

Thermodynamic characteristics of liquefaction via air throttling in LCAES

Patrick Samuel Hale^{1, a, *}, Raymond Leo Carter^{2, b}, Noah Owen Anderson^{3, c},

¹Lancaster University, University House, Bailrigg, Lancaster, LA1 4YW, United Kingdom

²Princeton University, 1 Nassau Hall, Princeton, New Jersey, 08544, United States

a.patrick_hale_ph@yahoo.com, b.aymond_carter075@outlook.com, c.noah_anderson_ahw712@outlook.com

***Corresponding Author**

Abstract: As the energy storage and release medium in energy storage systems, the change in physical properties of air exerts a significant impact on system efficiency. This paper first elaborates on the background of energy storage technologies. Furthermore, the thermodynamic performance of the air throttling liquefaction process of the energy storage system is analyzed and investigated through static simulation software Aspen Plus and experiments respectively. The correlation of factors affecting the efficiency of liquid compressed air energy storage systems is explored, and the results of the system thermodynamic modeling analysis are verified.

Keywords: Energy Storage Technology, Thermodynamics, Throttling Liquefaction

1. Introduction

Countries around the world have intensified the development of alternative energy sources such as wind energy, nuclear energy, solar energy and biomass energy [1]. However, practical results show that renewable energy including wind power, hydropower and solar power are intermittent and unstable energy forms with highly random and intermittent energy output. Large-scale integration of such power sources will lead to unstable grid voltage and frequency, drastic peak-valley fluctuations, and a series of problems including degraded power quality of power grids. Meanwhile, massive wind and hydropower curtailment occurs every year, resulting in irreversible waste of resources and economy [2]. Therefore, it is urgent to develop high-efficiency and large-scale energy storage technologies matched with renewable power generation to enhance system stability, improve power quality and raise resource utilization rate, which is critical to solving the consumption challenge of renewable energy. As one of the few technologies applicable to long-duration and high-power station energy storage [3], compressed air energy storage (CAES) can store air via more diverse storage modes compared with pumped hydro storage, featuring less surface land occupation and more flexible construction sites [4]. Nevertheless, the efficiency of compressed air energy storage systems has always been a core research focus. Based on the compressed air energy storage system, this paper investigates the key technologies of the air throttling liquefaction process. Through simulation and experimental analysis, the influencing factors and their correlations affecting the efficiency of liquid compressed air energy storage systems are identified, providing theoretical references for the future design and development of reliable energy storage systems for intermittent renewable energy.

2. Thermodynamic modeling

2.1. Principle of throttling liquefaction process

Schematic diagram of the throttling liquefaction process is shown in Figure 1.

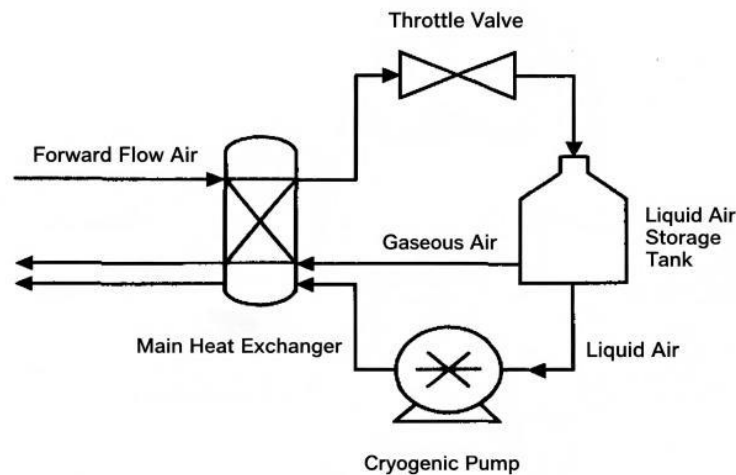


Figure 1 Schematic diagram of throttling liquefaction process

During the energy storage stage, air is compressed to high pressure and medium temperature (cooled by interstage coolers) in the air compression subsystem and then flows into the throttling liquefaction subsystem [5]. The throttling liquefaction subsystem consists of a main heat exchanger, a throttle valve, a liquid air storage tank and a cryogenic pump. In the main heat exchanger, the forward stream air (high-pressure air discharged from the air compression subsystem) absorbs cold energy and is cooled below its critical temperature, while the main heat exchanger absorbs and stores the heat released during air liquefaction. The cooled forward stream air is then depressurized through the throttle valve to realize cryogenic liquefaction. The liquefied liquid air is stored in the liquid air storage tank, and the unliquefied gaseous air is fed into the main heat exchanger to release cold energy.

During the energy release stage, liquid air from the liquid air storage tank is pressurized by the cryogenic pump, absorbs stored heat through the main heat exchanger, and warms up to form medium-temperature and high-pressure compressed air, which then flows into the expander subsystem for expansion and power generation.

2.2. Aspen plus modeling of throttling liquefaction process

The throttling liquefaction section of the energy storage system is modeled using the steady-state process simulation software Aspen Plus, with the basic initial simulation conditions listed as follows [7]:

Air is regarded as a binary mixture of oxygen and nitrogen, and the impacts of impurities, water vapor and CO₂ in air on the system thermodynamic process are ignored.

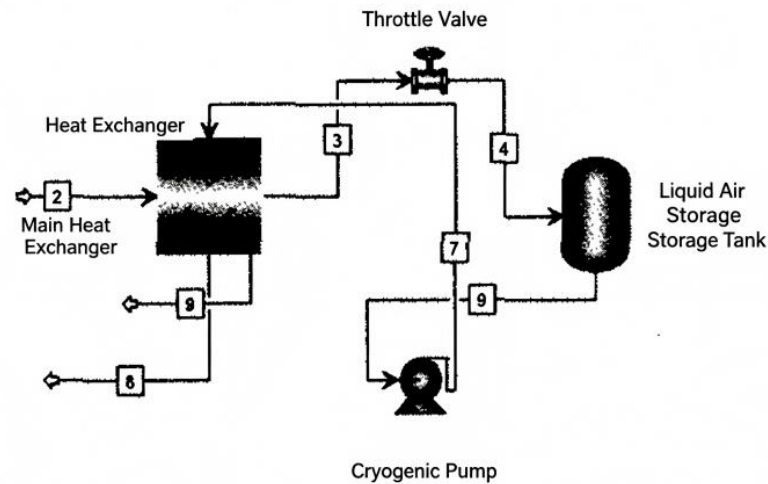


Figure 2 Thermodynamic model of throttling liquefaction process

Heat loss of all equipment in the system is neglected. The multi-stream heat exchanger MheatX model is adopted for heat exchangers of the energy storage system, the Valve model for throttle valves, the Pump model for cryogenic pumps, and the Flash2 two-outlet flash separator for liquid air storage tanks to realize gas-liquid separation. The PENG-ROB physical property method, which is widely applied in air separation systems, is selected for air, and the Mixer model is used for mixing of each material stream [6]. The modeling result is presented in Figure 2.

3. Thermodynamic analysis

3.1. Influence of pre-throttling pressure on liquefaction performance

First, it is assumed that air is throttled to atmospheric pressure to investigate the influence of pre-throttling air pressure on throttling liquefaction performance. Since the thermodynamic properties of air differ significantly around its critical pressure of 3.8 MPa, the liquefaction performance under throttling conditions above the critical pressure (10 MPa) and below the critical pressure (3 MPa) is studied separately.

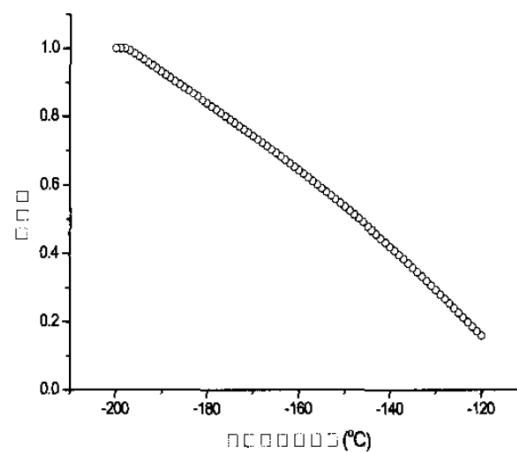


Figure 3 Effects of pre-throttling temperature on liquefaction rate of air at 10 MPa

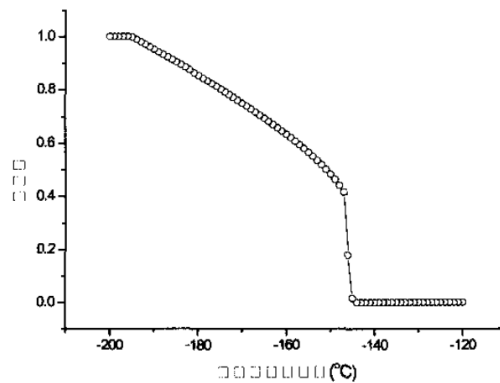


Figure 4 Effects of pre-throttling temperature on liquefaction rate of air at 3 MPa

It can be seen from Figures 3 and 4 that when the pressure is above the critical pressure of 3.8 MPa (10 MPa), the lower the pre-throttling air temperature, the higher the liquefaction rate after throttling. When the pre-throttling air temperature drops to -198°C , the liquefaction rate of air after throttling reaches 1. This indicates that at a fixed pressure, a lower pre-throttling temperature yields better liquefaction performance, and air must be pre-cooled to an extremely low temperature to achieve complete liquefaction. The influence of pre-throttling air temperature on liquefaction for air below the critical pressure is roughly consistent with that above the critical pressure. The distinction lies in that liquefaction only occurs after throttling for air at 3 MPa when the temperature is below approximately -145°C . This -145°C is the liquefaction temperature of air under 3 MPa, meaning air must be cooled to below its liquefaction temperature at subcritical pressure before liquefaction can take place after throttling to atmospheric pressure. It can thus be concluded that the liquefaction rate after throttling rises as the pre-throttling air temperature decreases.

3.2. Influence of pre-throttling temperature on liquefaction performance

First, air is assumed to be throttled to atmospheric pressure to investigate the effect of pre-throttling air temperature on throttling liquefaction performance. The thermodynamic critical temperature of air is -140°C , so the liquefaction characteristics under throttling conditions at subcritical temperature (-150°C) and supercritical temperature (-135°C) are studied separately.

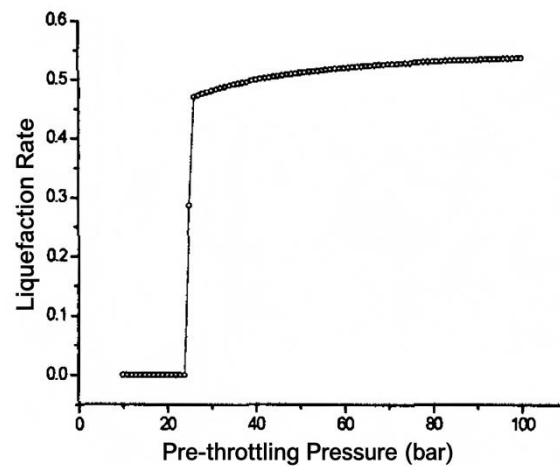


Figure 5 Effects of pre-throttling air pressure on post-throttling liquefaction rate at -150°C

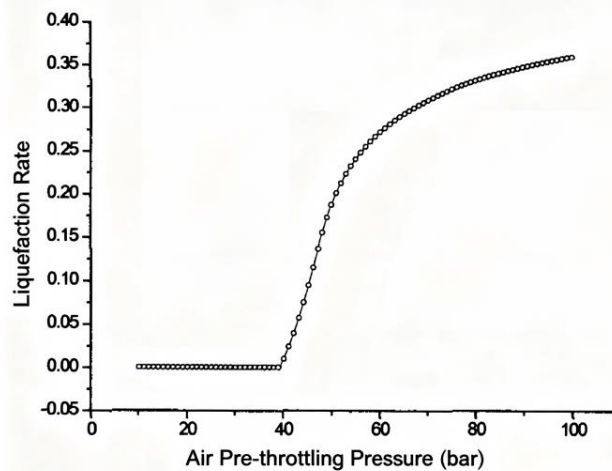


Figure 6 Effects of pre-throttling air pressure on post-throttling liquefaction rate at -135°C

It can be observed from Figures 5 and 6 that at the same initial air temperature, the liquefaction rate after throttling rises with the increase of pre-throttling pressure. Air at -150°C can only be liquefied after throttling when the pressure exceeds 2.5 MPa, which is verified as the saturated vapor pressure of air at -150°C . Therefore, air below its critical temperature must be pressurized above the corresponding saturated vapor pressure to achieve liquefaction after throttling. For air at -135°C , pressurization to nearly 4 MPa is required for liquefaction. It is concluded that air has to be pressurized at least above its corresponding saturated vapor pressure to realize liquefaction after throttling to atmospheric pressure.

Based on the above model analysis of the throttling liquefaction process, it is concluded that the pre-throttling pressure of the throttling liquefaction system should exceed the critical pressure of 3.8 MPa. Given a fixed throttling pressure, a lower pre-throttling temperature contributes to better liquefaction performance [8], and the liquefaction rate reaches 1 when the pre-throttling air temperature drops to -198°C . When air is throttled to atmospheric pressure, air below its critical temperature must be cooled below its liquefaction temperature. Therefore, lower pre-throttling temperature and higher pre-throttling pressure are beneficial for improving the air liquefaction rate.

4. Experimental scheme

To verify the conclusions drawn from thermodynamic modeling, experimental research on the air throttling liquefaction process of the liquid compressed air energy storage system is carried out in this section. Liquid nitrogen is adopted as the cold source of the system in this experiment to investigate the liquefaction behavior during air cooling and throttling. The effects of parameters such as pressure and temperature on air liquefaction are analyzed to identify the key parameters governing air liquefaction and explore the correlation among factors that affect the efficiency of liquid compressed air energy storage systems.

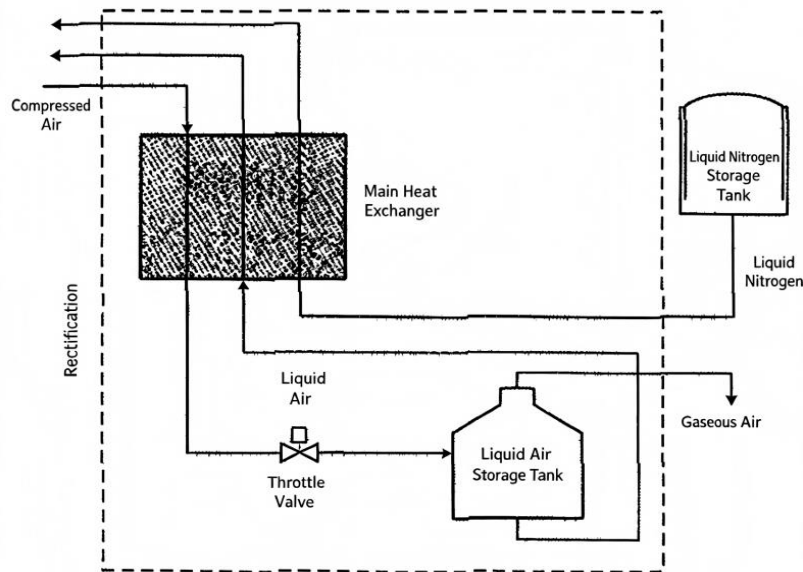


Figure 7 Schematic diagram of experimental apparatus for air throttling liquefaction process

A complete liquid air energy storage system mainly consists of air compression unit, throttling liquefaction unit, expansion power generation unit, waste heat recovery unit and other core units. Considering the large floor area of air compressors, expanders and other equipment, the experimental setup properly simplifies and simulates the liquid compressed air energy storage system. The air compression unit is used to compress air into high-pressure state and cool it to near ambient temperature via interstage coolers. Therefore, bundled compressed air cylinders (16-cylinder bundle) are adopted to replace the air compressor in this experimental setup. Since the air at the outlet of the air compression unit is high-pressure and ambient-temperature, it is reasonable and feasible to substitute the air compression unit with compressed air cylinders and adjust air pressure by regulating the opening of cylinder outlets. Meanwhile, the energy consumed to compress air to the inlet state can be calculated by measuring the inlet state parameters (temperature, pressure, etc.) of compressed air. By measuring the outlet state parameters (temperature, pressure, etc.) of air from the liquid compressed air energy storage experimental device, the energy released when the outlet air expands to atmospheric pressure in the expander can be calculated via thermodynamic methods. The efficiency and other parameters of the liquid compressed air energy storage system can be obtained by comparing compression power consumption and expansion output power, which helps screen appropriate system parameters and optimize the liquid compressed air energy storage system.

The temperature and pressure at each state point are measured by pressure gauges and thermocouples, and the inlet and outlet flow rates of the system are detected by flowmeters. Pressure values are read from pressure gauges, while temperature values are displayed on digital indicators. The main components, including the main heat exchanger, throttle valve and cryogenic liquid air storage tank, are all enclosed inside a cold box filled with perlite for thermal insulation.

5. Experimental results and analysis

5.1. Relationship between liquefaction rate, temperature and pressure

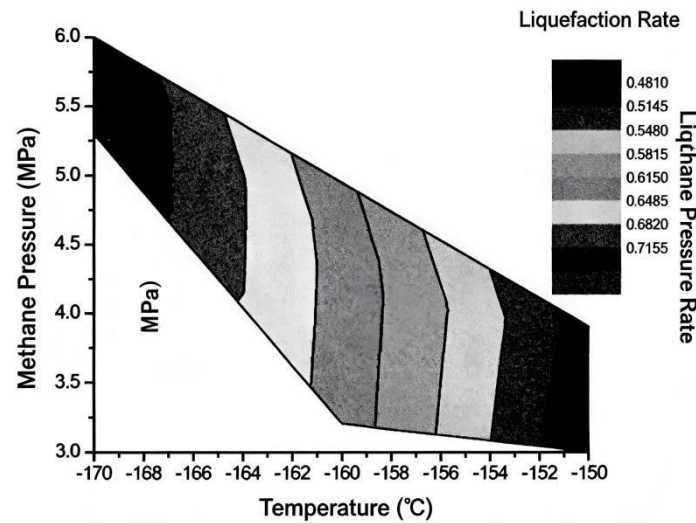


Figure 8 Effects of temperature and pressure on liquefaction rate after throttling to atmospheric pressure

As shown in Figure 8, when air is throttled to atmospheric pressure, the liquefaction rate after throttling rises with lower pre-throttling temperature and higher pre-throttling pressure [9].

5.2. Loss and efficiency analysis of experimental device

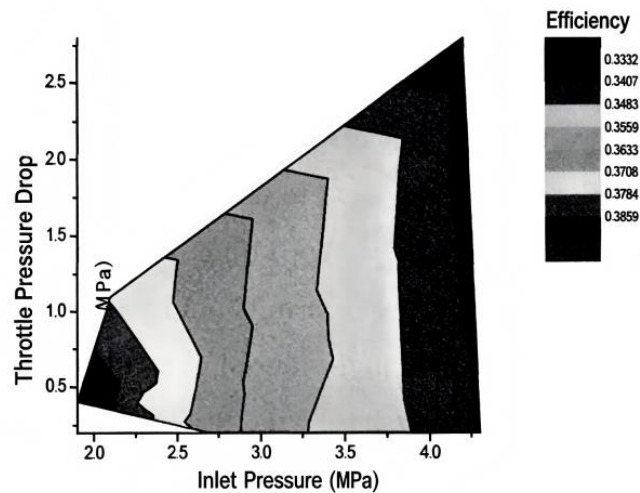


Figure 9 Variation of system efficiency with inlet pressure and throttling pressure drop

As shown in Figure 9, under sufficient cold energy supply, the efficiency of the liquid compressed air energy storage system decreases with the increase of inlet pressure and throttling pressure drop. The variation trend is consistent with the thermodynamic analysis and experimental conclusions presented in the previous section.

The efficiency of the liquid compressed air energy storage system is calculated based on experimental results, and the losses of each component are listed in Table 1[11].

Table 1 Efficiency and loss analysis of energy storage system

Power	Proportion of Loss to Total Loss	
Compression Power Consumption (kW)	2.3	/
Expansion Output Power (kW)	0.83	/
Compression Section Loss (kW)	0.12	8.2%
Expansion Section Loss (kW)	0.04	2.7%
Throttling Liquefaction Loss (kW)	0.3	20.45
Enthalpy Increase of Heat Exchange Medium and Air (kW)	1.01	68.7%
Total Loss (kW)	1.47	100%
Efficiency	36.1%	

6. Conclusion

In summary, thermodynamic steady-state simulation and experimental research demonstrate that lower pre-throttling temperature and higher pre-throttling pressure lead to a higher liquefaction rate after throttling. With sufficient cold energy, higher pre-throttling pressure and larger throttling pressure drop can achieve a greater liquefaction rate, whereas lower pre-throttling pressure and smaller pressure drop contribute to improved system efficiency [10]. 68.7% of the total loss in the experimental system originates from the enthalpy increment of the heat exchange medium and air. Maximized recovery of heat carried away by the heat exchange medium and supply of external heat sources will serve as effective approaches to enhance the efficiency of the energy storage system.

7. References

- [1] Xu Luming. Global Installed Wind Power Capacity in 2015: China Makes the Largest Contribution[J]. Construction Machinery, 2016: 3-14
- [2] Zhang Weidong. Analysis on Causes and Countermeasures of Wind Curtailment in China[J]. China Energy News, 2016(02): 26-29
- [3] Yang Jiefeng, Yang Rongsong. Further Discussion on Construction of Medium-sized Hydropower Stations in Yunnan Province[J]. Yunnan Water Power, 2002, 18(3): 9-11
- [4] Liquid Air Technologies. A Guide to the Potential[D]. 2013: 9-11
- [5] Li Zhixin, Jia Jincai, Zhang Shoukun. Application of Aspen Plus Process Simulation Software in Air Separation Equipment Design[J]. Cryogenic Technology, 1999(03): 25-27
- [6] Guo Huan. Research on Performance of Novel Compressed Air Energy Storage System[D]. 2013: 47-52
- [7] Li Zhixin, Jia Jincai, Zhang Shoukun. Application of Aspen Plus Process Simulation Software in Air Separation Equipment Design[J]. Cryogenic Technology, 1999(03): 25-27
- [8] Zhang Xinjing. Research on Several Problems of Compressed Air Energy Storage System[D]. 2011: 27-32
- [9] Wang Yalin, Chen Guangming, Wang Qin. Performance Analysis of Compressed Air Energy Storage System Applied to Cryogenic Refrigeration[J]. Journal of Engineering for Thermal Energy and Power, 2008, 29(12): 1998-2002
- [10] Research on Thermal Performance Simulation of Advanced Compressed Air Energy Storage System[D]. 2015: 03
- [11] Research on Thermal Performance Simulation of Advanced Compressed Air Energy Storage System[D]. 2015: 03