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Thermodynamic analysis of a novel liquid air energy storage system

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Abstract

In this study, a novel liquid air energy storage system for electrical power load shifting application is introduced. It is a combination of an air liquefaction cycle and a gas turbine power generation cycle without fuel combustion. Thermodynamic analysis is conducted to investigate the performance of this system. The results show that liquid air energy storage systems could be very effective systems for electrical power storage with high efficiency, high energy density and extensive application prospects.

Keywords: liquid air energy storage; energy density; regenerator; efficiency; multiple phase change

1. Introduction

Renewable energy is an important solution to reduce CO_2 emissions and could contribute as much as 21% of the reduction in energy-related CO_2 emissions by 2050 IEA (2008). With a vast increase in renewable energy, incorporating wind and solar energy into existing power grids is becoming the technology obstacle to its development. Wind power, for example, has the disadvantages of intermittence and randomness. These disadvantages will bring challenges to the safety and stabilization of power grid and restrict the scale of wind power development. Unlike other forms of energy, electricity can only be stored in large quantities in certain carriers, and

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be transformed to other forms such as chemical, potential, or thermal energy. Therefore, electricity supply and demand must always be balanced simultaneously.

Nomenclature

W	work (J)
k	adiabatic index
$\dot{m}$	mass flow rate (kg/s)
R_g	gas constant (J/kg K)
$\eta_{c,i}$	adiabatic efficiency of the compressor
$\beta_{c,i}$	pressure ratio of compressor
$\eta_{e,i}$	adiabatic efficiency of turbine
$\pi_{e,i}$	expansion ratio of turbine
C_p	specific heat of air (kJ/kg K)
t	time (s)
h	specific enthalpy (kJ/kg)
Q	heat transfer (J)
ε	efficiency of the cold-energy regenerator
η	energy efficiency of the system

Subscripts

i	stage number of compressor or turbine
c	compressor
e	turbine
air	air
LA	liquid air
p	cryogenic pump
$1,2,..8$	position of the point

Electrical Energy Storage system is the key technology to solve the problem of interconnection in Smart Grid Mc Larnon FR et al. (1989). Electrical Energy Storage refers to a process of converting electrical energy from a power network to a form that can be stored for converting back to electrical energy when needed. Such a process enables electricity to be produced at times of either low demand, low generation cost or from intermittent energy sources, and to be used at times of high demand, high generation cost or when no other generation means is available Haisheng Chen et al. (2009).

There are several energy storage technologies for the utility industry. The most well-known are: batteries, pumped hydroelectric power, flywheels and superconducting magnet energy storage in addition to CAES. In these technologies, electrical energy storage can be achieved from a few kilowatts to megawatts in the scale from minutes to several hours Samir Succar et al. (2008).

In this paper, a novel liquid air energy storage (LAES) system is introduced for electrical power load shifting application. This technology involves the storage of liquid air and thermal energy. Furthermore, the thermal energy could come from solar thermal, geothermal or waste process heat, etc., and is stored in the form of sensible heat in a thermal fluid. Thermodynamic analysis is conducted to investigate the performance of this system. Optimization is performed to improve the efficiency of the system.

2. System description

The schematic of the liquid air energy storage system is shown in Fig. 1. The system is made up of compressor, cold energy regenerator, liquid-vapor separator, cryogenic tank, cryogenic pump, turbine and generator. A cold energy regenerator filled with cold storage medium is employed to recycle the cold energy during the processes. The

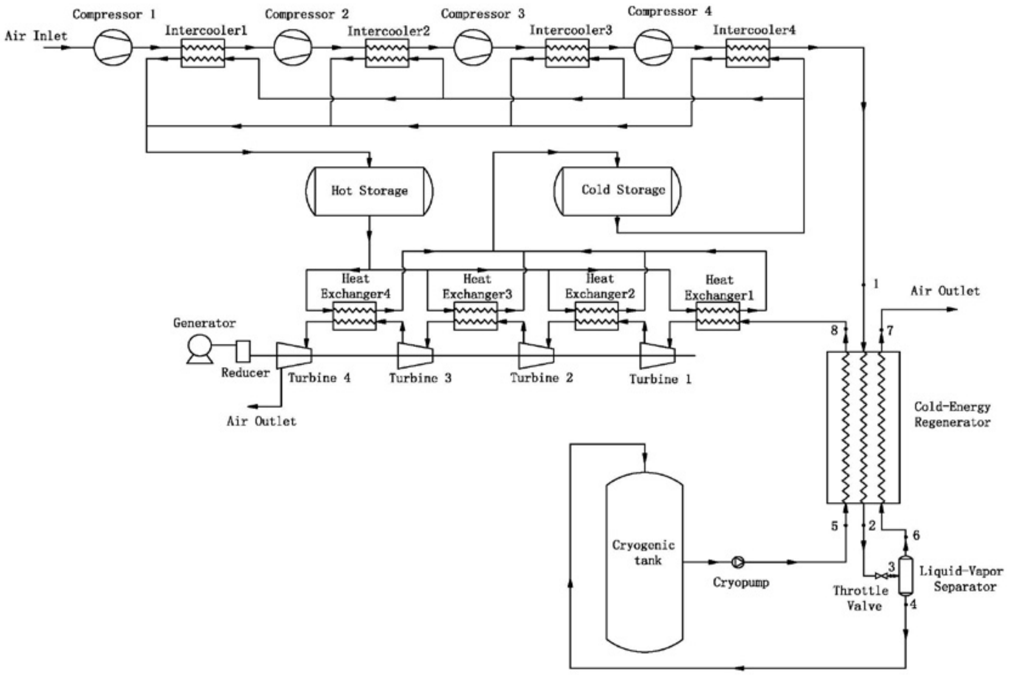

Fig.1. Schematic of the liquid air energy storage system.

operation process of the system can be divided into two operating processes: energy storage and power generation. The interval between two processes is more than 8 hour.

During the process of energy storage, ambient air is compressed to a high pressure by an air compressor and then poured into a cold energy regenerator. The air is cooled by the cold storage medium to a low temperature and converted into liquid air in the regenerator. The liquid air goes through a throttle valve causing pressure drop. And then different phases of the air are separated by a liquid-vapor separator. Liquid air will be stored in a cryogenic tank. Gaseous air will flow back through the cold energy regenerator to precool the high pressure air.

During the process of power generation, liquid air is compressed to a high pressure via a cryogenic pump, which is used to adjust the expanding pressure of the turbine. Then the high pressure liquid air enters the cold energy regenerator. In the regenerator, liquid air is heated by the cold storage medium. As the temperature of the air rises, liquid air is converted into gaseous air. Finally, the high pressure air expands to ambient pressure in turbines with reheating processes. The generator is driven by the turbine and output power to the grid.

3. Thermodynamic analysis

In order to simplify the calculation, assumptions being made are as follows:

- the air is ideal gas;
- kinetic and potential energy changes are neglected;
- there is no heat loss during the storage of the liquid air.

3.1 Compressor module

The air compressor works under steady conditions because the outlet air pressure and displacement are constant with time. The real compression process can be regarded as a series of different stages compressions as shown in Fig. 3. If the discharge pressure is p, the compression work of each stage is

$$W_{c,i} = \frac{k}{k-1}\frac{\dot{m}_c R_g T_{c,i}^{in}}{\eta_{c,i}}\left[(\beta_{c,i})^{\frac{k-1}{k}} - 1\right]. \tag{1}$$

The total work consumed by the compressor is

$$W_c = \sum(W_{c,i})\,. \tag{2}$$

3.2. Turbine module

After the energy storage process is finished, the power generation process can start whenever needed. High pressure air is discharged from the cold energy regenerator and enters the turbine. Discharging of the high pressure air is also a steady process. If the air pressure before expansion is p, the shaft work of each stage is

$$w_{e,i} = \frac{k}{k-1}\dot{m}_{\mathrm{e}} R_g T_{e,1}\eta_{e,i}\left[1-\left(\pi_{e,i}\right)^{-\frac{k-1}{k}}\right]. \tag{3}$$

The total shaft work of the turbine is

$$W_e = \sum(W_{e,i})\,. \tag{4}$$

3.3 Cold energy regenerator module

During the energy storage process, the cold energy regenerator cools down the passing air to a liquefaction temperature and stores the thermal energy in cold storage medium. The thermal energy is calculated according to:

$$Q_{1-2} = \int \dot{m}_{air} C_p (T_1 - T_2) dt\,. \tag{5}$$

During the power generation process, the passing liquid air cools down the cold energy regenerator to a low temperature and stores the cold energy in the cold storage medium. The cold energy is calculated according to:

$$Q_{5-8} = \int \dot{m}_{LA} C_p (T_8 - T_5) dt\,. \tag{6}$$

3.4. Cryogenic pump module

The cryogenic pump is used to compress liquid air to a high pressure. The power consumed by the cryogenic pump is calculated according to Eq. (7):

$$W_p = \dot{m}_{\mathrm{LA}}(h_5 - h_4)\,. \tag{7}$$

3.5. Definition of efficiency

Define the efficiency of the cold energy regenerator as follows:

$$\varepsilon = \frac{T_2 - T_1}{T_5 - T_8}\,. \tag{8}$$

Define the energy efficiency of the system as follows:

$$\eta = \frac{W_e - W_p}{W_c}. \tag{9}$$

4. Results and discussion

4.1. Influence of different adiabatic efficiency of the compressor

Fig. 2a presents the energy efficiency and power consumed by the compressor at different adiabatic efficiencies of the compressor. As can be seen, when the adiabatic efficiency of the compressor increases, energy efficiency increases and compressor power decreases. When the adiabatic efficiency is 0.9, the energy efficiency is 0.49 and the compressor power is 230 kW. In order to obtain higher energy efficiency of the LAES, it is necessary to improve the adiabatic efficiency of the compressor.

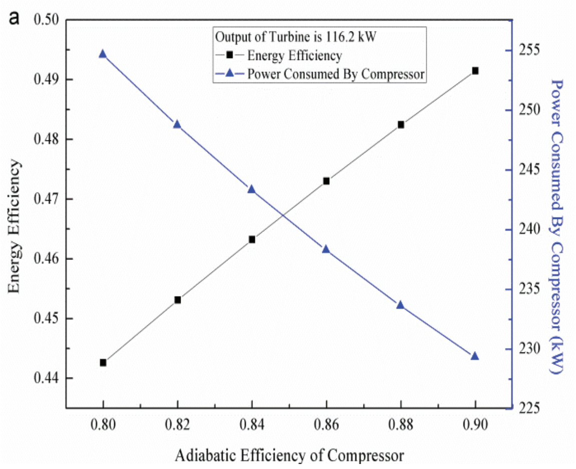

Fig. 2 (a). Influence of different adiabatic efficiencies of the compressor on the energy efficiency and the power consumed by the compressor.

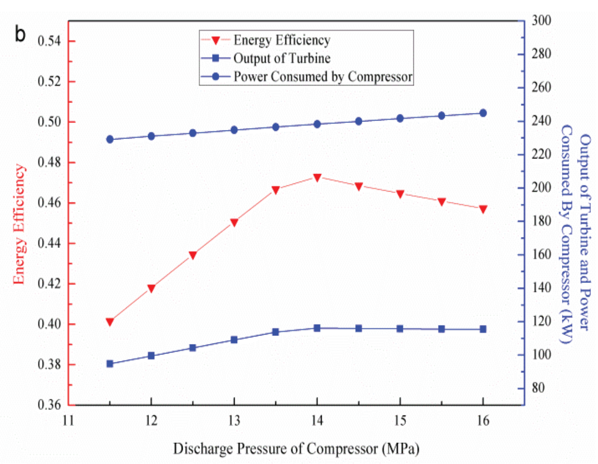

Fig. 2 (b). Influence of different discharge pressures of the compressor on the energy efficiency and power consumed by the compressor.

4.2. Influence of different discharge pressures of compressor

Fig. 2b presents the energy efficiency, compression power and output of turbine at different discharge pressures of the compressor. As can be seen, when the discharge pressure of the compressor increases, the compression power and the output of turbine increase. However, with the increasing of discharge pressure of the compressor the energy efficiency increases, and then decreases. When the discharge pressure of the compressor is 14 MPa, the energy efficiency reaches the maximum value of 0.472.

4.3. Influence of different pressures of liquid air in the cryogenic tank

Fig. 3a presents the energy efficiency and power consumed by the cryogenic pump at different pressures of liquid air in the cryogenic tank. As can be seen, when the pressure of liquid air in the cryogenic tank increases, the cryogenic pump power decreases, and the energy efficiency increases. By increasing the pressure of liquid air, a higher efficiency of the system can be obtained.

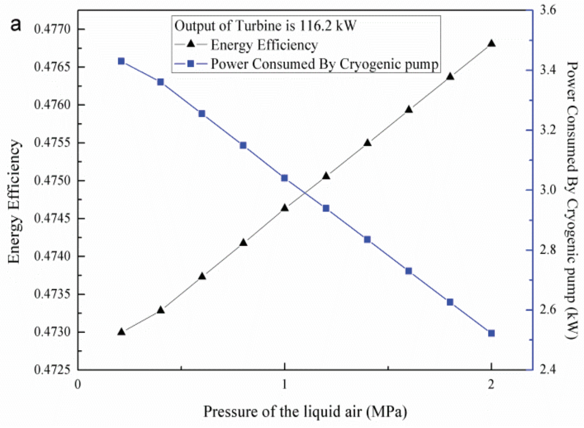

Fig. 3 (a). Influence of different pressures of liquid air on the energy efficiency and power consumed by cryogenic pump.

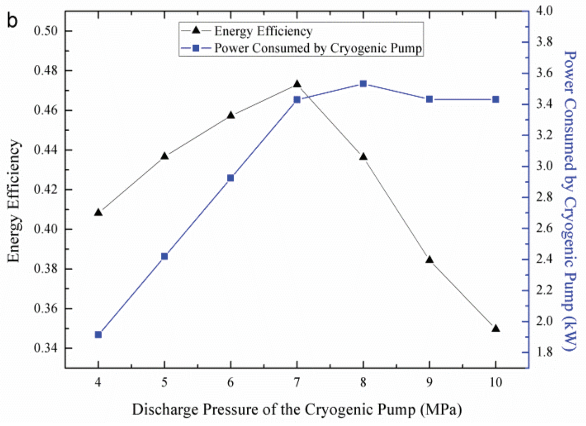

Fig. 3 (b). Influence of discharge pressures of the cryogenic pump on the energy efficiency and power consumed by cryogenic pump.

4.4 Influence of different discharge pressures of the cryogenic pump

Fig. 3b presents the consumed power of the cryogenic pump, output of the turbine and the energy efficiency at different discharge pressure of cryogenic pump. As can be seen, when the discharge pressure of cryogenic pump increases, the pump power, the output of turbine and the energy efficiency first increase and then decrease. When the discharge pressure of the cryogenic pump is 7 MPa, the energy efficiency reaches the maximum value of 0.472.

5. Conclusion

In this paper, thermodynamic analysis is performed to investigate the performance of a novel liquid air energy storage system. The results show that the energy efficiency will be improved with higher adiabatic efficiency of the compressor and a higher pressure of the liquid air. When the adiabatic efficiency of the compressor is 0.9, the discharge pressure of the compressor is 14 MPa, and the liquid air pressure is 7 MPa, the energy efficiency of the system will be 49%. However, LAES is a complicated system, and further studies should be conducted for the further optimization.

Acknowledgements

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References

Technology Perspectives 2008 (IEA, 2008) BLUE Map.
Mclarnon FR, Cairns EJ. Energy storage. Ann Rev Energy 1989;14:241–71.
Haisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan , Yongliang Li, Yulong Ding. Progress in electrical energy storage system: A critical review. Progress in Natural Science 19 (2009) 291–312.
Samir Succar, Robert H. Williams. Compressed Air Energy Storage: Theory, resources, and applications for wind power. Princeton Environmental Institute 2008.