storage materials. The energy stored in propane and methanol will be used later to cool the air in the liquefaction process increasing the liquid yield in the air liquification unit. At each stage of the turbine, the vapour air is superheated by the thermal oil to improve the work capacity and increase the generators output.

Meanwhile, the auxiliary generation based on Absorption Refrigeration Cycle (ARC) system and Organic Rankine Cycle (ORC), driven by the excess compression heat, are run together with the power recovery unit to increase the net output. The pumped rich ammonia-water solution is preheated and flowed into the Generator, where it is heated by the thermal oil obtaining ammonia and saturated weak ammonia-water solution. After the preheating and depressurization, weak ammonia-water solution flows into the Absorber. Gaseous ammonia flows into the Condenser and is cooled down and liquefied by cold water. The liquid ammonia, after depressurization, can provide cold energy from approximately 223 K to 253 K, and its evaporation temperature is chosen depending on the condensation temperature of the working medium of the ORC. Flowing out from the Condenser, ammonia is absorbed by the weak ammonia-water solution to obtain again a statured solution at the Absorber.

R134a is used to act working medium in ORC. Liquid R134a fluid, which obtains cold energy from ARC, is pumped to a high pressure and heated up by itself from turbine outlet and thermal oil, and then it is expanded through a turbine. Before condensation, R134a flows into heat exchanger to improve energy utilization efficiency of ORC.

3. System evaluation and simulation

3.1. Performance indexes

In LAES system, roundtrip efficiency is consisted of the net power output in discharging process by net power input in charging process. the roundtrip efficiency can be described as follow:

$$\eta_{rt} = \frac{W_{out}}{W_{in}} = \frac{\dot{m}_{12}(W_{T,LAES} - W_{pump,LAES})}{\dot{m}_1(W_{C,LAES} - W_{\exp,LAES})} \tag{1}$$

While in LAES-ARC-ORC system, the roundtrip efficiency can be described as follow:

$$\eta_{rt,enhance} = \frac{W_{out}^{'}}{W_{in}^{'}} = \frac{\dot{m}_{13}(W_{T,LAES} - W_{pump,LAES}) + \dot{m}_{G1}W_{T,ORC} - \dot{m}_{R1}W_{pump,ARC} - \dot{m}_{G1}W_{pump,ORC}}{\dot{m}_1(W_{C,LAES} - W_{\exp,LAES})} \tag{2}$$

3.2. Assumptions and default parameters

In this study, the constitutive calculation for LAES, ARC and ORC is implemented by MATLAB, the thermal properties of air, propane, methanol, ammonia and R134a are evaluated by REFPROP 8.1 software while thermal properties of thermal oil are calculated by ASPEN plus. The air is assumed to be composed of nitrogen (78.12%), oxygen (20.96%) and argon (0.92%). Some specification parameters are shown in Table 1, some key parameters can be found in reference [10], the main assumptions for system simulations are as follow:

Table 1. Default parameters of LAES-ARC-ORC.

Parameter	Value
Ambient Temperature	293 K
Ambient Pressure	100 K
Thermal oil temperature	293 K
Minimum propane temperature	95 K
Minimum methanol temperature	214 K
Cooling water temperature	293 K
Ammonia evaporation temperature	244 K
Pinch point of cooler	2 K
Pinch point of heater	5 K
Pinch point of cold box	5 K
Pinch point of evaporator	2 K
Relative pressure drop of heat exchanger	1%
Isentropic efficiency of compressor	85%
Isentropic efficiency of turbine	90%
Isentropic efficiency of cryo-expander	75%
Isentropic efficiency of pump	75%

4. Results and discussion

4.1. Performance of LAES and LAES-ARC-ORC

The performance of each cycle of LAES-ARC-ORC is shown in Table 2. In charging process, the pure air (20 kg/s) is compressed to 10 MPa with compression ratio of 2.154 for each stage, and then cooled down to 117.6 K in cold box. After expansion, 69.8% of supply air is liquefied, meanwhile, thermal oil recovers the compression heat and is stored in tank at temperature of 476 K. The total net power of electricity consumption is 11.1 MW. In discharging process, produced liquid air (13.97 kg/s) is pumped to 8 MPa, 66.7% of hot thermal oil is to superheat the air before expansion in the turbine and the net power of discharging process can approach to 5.9 MW. In these operation conditions, the roundtrip efficiency reaches 53.1%.

Table 2. Performance results of LAES-ARC-ORC cycles.

Items	Charging	Discharging	ARC	ORC
Net power (kW)	11104	5896	13.6	190.4
Exergy efficiency	0.841	0.853	0.454	0.614
Mass flow rate (kg/s)	20.00	13.97	2.26 (1.79)*	2.30
Yield	0.698			
Roundtrip efficiency	LAES: 53.1%; LAES enhance: 54.7%			

*strong ammonia-water solution is 2.26 kg/s and weak solution is 1.79 kg/s.

While the rest 33.3% of thermal oil is used to heat up strong ammonia-water solution in Generator at ARC section, the generation temperature is set to 430 K where the higher COP can be achieved. ARC section can create a low temperature environment of 244 K. After flowing out form Generator, the thermal oil flows into ORC section and heats up the R134a (2.30 kg/s) at heat exchanger. After expansion in turbine and cooling down in pre-heat exchanger, R134a is liquified in condenser though cold source created by ARC section. The net power of ORC is 190 kW. Thereby, the roundtrip efficiency obtains an increase to 54.7%.

4.2. Influence of compressor isentropic efficiency

The performance of compressor significantly effects the electricity consumption and roundtrip efficiency. To analyze how much contribution of isentropic efficiency of compressor to ARC-ORC auxiliary system, sensibility of charging pressure is considered under different compressor isentropic efficiency. Fig. 2 (a) illustrates the influence of charging pressure on roundtrip efficiency at compressor isentropic efficiency of 75%, it is possible to observe that an increase with the charging pressure growth until reaches maximum value of 51% at $P_{charging}$=140 MPa, and further increase of charging pressure brings no contribution to any increase of roundtrip efficiency. Meanwhile, the enhancing roundtrip efficiency from ARC-ORC system presented the same trend with that of LAES, the maximum value of 53% is shown at the same pressure of 14 MPa. It can be found that the trend of improvement shows a total opposite. The improvement (red line) drops significantly with the increase of charging pressure until hit bottom when roundtrip efficiency reaches peak point. It can be explained that LAES with lower roundtrip efficiency use less compression heat hence there is more idle compression heat can be utilized to generate ammonia at ARC section and lead to more cold energy of 244 K which contribute to enlarge the output of ORC.

Furthermore, for a LAES with higher isentropic efficiency, as shown in Fig. 2 (b), it can be clearly found that the average improvement with η_c=0.85% is obviously smaller than that with η_c=0.75%. The maximum roundtrip efficiency without ARC-ORC has already reached to 58.6% and only 2.27% of improvement can be achieved. It can be concluded that the series system using idle compression heat can significantly improve the independent LAES system operating at relatively low roundtrip efficiency, such as small-scale LAES.

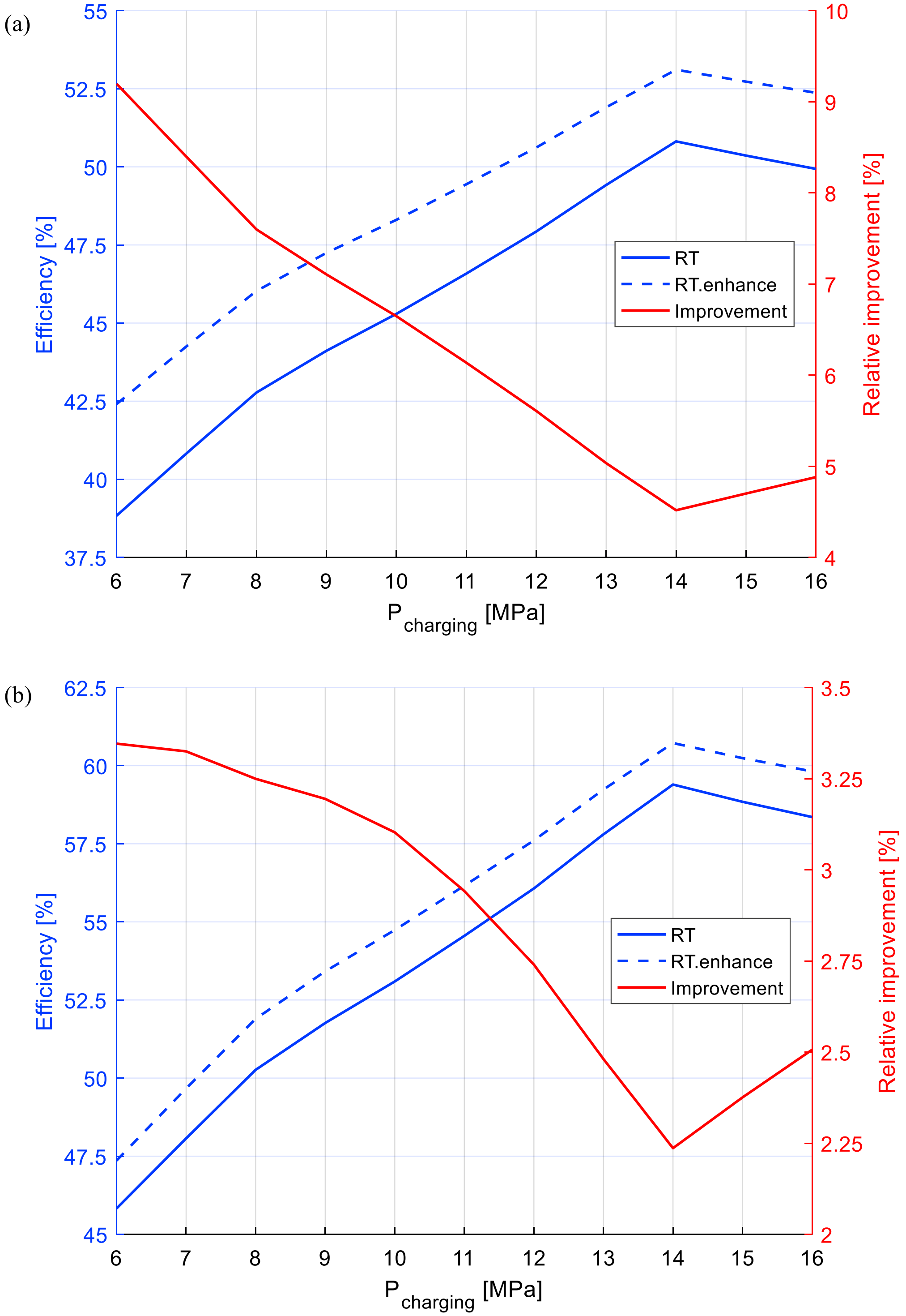

Fig. 2. Influence of charging pressure on roundtrip efficiency and its improvement (a) $\eta_c = 75\%$; (b) $\eta_c = 85\%$.

5. Conclusions

An innovative LAES integrated with an auxiliary system of Absorption Refrigeration Cycle and Organic Rankine Cycle was proposed. In this study, excess compression heat was first implemented to drive an ammonia-water ARC to produce a low temperature environment for the ORC, and then it worked as a heat source of the ORC to enlarge the net power output of current LAES and finally improve the roundtrip efficiency.

For the proposed system, the auxiliary system contributed significantly to LAES with lower isentropic efficiency of compressor, and the relative efficiency enhancement varied from 4.5% to 9.2%, when the maximum value of roundtrip efficiency grew from 51% to 53%. However, for LAES with better isentropic efficiency of compressor, the relative efficiency enhancement presented a slight increase from 2.25% to 3.3%, and the maximum efficiency could approach 61%. Consequently, it can be concluded that the ARC-ORC auxiliary system can improve the performance of LAES though excess compression heat utilization, especially for low-efficiency or small-scale LAES.

This study may provide an efficient method to utilize compression heat to improve the roundtrip efficiency for an independent LAES.

Acknowledgements

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