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THERMODYNAMIC PERFORMANCE ANALYSIS AND OPTIMIZATION OF LIQUID AIR ENERGY STORAGE SYSTEM BY ENUMERATION

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ABSTRACT

Liquid air energy storage system using Kapitza cycle is thermodynamically optimized with selected critical process variables by partial enumeration. With this method, the contour maps for the independent variables are illustrated, that give intuition to the behavior of the LAES systems. The Interaction between the variables can be found and thermodynamically analyzed. The optimized thermodynamic efficiency 40.0%, 48.8%, and 51.2% when compression pressure is set at 40 bar, 80 bar, and 120 bar, respectively.

Keywords: Energy storage systems, Cryogenic energy storage, Efficiency optimization, Thermodynamic analysis, Kapitza liquefaction cycle.

NONMENCLATURE

Abbreviations	
PHES	Pumped hydroelectric energy storage
CAES	Compressed Air Energy Storage
LAES	Liquid Air Energy Storage
Symbols	
ΔT_{min}	Minimum approach temperature
P_c	Charge pressure
P_{dis}	Discharge pressure
γ	Split ratio
T_{sp}	Split temperature
ΔT	End pinch temperature difference
η	Overall efficiency

1. INTRODUCTION

Liquid air energy storage (LAES, also called cryogenic energy storage) has several advantages: No geographical limitations, good economic feasibility for the large energy storage systems. However, it has low round-trip efficiency compared to the conventional PHES (Pumped Hydroelectric energy storage) and CAES (Compressed Air Energy Storage) [1].

Many efforts have been made to improve the efficiency of LAES systems through many methods, such as heat integration with other thermal system, adding an additional organic Rankine cycle, and using gas or fuel combustion [2-3]. Many studies improved the stand-alone LAES (without any thermal integration) with various liquefaction processes by sensitivity analysis [4]. These results are not sufficient to give the optimal values for LAES, and make it difficult to find which liquefaction cycle is the most beneficial. The optimization controlling all the variables has not been conducted.

The objective of this research is to find the optimal efficiency and conditions of important independent variables for Kapitza liquefaction cycle as a case study. The variables determine the overall thermodynamic performance in liquid air energy storage systems. These variables are investigated by partial enumeration that results optimal thermodynamic performance. The interaction of each variable is thermodynamically analyzed. The performance maps with the variables are to be illustrated.

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2. OPTIMZATION WITH PARTIAL ENUMERATION

2.1 Process simulation

The thermodynamic is modelled with commercial simulation tool, Aspen HYSYS v. 11. Peng-Robinson equation of states is adopted for the simulation. The detailed conditions for the simulations are listed in Table 1. Figure 1 shows the process flow diagram of LAES systems using Kapitza liquefaction cycle.

Table 1 Detailed information for simulation conditions

Simulation conditions	**Values**
Inlet air composition, pressure, and temperature	Ambient
Inlet TES composition, pressure, and temperature	Thermal oil, Pentane, Propane
L_{Air} storage pressure	2 bar
Pressure after expander	2 bar
Recycled air pressure	1.013 bar
Exhausted air pressure	1.013 bar
$T_{2c} = T_{6c}$	-
Compression/Expansion ratio is equal at each stage	-
ΔT_{min}	3 ^{o}C (5 ^{o}C for intercoolers)

2.2 Theoretical background and methodology

2.2.1 Independent variables selection

In the process simulation, independent variables should be carefully selected. The number of independent variables can be obtained by calculating the number of variables, equations, and simulation conditions. Liquid air energy storage system using Kapitza cycle has 38 streams and 28 streams for air and thermal energy storage medium, respectively. The equipment is modelled with several equations such as mass conservation, energy conservation, and phase equilibrium. With the degrees of freedom analysis, the number of independent variables is five for LAES using Kapitza liquefaction cycle. The independent variables are set as the charge pressure, discharge pressure, split ratio, split temperature, and the temperature difference between stream 13 and stream 6c. Table 2 presents the descriptions of independent variables. Table 3 shows the investigation ranges for the variables.

Table 2 Descriptions for selected independent variables

Variables	**Descriptions**
P_c	Charge pressure (Pressure at 11)
P_{dis}	Discharge pressure (Pressure at 26)
γ	Split ratio (Mass flow ratio at 22)
T_{sp}	Split temperature (Temperature at 2c)
ΔT	Temperature difference between 13 and 6c

Table 3 Investigation ranges for variables

Variables	**Values**	**Step size**
P_c (bar)	40, 80, 120	40
P_d (bar)	80 - 140	10
γ	0.11 – 0.67*	0.01
T_{sp} (^{o}C)	-133 - -76*	1.0
ΔT (^{o}C)	6 - 15	0.1

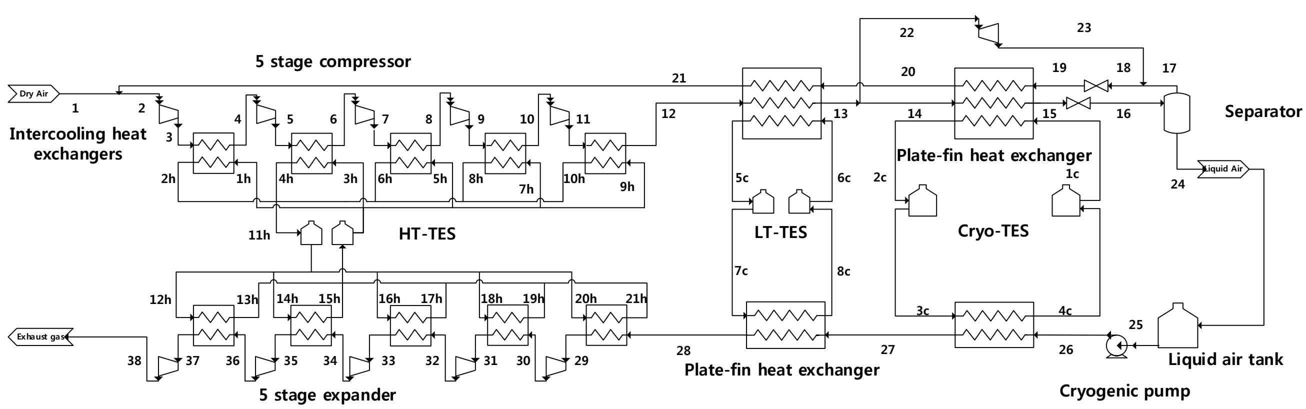

Fig 1 Process flow diagram of LAES with modified Kapitza cycle

2.3 Results and discussion

Figure 2 illustrate the performance contour maps between RTE, charge pressure P_c, discharge pressure P_d, split ratio γ, and split temperature T_{sp}. These graphs in the first, second, and third row are illustrated when P_c is set at 40 bar, 80 bar, and 120 bar, respectively. The contour graphs in each row share the same visual legend. These illustrations contain extensive data and should be analyzed carefully and deliberately.

The variable ΔT is omitted and automatically set as an optimal value in the figures for visibility. Likely, the independent variables that are not shown in the graph are necessarily set as optimized value to present optimal efficiency at a point. For example, for the contour graph, T_{sp}, and ΔT are set as the optimal value in the P_d to γ graphs, and P_d and ΔT are set as the optimal value in the γ to T_{sp} graphs. The white area in the contour map represents no value and this is resulted by the simulation conditions of minimum

In Figure 2, the peaks of the contours are found. There are some remarkable points: First, the peaks in all the P_d to γ graphs go right upward. The larger the P_d is, the smaller recovered cold energy is. The larger γ compensate the reduced cold energy by providing the additional expansion. Second, the optimized efficiencies do not change much in the same P_c. This is because the other independent variables compensate with the optimized values. The higher the P_c is, the more insensitive the optimized efficiency is. The efficiency differences depending on all the variables (without P_c) are small (less than 1-2%). Lastly, T_{sp} is not significantly dependent on γ and P_d.

Figure 3 shows optimized variables and efficiencies depend on the charge pressure P_c. Discharge pressure P_d is not largely changes with P_c. However, the split ratio γ increases with P_c. As P_c increases, the heat composite curve of the compressed air is linearized in the heat exchange process. The temperature difference in the heat exchanger is much smaller at a higher P_c. The

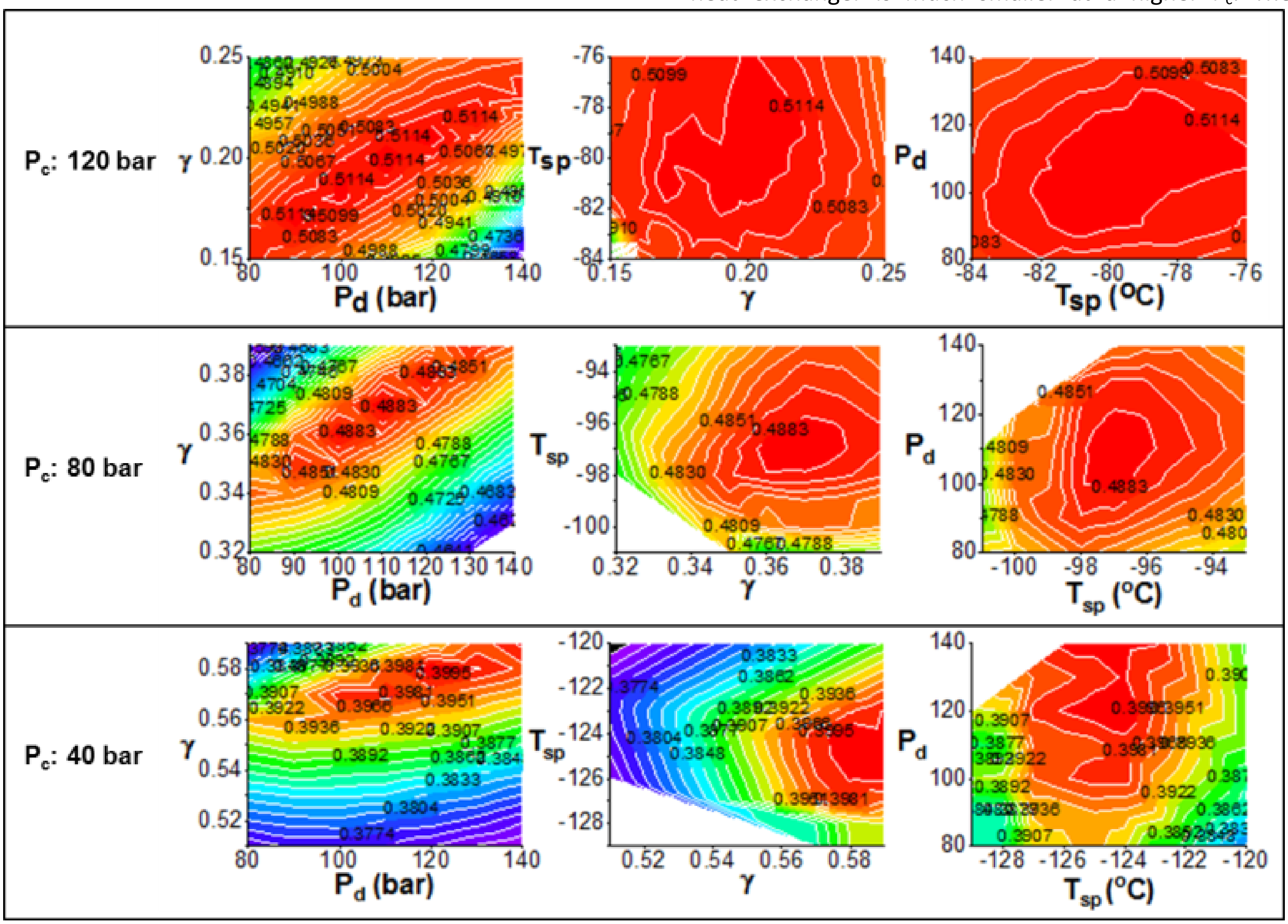

Fig 2 Overall efficiency versus P_d, γ, and T_{sp} panel contour graphs at Pc = 40, 80, and 120 bar

performance. The split temperature T_{sp} decreases with P_c. T_{sp} is related only with the variable. This is because P_c highly impacts the thermodynamic property of the air and the heat exchange efficiency. The optimized thermodynamic efficiency 40.0%, 48.8%, and 51.2% when compression pressure is set at 40 bar, 80 bar, and 120 bar, respectively.

2.4 Conclusions

The optimal efficiency and conditions of important independent variables for Kapitza liquefaction cycle are investigated by partial enumeration. The interactions between the optimized independent variables are analyzed. There are some remarkable points: First, the peaks in all the P_d to γ graphs go right upward. Second, the optimized efficiencies do not change much in the same P_c. Lastly, T_{sp} is significantly dependent not on γ and P_d, but on P_c. The optimized thermodynamic efficiency 40.0%, 48.8%, and 51.2% when compression pressure is set at 40 bar, 80 bar, and 120 bar, respectively.

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REFERENCE

[1] Letcher, T. M., Law, R., Reay, D. Storing energy: with special reference to renewable energy sources. Vol. 86. Oxford: Elsevier, 2016.

[2] She X et al. Enhancement of round trip efficiency of liquid air energy storage through effective utilization of heat of compression. Applied energy, 2017; 206: 1632-1642.

[3] Kim J, Noh Y, Chang D. Storage system for distributed-energy generation using liquid air combined with liquefied natural gas. Applied energy, 2018; 212: 1417-1432.

[4] Hamdy S, Moser F, Morosuk T, Tsatsaronis .. Exergy-Based and Economic Evaluation of Liquefaction Processes for Cryogenics Energy Storage. Energies, 2019; 12(3), 493.

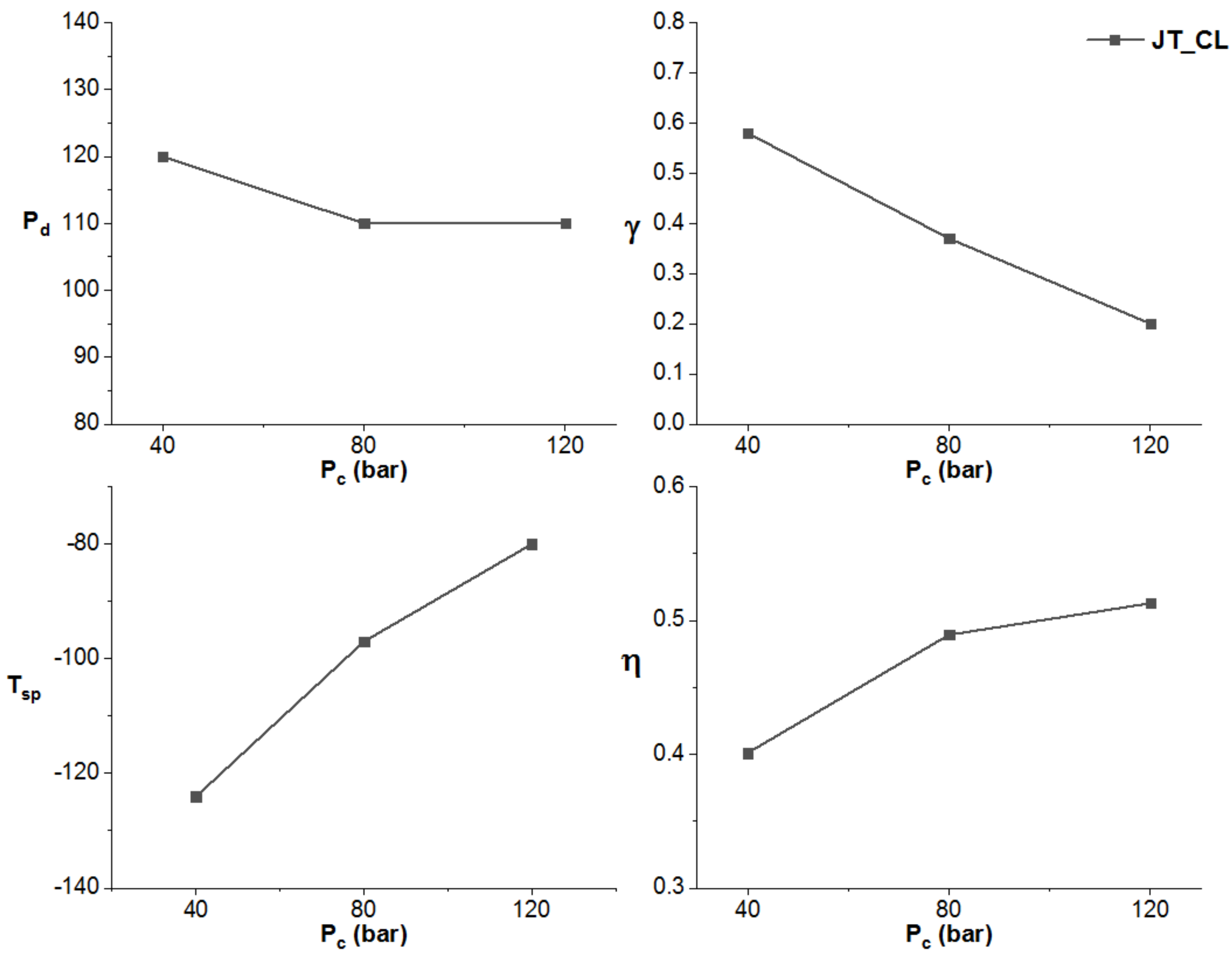

Fig 3 Optimal values of P_d, γ, and T_{sp}, and oveall efficiency at different P_c