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The application of cryogens in liquid fluid energy storage systems

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Abstract

This article describes the application of cryogens in liquid fluid energy storage systems and compares liquid fluid energy storage systems with conventional compressed air energy storage systems. The study focuses on the thermodynamic characteristics of different cryogens used in liquid fluid energy storage systems. It is found that liquid fluid energy storage systems have competitive factors like high energy density and no geographical limitation. A comparative analysis is conducted to present the advantages and disadvantages of different cryogens. The results show that liquid fluid energy storage systems have a promising future in large scale energy storage.

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Keywords: energy storage systems; liquid fluid; cryogens

1. Introduction

With the rapid development of renewable energy systems, the importance of large scale energy storage systems has been recognized because of its ability to smooth the natural intermittency of renewable energy (e.g. wind or solar). The storage can also move excess off-peak energy to service peak demand and pinch points, enhancing the stability of power grid network. Compressed air energy storage (CAES) systems are widely concerned in recent years due to their characteristics of high-capacity and long-service life for which Huntorf in Germany and McIntosh in USA are representative systems. The geographical limitation is the major barrier to the implementation of CAES

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systems. Containers for storing compressed air, for example can be an underground rock cavern, is an essential component. As a result of this, liquid fluid energy storage systems have been proposed considering the high energy density of cryogens. Highview has built independent liquid fluid energy storage systems (500 kW / 2 MWh) and claimed that the systems efficiency can be 70% integrating with utilization of industrial waste heat. This paper compares liquid fluid energy storage systems with conventional compressed air energy systems and analyses the characteristics of different cryogens.

2. Liquid fluid energy storage systems

The conventional CAES systems decouple the compression and expansion cycles of a gas turbine into two separate processes, and the input energy is stored in form of the elastic potential energy of compressed air. A simplified structure of CAES systems is shown in Fig. 1. In the compression process, electricity is consumed and converted into potential energy by a compressor, and compressed air is stored in an air container. Conversely, the compressed air expands in a gas turbine after combustion with fuel in a combustor and the stored energy is regenerated in the expansion process.

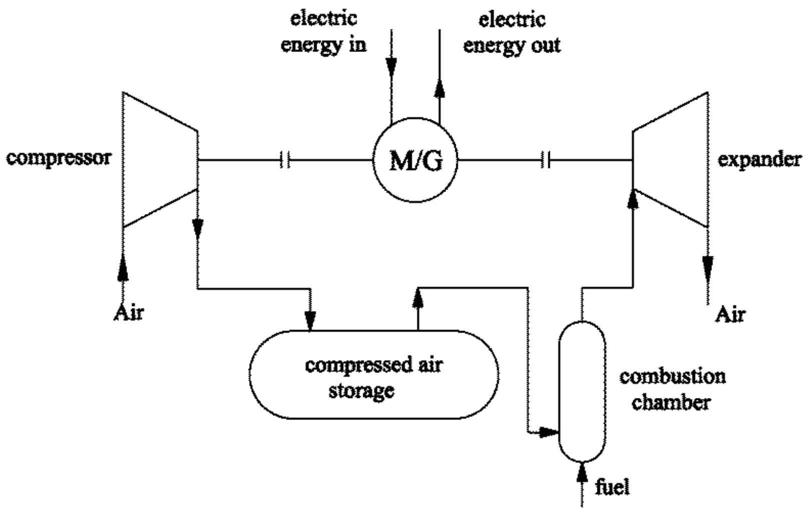

Fig. 1. Simplified structure of CAES systems.

Similar to the CAES systems, liquid fluid energy storage systems are also divided into two processes: liquefaction and expansion. Fig. 2 shows the simplified structure of liquid fluid energy storage systems (take liquid air as an example). In the liquefaction process, systems use off-peak energy or renewable energy to produce liquid cryogens. The liquid cryogens can be stored at atmospheric pressure or at a higher pressure (from 1 to 30 bar) according to the liquefaction cycle. Because of the high energy density, the cryogens need less volume for CAES systems, thus solving the problem of geographical limitation and lower the capital cost. In the expansion process, the cryogens absorb heat and transform to high pressure gas to drive the expander in which the stored energy is regenerated. The thermal energy storage is used to store the expelled heat during compression and to re-heat the air during expansion, thus to avoid carbon emission from the combustion.

Fig. 3 shows the theoretical working cycles of liquid fluid energy storage systems in the temperature-entropy plane (T-S diagram). When the electric power demand is low, the liquefaction processes are: (1) compression process 1-2 in which the air is compressed from the atmosphere pressure with inter-stage cooling simplified to the isothermal compression; (2) cooling process 2-3 with the pressurized air being isobarically cooled in the regenerator; (3) throttling process 3-4 in which the air is liquefied partially with the liquid air being stored and the process 5'-1' in which the cryogenic gaseous air cools the regenerator.

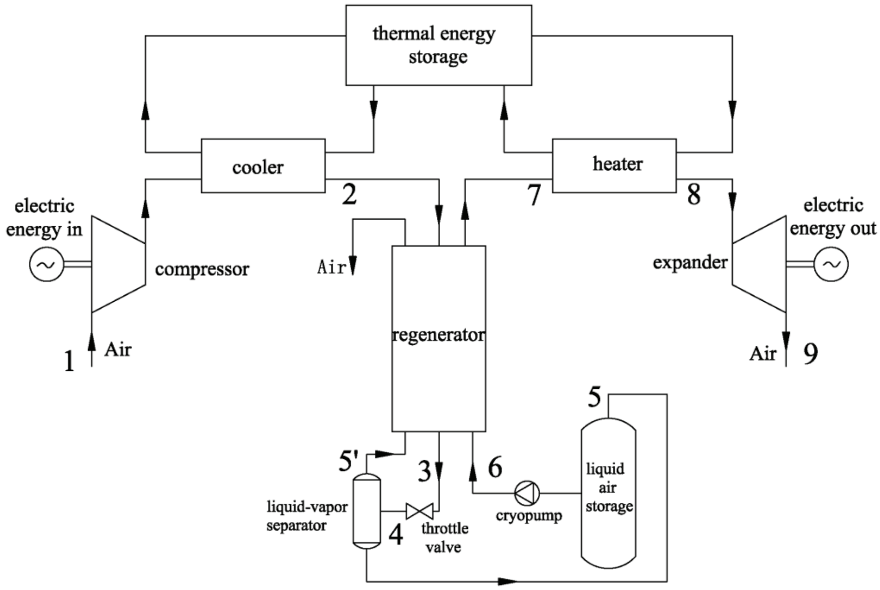

Fig.2. Simplified structure of liquid fluid energy storage systems

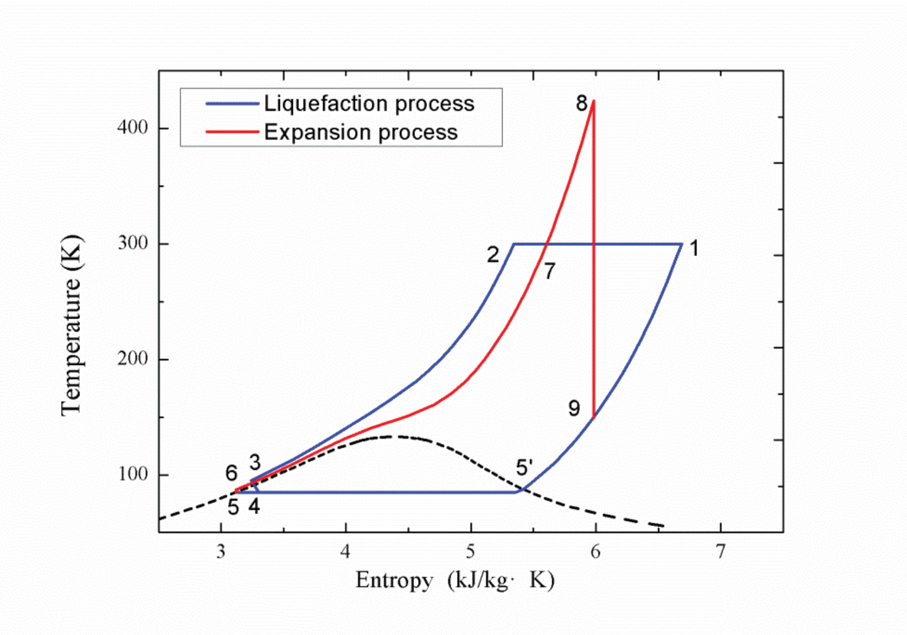

Fig. 3. T-S diagram of the theoretical working cycles.

When electric power is required, the expansion processes are: (1) pumping process 5-6 in which the air is pumped to higher pressure; (2) heating process 6-7-8 with the air being heated in the regenerator 6-7 and further heated 7-8 isobarically in the exchanger; (3) expansion process 8-9 in the expander.

In liquid fluid energy storage systems, the energy density can be defined as the amount of electricity generation per unit volume of fluid. From Fig. 3, we can see that the process 8-9 is the expansion process which generates the electricity, and the energy density can be described as:

$$e = \frac{w_{expansion}}{\rho_{liquid}} = \frac{h_8 - h_9}{\rho_{liquid}}, \quad (1)$$

where $w_{expansion}$ represents the electricity energy generation which is affected by the thermodynamic cycle of the expansion, here the definition is made in Equation (1) to compare the energy density of different fluids at the same expansion process without interstage reheating. In Equation (1), h_8 is mainly affected by the heating temperature T_8 and ρ_{liquid} is affected by the liquid storing state. Considering the easier approach to thermal energy storage, T_8 is 150℃.

Table 1 shows the comparison of CAES systems and liquid fluid energy storage systems. The results show that the density of liquid air at 1bar (saturation state) is 8.5 times higher than the density of compressed air at 100 bar (150℃), and 4.4 times higher than the density of compressed air at 200 bar (150℃), which means the storage volume is 4.4-8.5 times smaller than the compressed air to store the same mass. Liquid air is stored in insulated vessels which are normally used in the global industry and can store very large amounts of energy in the range of 10 MWh-1 GWh. Table 1 also shows that the energy density of liquid air at 1bar (saturation state) is 8.52 times higher than the energy density of compressed air at 100 bar (150℃) and 4.23 times higher than the energy density of compressed air at 200 bar (150℃).

Table. 1. Comparison of CAES and liquid fluid energy storage.

	Density kg/m^3	Energy Density kJ/Litre
Compressed air (100 bar, 150℃)	115.40	34.80
Compressed air (200 bar, 150℃)	221.84	70.07
Liquid air (1 bar， saturation)	983.56	296.6

3. Different cryogens

Table 2 shows the comparison of different cryogens chosen for liquid fluid energy systems. The boiling temperature of liquid air and liquid nitrogen is 81 K and 77 K at atmosphere. In the liquefaction process, the air or nitrogen is pressurized from ambient pressure to 150 bar and then throttled to 1 bar; the liquid fluid is stored low pressure. In the expansion process, the liquid fluid is pumped to 100 bar and heated to 150℃ with thermal energy storage. The energy density of liquid air and liquid nitrogen is 287.1 kJ/L and 255.8 kJ/L. For nitrogen, the energy storage systems should be closed systems.

As the triple point pressure of carbon dioxide (5.2 bar) is higher than the ambient pressure, liquid carbon dioxide can be stored at a pressure above 5.2 bar and the energy storage systems are also working in a closed cycle. The energy density of liquid carbon dioxide (10 bar) is 53.46 kJ/L which is lower than liquid air and liquid nitrogen because of the limitation of the expansion ratio. But carbon dioxide is easier to put into a supercritical state due to its lower critical pressure and temperature (73.8 bar, 31°C). This provides a solution to improve the energy density of carbon dioxide.

Integrating the heat supplement with waste heat utilization can improve the systems performance. The heating temperature T_8 can be further improved by the waste heat utilization. Fig. 4 shows the energy density as a function of heating temperature T_8. It is shown that, for a range of heating temperature T_8 (50-550℃), the energy density of both

Table. 2. Comparison of different cryogens.

	Density kg/m^3	Boiling Temperature ℃	Energy Density kJ/Litre
Liquid air (1bar)	984	-192	296.6
Liquid nitrogen (1bar)	808	-196	255.8
Liquid carbon dioxide (10bar)	1117	-40	53.46

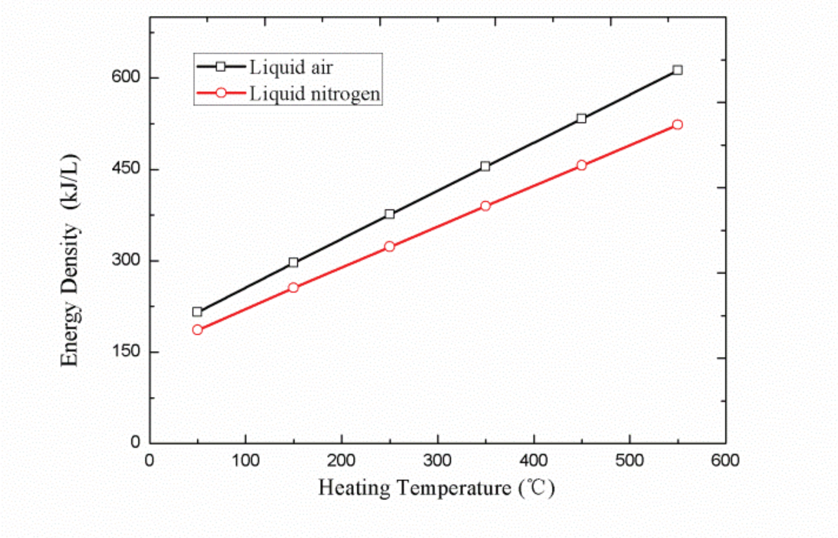

Fig. 4. Energy density as a function of heating temperature.

liquid air and liquid nitrogen increases with increasing heating temperature. This means that integrating heat supplement with waste heat utilization is favourable for liquid fluid energy storage systems.

4. Conclusion

The liquid fluid energy storage systems represent the approach to minimize the geographical limitation for large energy storage systems. The high energy density is a great potential of liquid fluid energy storage systems. Liquid air and liquid nitrogen are suitable liquid fluid energy storage systems. Furthermore, integrating heat supplement with waste heat utilization can improve the energy density.

Acknowledgements

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