

Performance analysis of liquid air energy storage utilizing LNG cold energy

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Abstract. As the high energy density and can be stored in a long period, the liquid air is regarded as the potential energy storage medium. In the liquid air energy storage (LAES) system, liquid air is produced in the liquefaction processes by using the renewable energy or off-peak energy. The compressor is used to supply and recycle the air in liquefaction processes. In this paper, a LAES model is established, and the impact of compressor on LAES system is analysed theoretically. Liquid air energy storage (LAES) system utilizing LNG cold energy is also described. The results show that the round trip energy efficiency is enhanced and the utilizing has promising application prospect for large scale energy storage.

1. Introduction

In the recent years, the renewable energy sources such as wind and solar energy are paid wide attention. However instability is a severe obstacle for renewable energy, which could cause inconvenience for energy utilization. Thus energy storage has been brought to research attention to create flexible energy system with high share of fluctuating renewable energy sources [1-2]. Liquid air energy storage (LAES) system is regarded as the potential energy storage medium as the high energy density and can be stored in a long period. The storage volume of LAES system can be 5-10 times smaller than the compressed air energy storage system [3-5]. The compressor is used to supply and recycle the air in liquefaction processes of LAES system. In this paper, a LAES model with hot storage and cold storage is established, and the impact of compressor on LAES system is analysed theoretically. The outlet air pressure is critical for the cold storage in which the isobaric heat capacity is affected by the air pressure. The influence of outlet pressure on energy storage is investigated.

In this paper, a novel LAES system utilizing LNG cold energy is also analyzed. The novel system combined with LNG cold energy has an improved efficiency compared with the conventional LAES system. Also, the cold energy of LNG can be taken full advantage of. Thermodynamic analysis is conducted to investigate the performance of this system, and the optimization analysis is performed to improve the system efficiency.

2. Compression of LAES

Figure1 presents the design process flow diagram of the typical LAES system. The LAES cycle can be divided into two processes: the liquefaction process and recovery process. In the liquefaction process, the compressor is driven by the motor to compress the air to high pressure. The electrical energy is



consumed and the hot storage is applied to capture the compression air heat. Two stages cooling heat-exchangers are adopted. According to the outlet air temperature of each stage compression, the heat transfer oil is used as the thermal energy storage working medium. In figure 1, the compression is accomplished in two stages and its outlet air pressure is limited to about 8MPa by the outlet air temperature of each compression. More compression stages are needed to achieve higher outlet air pressure. The compressed air is cooled in the cold box by the returning backflow air from the air separator and cold fluids stored in cold storage-1 and cold storage-2. Then the air is liquefied partially in the throttling valve with the liquid air being stored and gaseous air backflow. In this paper, REFPROP 9.0 is used to calculate the fluid properties.

In the recovery process, the liquid air is pumped into high pressure. Then the pumped air is heated in cold storage-1 and cold storage-2 and the cold energy of liquid air is stored in cold storage. The air is expanded through air turbine and heated in two stages heating-exchangers by heat transfer oil. The generator is driven by the air turbine to produce the output electricity energy.

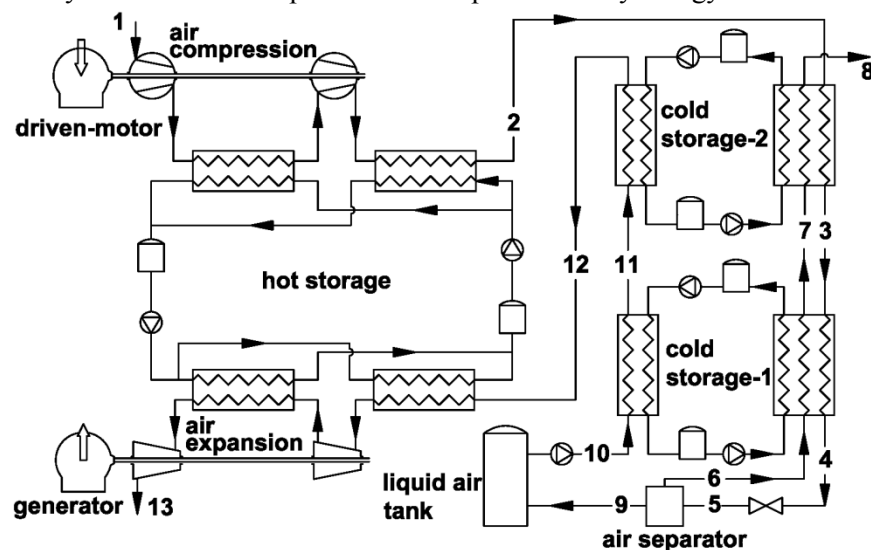


Figure1. Process flow diagram of LAES

The cold storage is the key process in which the compressed air is cooled and the pumped air is heated. Because the liquefaction process and recovery process are not carried out simultaneously, the cold energy storage working medium is needed. The cold liquid fluids are preferred to the solid media such as pebbles or concrete due to the higher heat transfer coefficient of air and fluids [6]. The R123 and propane are taken as the cold fluids in this paper considering the heat capacity and freezing point. Considering the storage conditions, the R123 of which the evaporating temperature higher than the ambient temperature is chosen.

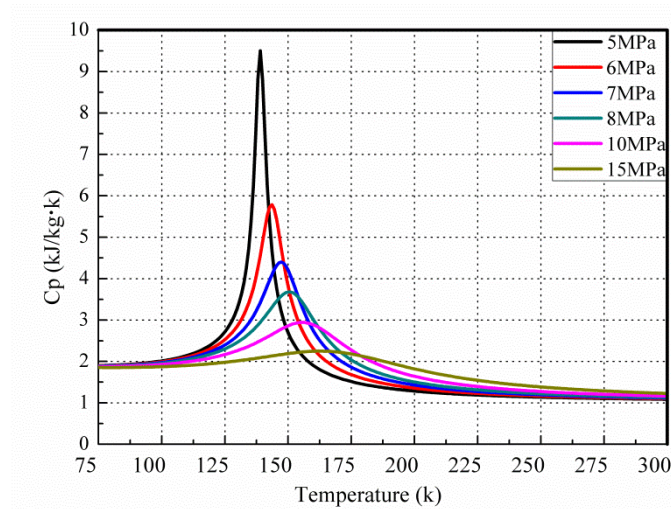


Figure 2. Isobaric heat capacity of air

The figure 2 shows the isobaric heat capacity of air under different air pressure. It can be seen that the isobaric heat capacity of air is a function of temperature at different pressures. The isobaric heat capacity of air exhibits the maximum value near the critical temperature air from 130K-170K. The maximum value of the isobaric heat capacity increases with the air pressure decreases. This will influence the heat-exchange between the compressed air and cold fluids in the cold storage. And the minimum temperature difference will appear at the point of the maximum value of air isobaric heat capacity. The figure 3 shows the design cold storage heat-exchange diagram of LAES under liquefaction air pressures of 7MPa and 11MPa. In figure 3, the minimum temperature difference is 1K. The slope of the air temperature gradients decreases with the liquefaction air pressure increasing from 7MPa to 11MPa. It's beneficial to match the temperature gradients of the air and cold fluids to decrease the minimum temperature difference. The air temperatures after cooling also decreases with the liquefaction air pressure increasing, and this enhance the air liquefaction ratio and more generated energy can be obtained in recovery process. However the increasing of the air liquefaction pressures needs more compression work.

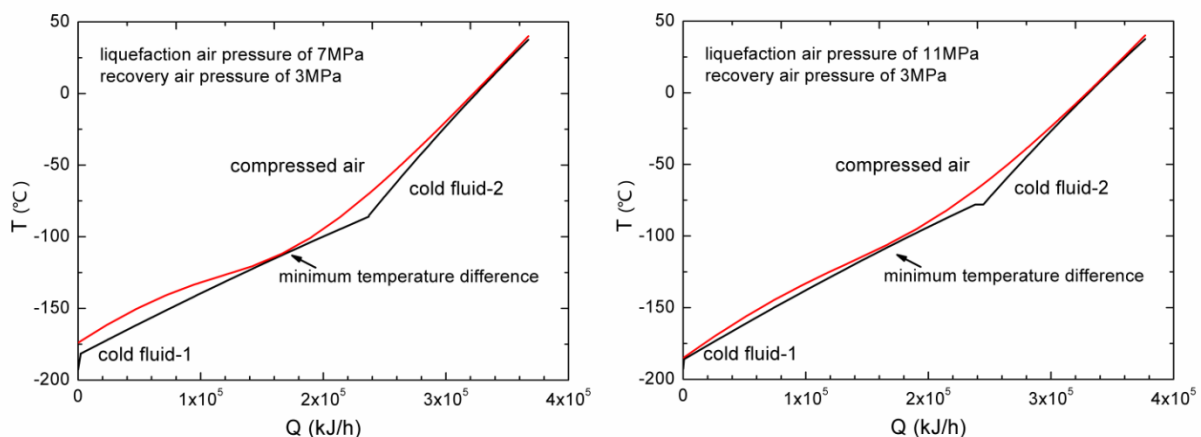


Figure 3. Cold storage heat-exchange diagram of LAES under different liquefaction air pressures

The figure 4 shows the theoretical influence of the liquefaction air pressure on round trip energy efficiency. The results show that each liquefaction air pressure is corresponding to an optimum recovery air pressure. Under the same liquefaction air pressure, the round trip energy efficiency increases with the recovery air pressure increasing at the beginning. And the energy efficiency decreases if the liquefaction air pressure is further increased. The optimum energy efficiency increases with the liquefaction air pressure from 5MPa to 11MPa, and gradually unchanged with the

liquefaction air pressure from 11MPa to 15MPa. The optimum energy efficiency in the range 40-55% can be obtained with reasonable design parameters.

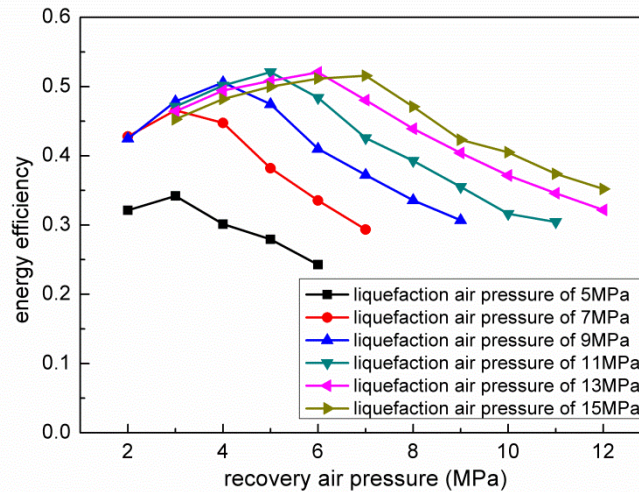


Figure 4. Influence of the liquefaction air pressure on round trip energy efficiency

3. Liquid air energy storage utilizing LNG cold energy

The structure of the LAES utilizing LNG is represented in figure 5. The compression process is same with above. In cooling process, the compressed air is first cooled by LNG cold energy before entering a cold storage. At the same time, the natural gas is heated to air temperature and expanded in NG turbine to recycle the energy. In the recovery process, the liquid air first flow through the cold storage (10-11), then the remaining cold energy is transferred to electric power by generator-2 (11-12) which is driven by the propane turbine. Process 12-13 is similar to the expansion process of conventional LAES system.

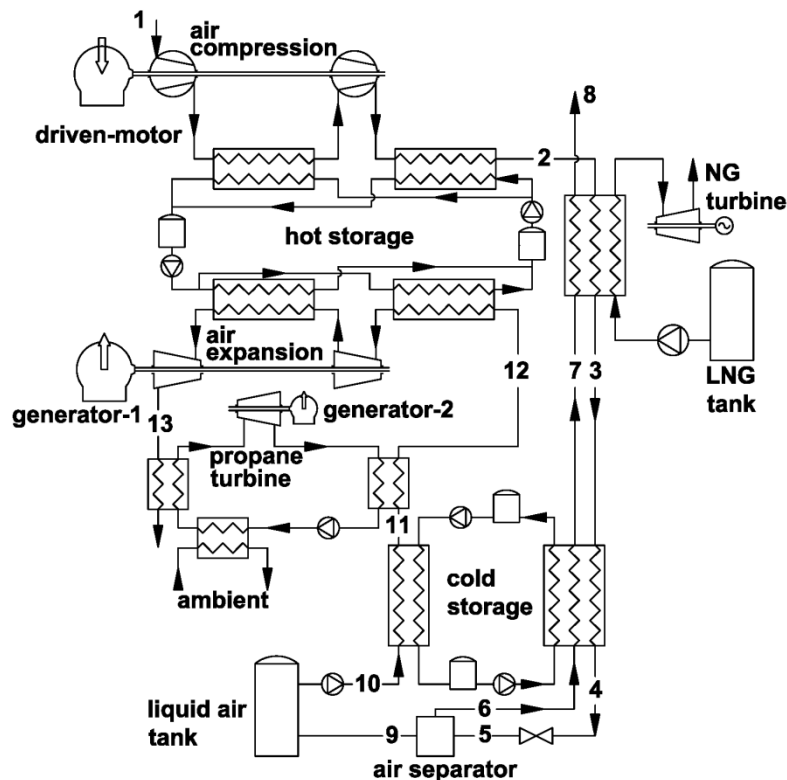


Figure 5. Process flow diagram of the LAES utilizing LNG

The primary design air stream data of the conventional LAES system and the LAES system utilizing LNG are given in Table 1 and Table 2 respectively. The key parameters of the LAES are air pressures both in the liquefaction process and in the recovery process (pressure P_2 and P_{10}). The air isobaric heat capacity is a function of temperature at different pressures which greatly influence the cold storage. Thus the same values of air pressures in the conventional LAES and the LAES utilizing LNG are designed to compare the performance of these two systems.

Table 1. Air stream data of the conventional LAES system

	$q_m/q_{m,1}$	Pressure, MPa	Temperature, K	Density, kg/m ³
1	1	0.1	318.15	1.17
2	1	7	313.15	79.5
3	1	6.98	203.15	143.9
4	1	6.96	99.05	760.0
5	1	0.12	80.35	27.9
6	0.19	0.12	80.35	5.44
7	0.19	0.11	187.15	2.06
8	0.19	0.1	310.55	1.12
9	0.81	0.12	80.35	816.8
10	0.81	3	82.95	814.5
11	0.81	2.98	184.4	63.8
12	0.81	2.96	306.76	34.3
13	0.81	0.12	397.45	0.92

Table 2. Air stream data of the LAES system utilizing LNG

	$q_m/q_{m,1}$	Pressure, MPa	Temperature, K	Density, kg/m ³
1	1	0.1	318.15	1.17
2	1	7	313.15	79.5
3	1	6.98	121.15	656.3
4	1	6.96	87.05	809.1
5	1	0.12	80.35	63.40
6	0.08	0.12	80.35	5.44
7	0.08	0.11	113.15	3.44
8	0.08	0.1	318.15	1.17
9	0.92	0.12	80.35	816.8
10	0.92	3	82.95	814.5
11	0.92	2.98	116.75	637.7
12	0.92	2.96	273.15	38.73
13	0.92	0.12	397.45	0.92

The round trip energy efficiency of the conventional LAES system is

$$\eta_{energy} = \frac{W_e - W_{e,pump}}{W_c + W_{c,pump}} \quad (1)$$

Where the W_e is generated energy, $W_{e,pump}$ is consumed electric energy of pumps in recovery process; W_c is consumed electric energy of compressor, $W_{c,pump}$ is consumed electric energy of pumps in the liquefaction process.

The round trip energy efficiency of the LAES system utilizing LNG is

$$\eta_{energy} = \frac{W_{e,1} + W_{e,2} - W_{e,pump}}{W_c - W_{NG} + W_{c,pump}} \quad (2)$$

Where the $W_{e,1}$ is generated energy of air turbine and $W_{e,2}$ is generated energy of propane turbine, $W_{e,pump}$ is consumed electric energy of pumps in recovery process; W_c is consumed electric energy of compressor, W_{LNG} is generated energy of NG turbine, $W_{c,pump}$ is consumed electric energy of pumps in the liquefaction process.

The results of the calculation are given: the reference configurations are defined by the designed parameters given in Table 1 and Table 2. The optimum liquefaction air pressure is 7MPa and recovery air pressure is 3MPa. The round trip energy efficiency of conventional LAES system and the LAES system utilizing LNG are 46.6% and 60.1% respectively.

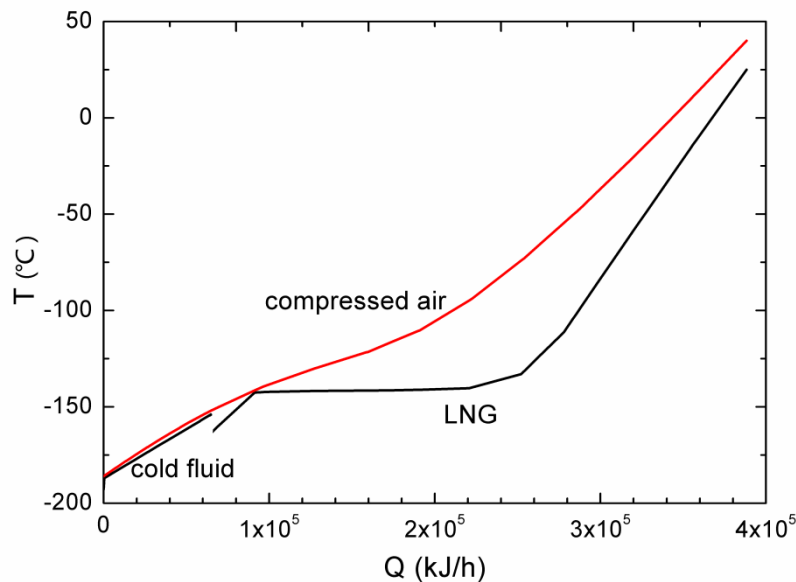


Figure 6. Cold storage heat-exchange diagram of LAES system utilizing LNG

Figure 6 shows the cold storage heat-exchange diagram in the liquefaction process of LAES system utilizing LNG. In the heat-exchange, the minimum temperature difference limits the performance of cold storage and causes inefficient heat-exchanges. The isobaric heat capacity of air is a function of temperature at different pressures and it exhibits the maximum value near the critical temperature. Thus two cold fluids in the conventional LAES system are used to cool the compressed air and match the temperature gradients of the air and cold fluids to decrease the minimum temperature difference. The LAES system utilizing LNG can adopt the latent cold energy from the liquefied natural gas of which the vaporization temperature is near the air critical temperature, and the minimum temperature difference can be reduced. The air temperatures after cooling (temperature T_4) are 99.05K in the conventional LAES system and 87.05K in the LAES system utilizing LNG. Thus the air liquefaction ratio is increased from 0.81 to 0.92, and generated energy of air turbine can be enhanced.

Meanwhile, the propane turbine and generator-2 are employed by using the cold air (11-12) as the cold source and using the hot exhausting air from the air turbine (13) as the heat source. The generated energy of propane accounts for 8% the air turbine. More generated energy can be produced by the propane turbine in the recovery process. In the liquefaction process of LAES system utilizing LNG, the LNG is pumped to the high pressure and the natural gas turbine can also recycle the cold energy of LNG. This generated energy can be used in the air compression process to improve the energy efficiency of the system.

4. Conclusion

In this paper, impact of compressor on the performance of LAES system is analysed theoretically and influence of outlet pressure on energy storage is investigated. The results show that the air liquefaction ratio increases with the liquefaction air pressure increasing due to the fact that it's more beneficial to match the temperature gradients of the air and cold fluids to decrease the minimum temperature difference in the higher liquefaction air pressure. The optimum energy efficiency increases with the

liquefaction air pressure from 5MPa to 11MPa, and gradually unchanged with the liquefaction air pressure from 11MPa to 15MPa. The optimum energy efficiency is in the range 40-55%. It is also important to improve the adiabatic efficiency of the compressor to acquire higher energy efficiency.

The round trip energy efficiency can be improved from 46.6% to 60.1% under the optimum liquefaction air pressure of 7MPa and recovery air pressure of 3MPa. The latent cold energy from LNG can be applied to improve the performance of cold storage heat-exchanges and increase the air liquefaction ratio. More generated energy can be produced by the propane turbine in the recovery process and the cold energy of LNG can be also recycled by the natural gas turbine.

Acknowledgements

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