

Selection of the optimal air liquefaction cycle for liquid air energy storage

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ABSTRACT

The report analyzes and selects the liquefaction cycle for Liquid Air Energy Storage. The specific liquefaction coefficient and the coefficient of thermodynamic perfection were calculated for the following cycles: the Linde-Hampson cycle, the Claude cycle, the Heylandt Cycle, the Collins cycle, and the cycle with two expanders. The criterion for optimizing cycles is the maximum value of the liquefaction coefficient. The Claude cycle was chosen as the optimal cycle for use in the Liquid Air Energy Storage. Its exergy efficiency was calculated.

Keywords: Liquid Air Energy Storage, air liquefaction cycle, exergy analysis.

INTRODUCTION

One of the promising methods of energy storage is a liquid air-based energy storage unit (LAEU). The operation principle of such storage is quite simple. It consists of an air purification system, an air liquefaction system, liquid storage tanks, and an electricity generation system. The operating concept is based on the following processes: air liquefaction during off-hours, storage, electricity generation during peak hours by driving the turbines with warmed air.

Thus, the air liquefaction process is one of the key processes in this system, and the overall electrical efficiency coefficient of the unit depends on the proper selection of liquefaction parameters [1].

Air liquefaction cycles

Liquefaction is a refrigeration process followed by a gas-liquid phase change. The industrial production of liquid nitrogen began in Europe in 1902 with the help of scientists such as Willian Hampson, Carl Linde, Georges Claude, and Charles Trifler [2]. Linde patented his cycle in 1903, the cycle is considered the simplest among gas liquefaction cycles, but not the most convenient because it involves high pressures (20 MPa required on a high-pressure line), (Figure 1).

Additionally, this cycle gives a low relative speed of liquid production. The fraction of the liquefied gas fraction of the Linde-Hampson cycle can be determined by the formula:

$$X_f = \frac{h_1 - h_2}{h_1 - h_f} \quad (1)$$

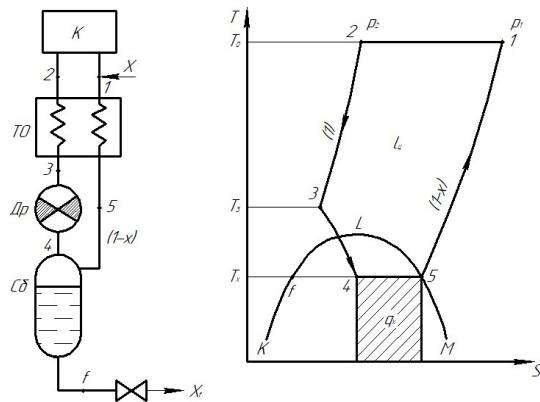


Figure 1. Linde-Hampson cycle

Aiming to develop a cycle with lower operating pressure, Claude suggested a solution with two expansion mechanisms, throttling (Joule-Thompson effect) and expander, which is located along the bypass, after the first heat exchanger (Figure 2). The fraction of the liquefied petroleum gas to be withdrawn for Claude's cycle is determined by the formula:

$$X_f = \frac{h_1 - h_2}{h_1 - h_f} + D \frac{h_6 - h_3}{h_1 - h_f} \quad (2)$$

Considering the exit pressure of the compressor equal to 4 MPa, D=80% (selected randomly), it is possible to determine the fraction of liquefied gas, which is 14,5%.

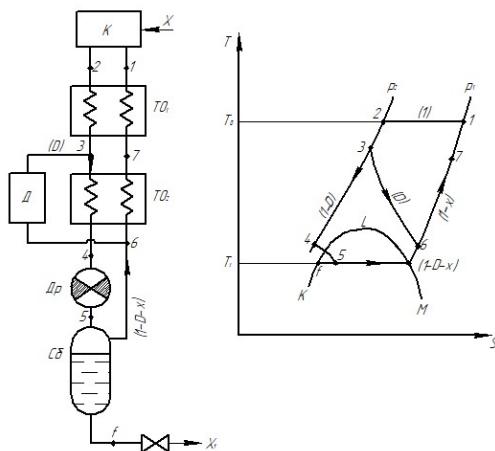


Figure 2. Clod cycle

For the same difference ($i1-if$) the Linde-Hampson system operating at a higher pressure (20 MPa) produces 7% liquefied air. Assuming that at such cryogenic temperatures the processes are only close to adiabatic, and suggesting that the real efficiency of the heat exchanger is about 80 percent, the fraction of

liquid production for the Claude system decreases to 7.1 percent. This value can be improved by using the Collins cycle, which uses the same concept as Claude but uses a larger number of expanders included in parallel. For this case, the fraction of the liquefied gas discharged is determined by the formula:

$$X_f = \frac{h_1 - h_2}{h_1 - h_f} + \sum_i D_i \frac{\Delta h_i}{h_1 - h_f} \quad (3)$$

where i is the number of expanders in a cycle,
 Δh_i is the work obtained from the i -th turbine.

If $i=1$, the Collins system will have the same configuration as the Claude cycle, and if $D=0$ (detanders are not considered), the Claude system will be converted to the Linde-Hampson system. Using the Collins cycle, the pressure may be even lower than for the Claude cycle, and fluid production may be higher.

The following cycles were considered in the Hysys program: the Linde-Hampson cycle, the Gayland cycle, the Collins cycle, the Claude cycle, and the VD cycle with 2 expanders [3]. The criterion for optimizing the cycles is the maximum value of the recovery factor [4]. The results of the calculations are presented in Table 1, and their schemes in the Hysys program are also presented in Annex A.

The Linde-Hempson cycle has very low performance in terms of product recovery and therefore cannot be used in a cryogenic battery system. The Heylandt and Claude cycles are close in performance and both have a relatively simple structure and a high coefficient of thermodynamic perfection. The Collins cycle requires careful selection of the mass fraction of the gas released for expanding for each cooling stage. The cycle with two expanders (4MPa) has the highest recovery factor for these conditions.

Title	x	$l_0, \text{kJ/kg}$	ϵ	η_t
Linde-Hempson Cycle (20MPa)	0.07	19371	0.03	0.052
Heylandt Cycle (10MPa)	0.16	6118	0.101	0.177
Collins Cycle (4MPa)	0.145	4662	0.092	0.16
Claude Cycle (4MPa)	0.145	4586	0.104	0.182
Cycle with 2 expanders (4 MPa)	0.175	3750	0.166	0.29

Table 1. Characteristics of cycles

Let us consider how the characteristics of a cycle with two expanders change when the discharge pressure changes (Figure 3).



Figure 3. Dependence of the fraction of the liquefied gas discharged from the degree of compression in the compressor at a constant suction pressure of 1 bar

The fraction of the liquefied gas discharged depends directly on the degree of compression in the compressor; the specific operation is virtually unchanged. As the compressor's compression ratio increases, the proportion of gas withdrawn for expanding increases (Figure 4).

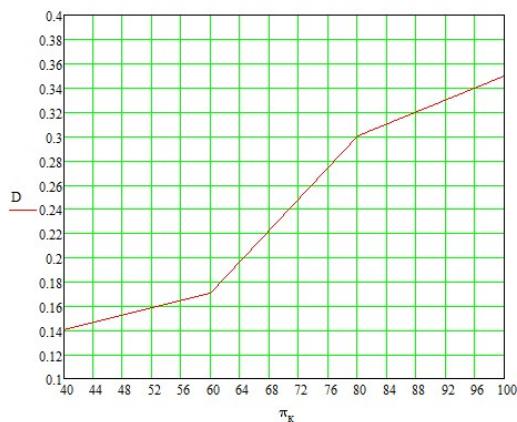


Figure 4. Dependence of gas fraction, taken for expanding, from the degree of compression in the compressor at a constant suction pressure of 1 bar

Based on the technical and economic conditions determined by the need to have backup power in the system at the shutdown of the most powerful unit, the Claude cycle was chosen as the air liquefaction cycle of the unit (Figure 5). Its relatively simple structure makes it possible not to use a large number of complex and expensive equipment. The exergy analysis of the cycle was carried out

according to the work of Brodiansky [5]. Calculation and optimization of the cycle were carried out according to training manual [6,7].

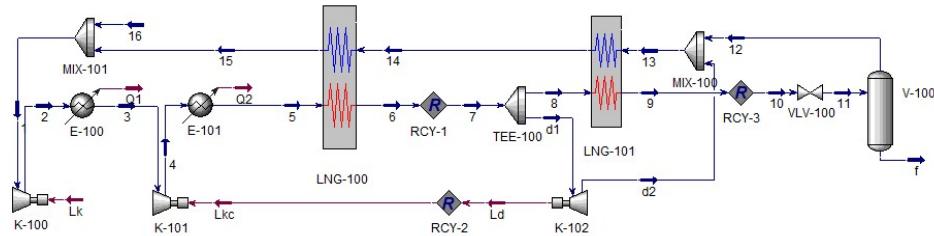


Figure 5. Cycle diagram in HYSYS V8.0

The fraction of the liquid passing through the expander is 0.74 of the total flow. During the exergy analysis, specific exergy losses in each element were calculated:

$$\Delta e_k = \frac{\Delta e_k^d - \Delta e_k^t}{x}, \quad (4)$$

where Δe_k^d is the actual change of exergy in that element,
 Δe_k^t is the theoretical change of the exergy in the k-element,
 x is the liquefaction index.

And also the exergy efficiency of the element:

$$\varepsilon_k = 1 - \frac{\Delta e_k}{\Delta e_k^d} \quad (5)$$

Let us consider the electricity production system (Figure 6) [8]. The production capacity is 1000 kW. For this purpose, the pump needs to pump 14250 kg/h.

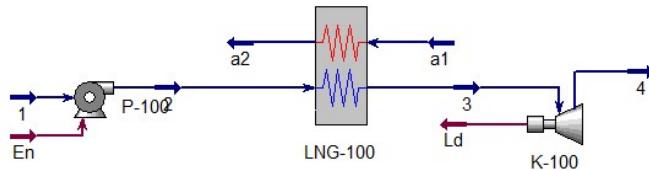


Figure 6. Electricity generation scheme in HYSYS V8.0

The operating time of the unit is 8 hours. In 1 hour unit produces 15680 kg of liquid air, $G = 15680 \text{ kg/h}$. The temperature of the environment will take 300 K. Let us calculate an approximate value of energy produced by liquid air during the expansion [9].

In an adiabatic process, the work l , performed by the ideal gas during expansion into the atmosphere is determined by the formula:

$$l = \frac{\vartheta R T}{\gamma - 1} \left[1 - \left(\frac{V_2}{V_1} \right)^{\gamma-1} \right], \quad (6)$$

where ϑ is the number of moles,
 γ is the adiabatic exponent,
 R is a universal gas constant,
 T is the absolute temperature,
 V_1 is the initial gas volume,
 V_2 is the final gas volume.

The system produces:

$$l = \frac{-540\,690 \cdot 8,31 \cdot 300}{1,4 - 1} \cdot [1 - (700)^{1,4-1}] \sim 42\,940 \text{ MJ} \sim \\ \sim 11\,930 \text{ kW} \cdot \text{hour per cycle.}$$

Table 2 shows the exergy losses and exergy efficiency for each element of the cryogenic energy storage system.

Exergy analysis of LAEU		
Element	Exergy Loss, MW	Exergic efficiency, %
Compressor	5.96	56
TO 1	0.59	57.6
Turboexpander	1.83	60
TO 2	3.16	90.3
Throttle	0.18	5.2
TO	1.68	73.6
Turbine	1.53	34.6
Energy output	11.1	18
Power generation system		
Pump	0.016	57
Heat exchanger	0.793	35.8
Turbine	0.529	65.4

Table 2. Exergy losses in systems

The most vulnerable elements are turboexpander, compressor, and throttle. However, the exergy efficiency of the compressor is quite high. Despite the high

absolute values of irreversibility in the component, this component is quite perfect from the thermodynamic point of view, and the reason for the high value of the exergy losses can be large mass flow of the working substance. The compressor, turbine, and turbo expander in the plant should be improved.

CONCLUSION

The analysis of cryogenic cycles has shown that the most optimal cycle for use in the liquid air energy storage is the Claude cycle (with the possibility of pre-cooling). The exergy efficiency of the cycle relative to the product is 18%, and the liquefaction rate is 0.22.

DESIGNATIONS

LAEU	liquid air-based energy storage unit	R	universal gas constant (8.31447 J×mol ⁻¹ ×K ⁻¹)
X_f	liquefaction rate	γ	adiabatic exponent
h	enthalpy (J)	D	liquid percentage in the detander
l_0	per-unit work (J×kg ⁻¹)	η_t	thermodynamic perfection rate
ε	refrigeration index	ε_k	exergic efficiency
g	number of mols	Δe	change of exergy (J)
T	temperature (K)	V	volume (m ³)

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