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Abstract

Renewable energy sources have a growing share in the energy market due to the threat from climate change, which is caused by emissions from fossil fuels. A future energy scenario that is likely to be realized is distributed energy systems (DES), where renewable energy sources play an increasing role. Energy storage technologies must be adopted to achieve these two expectations. Liquid Air Energy Storage (LAES), is a cryogenic technology that is discussed in this paper. Two cases are considered in this work to represent different operating modes for the LAES process: with and without an extra amount of hot oil in the discharging process. The performance of the LAES system will be analyzed with different number of compression stages and expansion stages in each mode. A Genetic Algorithm (GA) is used to optimize the LAES process. The round-trip efficiency is 63.1 % after flowsheet improvement and optimization.

Optimization of Liquid Air Energy Storage (LAES) using a Genetic Algorithm (GA)

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Abstract

Renewable energy sources have a growing share in the energy market due to the threat from climate change, which is caused by emissions from fossil fuels. A future energy scenario that is likely to be realized is distributed energy systems (DES), where renewable energy sources play an increasing role. Energy storage technologies must be adopted to achieve these two expectations. Liquid Air Energy Storage (LAES), is a cryogenic technology that is discussed in this paper. Two cases are considered in this work to represent different operating modes for the LAES process: with and without an extra amount of hot oil in the discharging process. The performance of the LAES system will be analyzed with different number of compression stages and expansion stages in each mode. A Genetic Algorithm (GA) is used to optimize the LAES process. The round-trip efficiency is 63.1 % after flowsheet improvement and optimization.

Keywords: Liquid air energy storage, round-trip efficiency, flowsheet improvement, genetic algorithm

1. Introduction

With the increasing focus on the environment, a lot of measures have been taken to reduce the emission of greenhouse gases. Renewable energy technologies are considered to replace traditional fossil fuels. However, once renewable energy is introduced in the energy market, the most important challenge is to keep the stability of energy supply due to the intermittent nature of renewable energy sources such as wind and solar.

Another likely trend for future energy systems is decentralization in the form of distributed energy hubs. These hubs are located close to available energy forms and specific energy demands. The advantages of distributed energy systems mainly include the flexibility to utilize various energy conversion technologies and the improved reliability of energy supply (or reduced vulnerability of the overall system) by operating these distributed energy systems in networks and integrating with local energy resources (Alanne and Saari, 2006).

Energy storage technologies must be adopted to smoothen variations in supply (typical for renewable energy sources) and demand (daily or seasonal variations) and to guarantee supply during energy deficit periods. Pumped hydroelectric energy storage (PHES) (Rehman et al., 2015), compressed air energy storage (CAES) (Bullough et al., 2004), and battery energy storage (BES) (Aneke and Wang, 2016) are mature energy storage technologies. However, because of the geographical constraints of PHES and CAES and capital considerations for BES, the application of these technologies is still limited.

Energy storage technologies that can overcome the drawbacks of the existing technologies are more likely to be adopted in future energy systems. Among the proposed energy storage technologies, liquid air energy storage (LAES) seems to be a promising option (Guizzi et al., 2015), since LAES can benefit from established technologies, such as gas liquefaction and air separation units, and it is not geographically constrained.

Until now, the largest reported LAES implementation is a plant with 15 MWh storage capacity that was built in the UK (Highview Power, 2019). The round-trip efficiency of the standalone process is around 60 %. Li et al. (2014) studied the integration of LAES and a nuclear power plant, and the round-trip efficiency was claimed to reach 70 %. An approach with a liquid air Rankine cycle was proposed by Ameel et al. (2013), and a round-trip efficiency of 43 % was achieved. A standalone LAES plant was simulated with a round-trip efficiency of 55 % (Guizzi et al., 2015). None of these studies have been applied in large scale. In addition, since the round-trip efficiency of a standalone LAES plant is lower than 60 %, there is still considerable need for improvement before the technology can be industrialized. However, very few papers are trying to optimize standalone LAES systems. Instead, the integration of LAES with external heat sources have been gaining more focus recently. A standalone LAES with optimal design integrated with external heat sources should be tested to further enhance the round-trip efficiency of the process. Thus, the LAES first needs investigation to increase overall efficiency, store hot and cold thermal energy efficiently, and obtain good response times, so that the technology with its potential advantages can be used in practical applications. In this paper, two operating modes are studied for the LAES process: with or without introducing extra amounts of hot oil in the discharging process. A genetic algorithm (GA) is adopted to optimize the LAES process. GA is a search method used to find approximate solutions and is based on the concepts of "natural selection" and "genetic inheritance". The objective function is the round-trip efficiency (RTE, η_{RT}), which is the ratio of work output (W_{out}) in the discharging process and the work input (W_{in}) in the charging process. Results show that optimization with η_{RT} as objective function gives modest improvements compared with the original case.
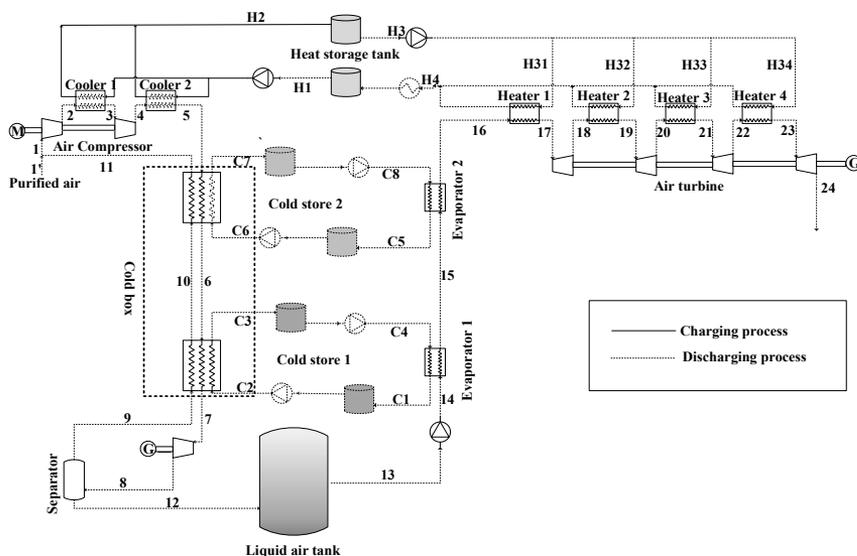
Figure 1: Flow diagram for the liquid air energy storage process

2. Design basis and optimization

The process in Figure 1 shows the liquid air energy storage process, having hot and cold thermal energy storages (Guizzi et al., 2015). The process is simulated in Aspen HYSYS V10.0 (Aspen HYSYS, 2017). The air, consisting of 78.82 % nitrogen, 21.14 % oxygen and 0.04 % argon, is assumed as the feed gas and is liquefied through this modified Claude process. The pre-purification unit (PPU) for the removal of CO_2, H_2O and other trace components is not included in the simulation. Other design conditions and assumptions used in this work are shown in Table 1.

The simulation model is optimized to maximize round-trip efficiency of the process. The pressures after the last-stage compressor and pump are set as variables. In addition, the operating temperatures and mass flow rates of hot oil, methanol and propane are defined as variables in order to manipulate the duty of heat exchangers during optimization. The inlet temperatures of compressors and turbines are also considered as variables, and this has direct effects on electricity consumption and generation in the process. The constraints applied in the optimization problem are the minimum temperature differences for heat exchangers, where 10 K for coolers and heaters and 3 K for evaporators and heat exchangers in the cold box have been assumed.

Table 1: Simulation conditions and assumptions

Parameter	Value	Unit
Ambient temperature	293	K
Ambient pressure	101.325	kPa
Cooling water temperature	288	K
ΔT_{min} of cooler	10	K
ΔT_{min} of heater	10	K
ΔT_{min} of cold box	3	K
ΔT_{min} of evaporator	3	K
Relative pressure drops of heat exchanger	1	%
Isentropic efficiency of compressor	85	%
Isentropic efficiency of turbine	90	%
Isentropic efficiency of cryo-turbine	75	%
Isentropic efficiency of pump	80	%

3. Results

3.1. Key performance indicators

In order to evaluate the performance of the different processes, two parameters will be introduced in this section: liquid yield and round-trip efficiency. Liquid yield η_{LA} is defined as the ratio between the mass flow rate of liquid air (m_{liq}) and the total mass flow rate of compressed air (m_{comp}) that includes the recycle of air:

$$\eta_{LA} = \frac{m_{liq}}{m_{comp}} \tag{1}$$

The most important parameter is the round-trip efficiency η_{RT} that is defined as the work output (W_{out}) in discharge mode divided by the work input (W_{in}) in charge mode:

$$\eta_{RT} = \frac{W_{out}}{W_{in}} = \frac{m_{liq}\, w_T}{m_{comp}\, w_C} = \eta_{LA} \cdot \frac{w_T}{w_C} \tag{2}$$

where w_T and w_C represent the specific work [kJ/kg] of the expanders and the compressors, respectively.

3.2. Effects of different number of compression stages and expansion stages on the round-trip efficiency

Minimum compression work for a compressor is obtained by isothermal operation, thus multi-stage compression at low temperature with inter-stage cooling is used to minimize work consumption. Likewise, expansion at high temperature with inter-stage reheating maximizes work production. However, from an economic point of view, the number of compressors and expanders affects the capital cost, which increases with number of units and flowsheet complexity.

In the LAES process, when the number of compressor stages (with interstage cooling) is increased, the compression heat that can be recovered by hot oil and utilized in the discharging process decreases. The achieveable temperature of the hot oil is decreased, however, since cooling of air after compressor stages is repeated, the mass flow rate of hot oil increases. These two changes have opposite effects on the round-trip efficiency and power generation. Reduced temperature of hot oil has a negative effect, while increased mass flow rate of hot oil has a positive effect. The trade-off between the number of compressors, capital cost and compression heat (temperature and mass flow rate of the hot oil) should be balanced. In this section, two operating modes are discussed: with or without introducing extra amounts of hot oil in the discharging process. The performance of the LAES system will be analyzed with different number of compression stages and expansion stages in each mode. First, the case without extra amounts of hot oil is studied.

3.2.1. Without extra amounts of hot oil in the discharging process

Figure 2 demonstrates the effects of different number of compression stages and expansion stages on the RTE of the process without extra amounts of hot oil in the discharging process. As can be seen from the figure, the highest RTE (58.2 %) is obtained with 2-stage compressor and 3-stage expander. Common for all cases without extra hot oil, is the fact that the pinch points in the expansion heat exchangers are in the cold end. The reason why the combination of 2-stage compressor and 3-stage expander has the best performance with respect to RTE, is that the composite curves are closer to parallel than for other combinations. For 3-stage expansion, the RTE is reduced with increased number of compression stages. This is due to the fact that the reduction of hot oil temperature leads to a decreased temperature of inlet air to the expanders, even if the pinch points in the expansion heat exchangers are in the hot end when the number of compression stages is equal to or larger than 3. The decreasing temperature of hot oil has a decisive influence on the RTE in the case with 3-stage compressor and 3-stage expander.From the previous discussion, both temperature and mass flowrate of hot oil are affected by the number of compressor stages in the charging process. Since hot oil is used to transfer compression heat to the expansion section in the discharging process in order to increase work production, there is a strong link between the number of compression stages and the number of expansion stages. The location of the pinch points in the heat exchangers also plays an important role. As a result, for a given number of compressor stages, there exists

an optimal number of expansion stages. This optimal matching can be found in Figure 2. Even though 4-stage expansion has a maximum RTE for 3-stage compression and similar for 5-stage expansion and 4-stage compression, these combinations have lower RTE than the simpler case with 3-stage expansion and 2-stage compression, which is the best combination overall.
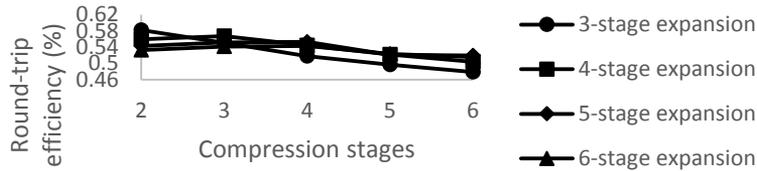
Figure 2: RTE of the LAES for combinations of compression and expansion stages

3.2.2. With extra amounts of hot oil in the discharging process

The pinch point analysis for the LAES process with 2-stage compression and 3-stage expansion indicates that the RTE can be further improved by shifting the pinch points to the hot end to reach a higher inlet temperature to the expanders. This can be achieved by providing enough hot oil in the discharging process. The effect of increasing the number of expansion stages on the RTE when the number of compression stages is fixed at 2, while other variables (such as pressure after the pump and inlet temperature to the expanders) are unchanged, is illustrated in Figure 3. There is a diminishing return on investment when increasing the number of expansion stages. When combining the economic considerations with the RTE, for 2-stage compression in the charging process, 4-stage expansion is recommended in the discharging process when sufficient amounts of hot oil is available. Key performance indicators are listed in Table 2. In this case, an extra amount of hot oil (731 kg/h) is added in the discharging process.
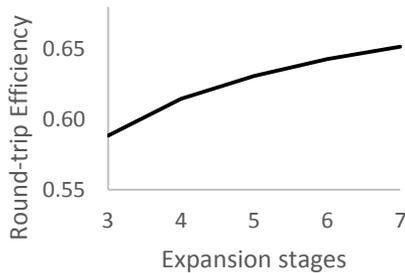
Figure 3: Analysis of the RTE when changing the number of expansion stages

Table 2: Key performance indicators for the LAES process with a 2-stage compressor and a 4-stage expander

Parameter	LAES	
	Charging	Discharging
Work (kW)	499.3	309.3
Liquid yield	0.865	
Round-trip efficiency	61.9 %	

Table 3: Genetic algorithm results

Parameter	LAES	
	Charging	Discharging
Work (kW)	498.9	314.8
Liquid yield	0.865	
Round-trip efficiency	63.1 %	

3.3. Optimization results

The work consumed in the charging process and produced in the discharging process, liquid yield, and the round-trip efficiency are shown in Table 3. Based on the results, the round-trip efficiency has been slightly improved from 61.9 % to 63.1 % by using GA.

4. Conclusions

Liquid air energy storage (LAES) is a viable option for grid-scale electrical energy storage, with the advantage that it is not geographically constrained. However, a low round-trip efficiency has limited the application of this technology. In this study, the cases without introducing extra hot oil in the discharging process is first studied, and the LAES process with a 2-stage compressor and 3-stage expander has the highest round-trip efficiency of 58.2 %. There is an optimal combination of number of compression stages and expansion stages. The combinations corresponding to 4 to 6 expansion stages are 3-stage, 4-stage and 4-stage compression, respectively. However, when introducing an extra amount of hot oil in the discharging process, the LAES process with a 2-stage compressor and 4-stage expander is recommended. An optimization method (Genetic Algorithm) is used to further improve the round-trip efficiency from 61.9 % to 63.1 %.

Acknowledgements

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