#568: Cascaded utilization system of LNG cold energy

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Abstract: Cascaded utilization is the most promising solution for the comprehensive recovery of LNG cold energy across the entire temperature range. In this article, the author proposed a cascaded LNG cold energy utilization system, which includes cryogenic air separation (CAS), organic Rankine cycle (ORC), graded cold storage (GCS), and direct expansion (DE). A thermodynamic model of the proposed system was established. Based on this, with the objective of maximizing exergy efficiency, a global optimization of the proposed system was carried out using the particle swarm optimization algorithm. The results indicated that the optimized system could achieve efficient utilization of LNG cold energy. The total cold energy provided by LNG is 860.90 kW, of which 708.07 kW is utilized by the process, accounting for 82.24% of the total cold energy. Within different temperature ranges, the CAS, ORC, and GCS subsystems respectively utilize 21.23%, 21.34%, and 30.87% of the LNG cold energy. The total exergy loss of the system is 385.67 kW, with an exergy efficiency of 79.55%. Moreover, the total simulated power generation of the CAS-ORC-GCS-DE-LNG system is 120.92 kW, and the three expansion devices, the expander, Turbine 1 and Turbine 2, generate 12.85 kW, 29.12 kW, and 78.95 kW each. Additionally, the exergy loss of the cryogenic air separation module is 229.25 kW, accounting for 59.44% of the total exergy loss of the proposed system. Therefore, optimizing the cryogenic air separation module is a feasible approach to improving the thermodynamic performance of the proposed system.

Keywords: LNG Cold Energy, Cascade Utilization, Energy Analysis, Exergy Analysis

1. INTRODUCTION

Liquefied natural gas (LNG) refers to an advanced energy source produced by purifying natural gas from gas fields and then cooling it to below -162°C through a series of ultra-low temperature liquefaction processes. Due to its low CO_2 emissions, high calorific value, and convenient transportation, LNG is increasingly being widely used. However, a large amount of cold energy is released during the regasification process of LNG, which is usually discharged into the environment or utilized by single technologies with large temperature differences in heat exchange, resulting in significant cold energy losses. Utilizing multiple methods in succession for the cascaded utilization of cold energy, thereby reducing the heat exchange temperature difference, is an effective technical means to reduce energy loss in the LNG production and utilization process.

Currently, mature forms of LNG cold energy utilization include cold energy air separation (Ge et al., 2006), light hydrocarbon separation (He et al., 2019), power generation (Kanbur et al., 2017), cryogenic energy storage (Park et al., 2017), cold storage refrigeration(Xu and Wang, 2022), and cryogenic CO_2 capture(Gómez et al., 2016). How to combine these single technologies to form a cascaded utilization system and achieve higher energy utilization efficiency is a research-worthy topic. He et al. (2020) proposed the CES-ORC-DC-LNG system, which utilizes cryogenic energy storage, organic Rankine cycle, and direct cooling for the three-stage utilization of LNG cold energy. They optimized the composition and proportion of the working fluid using ASPEN HYSYS and MATLAB software to improve exergy efficiency. Yin Yongming et al. (2021) used ASPEN HYSYS software to simulate and establish an integrated scheme of cold energy air separation for nitrogen production, light hydrocarbon recovery, and cold energy power generation. Pan et al. (2022) proposed the LNG-LHS-ORC-DC system, which integrates the light hydrocarbon separation process, organic Rankine cycle, and direct cooling process. They performed detailed thermodynamic and economic analysis and multi -objective optimization of the system using ASPEN HYSYS and MATLAB software, enhancing energy utilization efficiency. It can be observed that in recent years, research on the cascaded utilization of LNG cold energy has widely recognized the use of ASPEN HYSYS software for process simulation, often combined with MATLAB software for optimization. Moreover, most studies have adopted two-stage or three-stage cascaded utilization systems, with little exploration of cascaded utilization systems beyond three stages.

In this article, the author proposed an energy and exergy-efficient process for LNG cold energy utilization, called the "CAS-ORC-GCS-DE-LNG" system. It employed cryogenic air separation (CAS), organic Rankine cycle (ORC), graded cold storage (GCS), and direct expansion (DE) for the cascaded utilization of LNG cold energy within the temperature range of approximately -162°C to 15°C. To deepen the understanding of the thermal characteristics of the CAS-ORC-GCS-DE-LNG system, the author established a theoretical static model of the system, including energy calculation and exergy calculation models, and analysed the method for calculating the system's cold energy utilization efficiency. Based on this, a global optimization of the CAS-ORC-GCS-DE-LNG system was performed using a general algorithm. The thermodynamic analysis was conducted based on the optimization results to evaluate system performance.

In summary, the author proposed a novel energy and exergy-efficient LNG cold energy utilization process (CAS-ORC-GCS-DE-LNG system) in this article and used particle swarm optimization to improve the system's exergy efficiency, providing a new and efficient process option for the cascaded recovery and utilization of LNG cold energy.

2. CAS-ORC-GCS-DE-LNG SYSTEM

2.1. System description

The diagram of the CAS-ORC-GCS-DE-LNG system labelled with stream names is shown in Figure 1. The specific processes for each module are as follows: In the air separation module, air enters a molecular sieve purifier to remove moisture, carbon dioxide, acetylene, propylene, hydrogen, and other impurities. The air is then pressurized to 0.63 MPa by a combination of two-stage air precoolers and compressors (stream A4), enters Heat Exchanger 2 for cooling (stream A5), and is split into two streams (streams A6 and A9) by a splitter. Stream A6 enters Heat Exchanger 1 for further cooling (stream A7), is throttled by a throttle valve (stream A8), and enters the middle layer of the reflux distillation column. Stream A9 is expanded by an expander (stream A10) and enters the bottom layer of the reflux distillation column. The top gas outlet of the reflux distillation column is high-purity liquid nitrogen, and the bottom liquid outlet is oxygen-rich liquid air. LNG from the storage tank is pressurized to 24 MPa by a cryogenic pump (stream L1), enters Heat Exchanger 1 to exchange heat with stream A6, and exits as stream L2. It then enters Heat Exchanger 2 to exchange heat with the twice-compressed air, using its cold energy for pre-cooling the air before each compression. In the ORC module, the working fluid leaves the evaporator (stream F1), enters the turbine for power generation, and exits as stream F2. It then enters the precooler for heat exchange and exits as stream F3. Stream F3 enters the condenser to exchange heat with LNG (stream L5) that has pre-cooled the air. The working fluid leaves the condenser (stream F4), is pressurized by a pump (stream F5), and sent to the evaporator to exchange heat with seawater, completing the working fluid cycle. In the graded cold storage module, LNG from the condenser outlet (stream L6) enters Heat Exchanger 3 to exchange heat with the primary cold storage working fluid, propylene glycol (PG3). The propylene glycol leaves the condenser (stream PG1), is pressurized by circulation pump 1 (stream PG2), and used for primary cold storage refrigeration. LNG exiting Heat Exchanger 3 (stream L7) enters Heat Exchanger 4 to exchange heat with the secondary cold storage working fluid, ethylene glycol (EG3). The ethylene glycol leaves the condenser (stream EG1), is pressurized by circulation pump 2 (stream EG2), and used for secondary cold storage refrigeration. In the direct expansion module, LNG exiting Heat Exchanger 4 (stream L8) first enters the NG superheater to be heated by seawater. After leaving the NG superheater, it enters turbine 2 for power generation

and cooling. It then enters the precooler to exchange heat with the ORC working fluid, utilizing the cold energy of the mixed working fluid before entering the ORC condenser. Finally, the LNG is heated to ambient temperature by seawater and integrated into the long-distance natural gas pipeline network. This detailed process ensures maximum utilization of LNG

cold energy, improving the overall system efficiency.

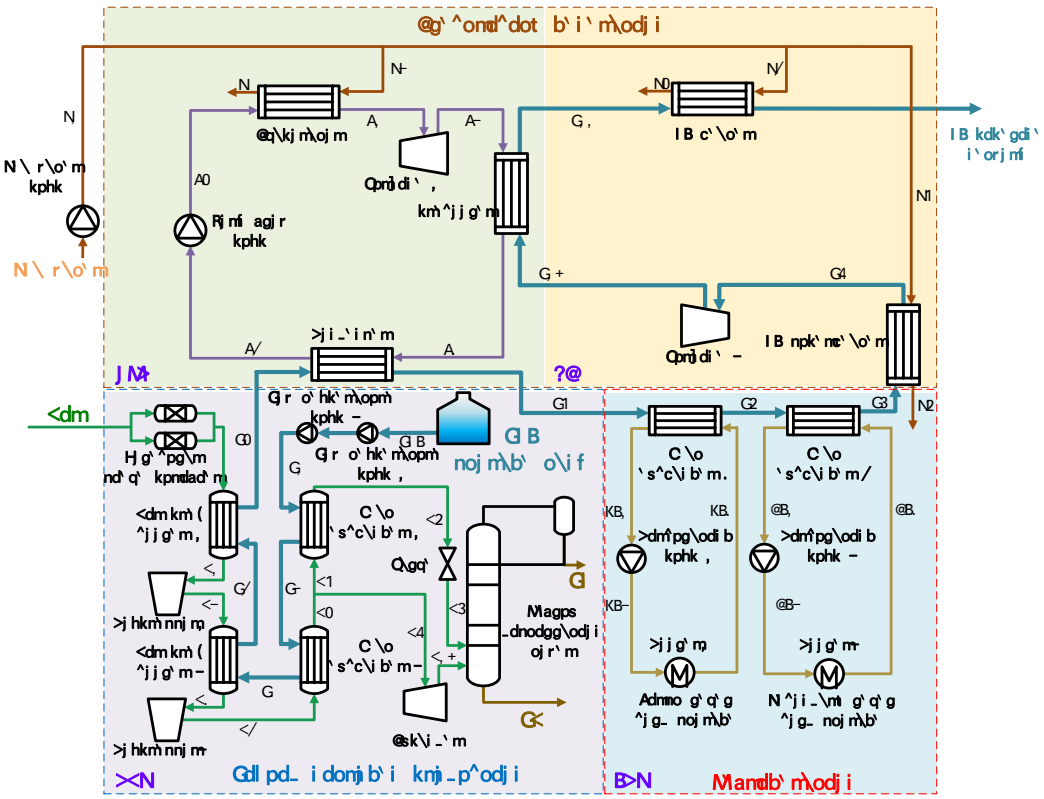

Figure 1: CAS-ORC-GCS-DE-LNG system diagram labelled with stream name

2.2. Working fluids

In the simulation, it is first necessary to determine the composition and physical property methods of the working fluids. The simulated composition of LNG is shown in Table 1, and the physical property equation used by the author was the Peng-Robinson (PR) equation. The air was assumed to be purified, and its simulated composition is shown in Table 2, with the physical property method also using the PR equation. The composition of the ORC working fluid is shown in Table The selection principle for the proportions of each component is to make the temperatures on both sides of the precooler as close as possible, with the physical property method also using the PR equation. The working fluids for the first and second stage cold storage are ethylene glycol and propylene glycol, respectively, and their physical property method wasthe CPA-EOS method. The accuracy of the seawater simulation has a minimal impact on the overall system simulation; therefore, it can be simplified to pure water, with the physical property method using the NRTL equation.

Table 1: Compositions of LNG (He et al., 2020)

Compositions	Mole fraction
CH_4	91.15 %
C_2H_6	5.55 %
C_3H_8	2.16 %
i-C_4H_{10}	0.51 %
n-C_4H_{10}	0.51 %
N_2	0.12 %

Table 2: Compositions of air (Li, 2015)

Compositions	Mole fraction
O_2	78.118 %
N_2	20.95 %
Ar	0.932 %

Table 3: Compositions of ORC working fluid

Compositions	Mole fraction
C_2H_4	25 %
C_2H_6	40 %
R134a	10 %
R152a	25 %

2.3. Simulation model

To effectively evaluate the thermodynamic performance of the designed system, a comprehensive mathematical model consisting of energy and exergy calculation models must be established. The following are some basic assumptions:

(1) The process is assumed to be in a steady state, with no consideration of kinetic and potential energy effects.
(2) The pressure drop in heat exchangers is assumed to be 10 kPa, and the minimum temperature difference is 3°C.
(3) The upper pressure limit of the storage tank is assumed to be 21 MPa (Lee and You, 2019).
(4) The seawater temperature is assumed to be 25°C, cooling down to 15°C after heating.
(5) The air is assumed to be purified and at standard temperature and pressure (STP).
(6) The compressors have the same compression ratio and an adiabatic efficiency of 92%.
(7) The expanders have the same expansion ratio and an adiabatic efficiency of 92%.
(8) The pump efficiency is assumed to be 90%.
(9) The environmental conditions for calculating energy consumption are 101.325 kPa and 25°C.

Based on these assumptions, an energy analysis model of the CAS-ORC-GCS-DE-LNG system was established. The energy equations for each component are listed in Table 4. The subscript HEX stands for heat exchangers, H and C refer to heat flow and cold flow, exp and com refer to expanders and compressors, p stands for pump, is stands for isentropic.

Table 4: Energy equations of each component

Components	Equations
Heat exchangers	$\dot{Q}_{\mathrm{HEX}} = \dot{m}_H(h_{\mathrm{H2}} - h_{\mathrm{H1}}) = \dot{m}_C(h_{\mathrm{C2}} - h_{\mathrm{C1}})$
Expanders	$W_{\mathrm{exp}} = \dot{m}_{\mathrm{exp}}(h_{\mathrm{exp},2} - h_{\mathrm{exp},1})\eta_{\mathrm{is,exp}}, \eta_{\mathrm{is,exp}} = 92\%$
Compressors	$W_{\mathrm{com}} = \dot{m}_{\mathrm{com}}(h_{\mathrm{com},2} - h_{\mathrm{com},1})\,\eta_{\mathrm{is,com}}, \eta_{\mathrm{is,com}} = 92\%$
Pumps	$P_{\mathrm{p}} = \dot{m}_{\mathrm{p}}(h_{\mathrm{p2}} - h_{\mathrm{p1}})/\eta_{\mathrm{is,p}}, \eta_{\mathrm{is,p}} = 90\%$

Where:

- $\dot{Q}$ = energy (kJ)
- $\dot{m}$ = mass flow rate (kg)
- h = enthalpy (kJ/kg)
- η = efficiency (%)

The LNG cold energy utilization efficiency can be used as the overall performance indicator for the CAS -ORC-GCS-DE-LNG system proposed in this article. Its calculation primarily depends on the heat transfer efficiency between the cold and hot streams in the heat exchangers, as shown in equation 1. The superscript C represents the cold flow side, i can be taken as 1,2...,13, respectively representing heat exchanger 1, heat exchanger 2, air precooler 1, air precooler 2, condenser, heat exchanger 3, heat exchanger 4, NG superheater, precooler, NG heater, evaporator, cooler1, cooler2.

Equation 83: LNG cold energy used by each heat exchanger.

$$\dot{Q}_{\mathrm{LNG-i}} = \dot{m}_{\mathrm{LNG}}\Delta h^{C}_{\mathrm{HEX-i}}$$

Where:

- Δh = enthalpy difference between the inlet and outlet of LNG in a heat exchanger (kJ)

The cold energy is sequentially utilized by air, ORC working fluid, first-stage cold storage fluid PG, and second-stage cold storage fluid EG. The calculation equations for the cold energy of each working fluid are shown in equation 2 to 5. The superscript H represents the heat flow side. The subscript AIR stands for air, ORC stands for organic Rankine cycle, w f stands for working fluid, PG and EG stands for first stage and second-stage cold storage fluid. Others see previous equations.

Equation 84: Cold energy gained by air.

$$\dot{Q}_{\mathrm{AIR}} = \dot{m}_{\mathrm{AIR}}\sum_{\mathrm{i}=1}^{3}\Delta h^{\mathrm{H}}_{\mathrm{HEX-i}} + 0.5\dot{m}_{\mathrm{AIR}}\Delta h^{\mathrm{H}}_{\mathrm{HEX-4}}$$

Equation 85: Cold energy gained by ORC working fluid.

$$\dot{Q}_{\mathrm{ORC},wf} = \dot{m}_{\mathrm{ORC}}\sum_{\mathrm{i}=5,9}\Delta h^{\mathrm{H}}_{\mathrm{HEX-i}}$$

Equation 86: Cold energy gained by PG.

$$\dot{Q}_{\mathrm{PG}} = \dot{m}_{\mathrm{PG}}\Delta h^{\mathrm{H}}_{\mathrm{HEX-6}}$$

Equation 87: Cold energy gained by EG.

$$\dot{Q}_{\mathrm{PG}} = \dot{m}_{\mathrm{EG}} \Delta h^{\mathrm{H}}_{\mathrm{HEX-7}}$$

The definition of cold energy utilization efficiency is the ratio of the cold energy utilized by the system to the total input cold energy. The direct expansion process does not involve heat exchangers and does not directly utilize cold energy, so its cold energy utilization efficiency is not discussed. The cold energy utilization efficiencies for the CAS, ORC, GCS subsystems and the total cold energy utilization efficiency of the CAS-ORC-GCS-DE-LNG system are shown in equation 6 to 9. The subscript u represents cold energy utilization, CAS stands for cryogenic air separation, GCS stands for graded cold storage, sys stands for system. Other see previous equations.

Equation 88: Cold energy utilization efficiency of CAS.

$$\eta_{u,\mathrm{CAS}} = \frac{\dot{Q}_{\mathrm{Air}}}{\sum_{\mathrm{i=1}}^{10} \dot{Q}_{\mathrm{LNG-i}}}$$

Equation 89: Cold energy utilization efficiency of ORC.

$$\eta_{u,\mathrm{ORC}} = \frac{\dot{Q}_{\mathrm{ORC}}}{\sum_{\mathrm{i=1}}^{10} \dot{Q}_{\mathrm{LNG-i}}}$$

Equation 90: Cold energy utilization efficiency of GCS.

$$\eta_{u.\mathrm{GCS}} = \frac{\dot{Q}_{\mathrm{PG}} + \dot{Q}_{\mathrm{EG}}}{\sum_{\mathrm{i=1}}^{10} \dot{Q}_{\mathrm{LNG-i}}}$$

Equation 91: Cold energy utilization efficiency of system.

$$\eta_{\mathrm{sys}} = \eta_{\mathrm{CAS}} + \eta_{\mathrm{ORC}} + \eta_{\mathrm{GCS}}$$

When ignoring kinetic and potential energies, exergy includes physical exergy and chemical exergy (Liu and He, 2020). Since there are no chemical reactions in the system described in this article, the chemical exergy remains unchanged, and only physical exergy is considered. The mathematical representation of physical exergy is shown in equation 10 (Pan et al., 2022) The subscript 0 stands for environmental state.

Equation 92: The formula for calculating physical exergy.

$$\mathrm{Ex} = \dot{m}[(h - h_0) - T_0(s - s_0)]$$

where:

- T = temperature (℃)
- Ex = physical exergy (kJ)
- s = entropy (kJ/kg)

The exergy balance equation for the system is shown in equation 11(Pan et al., 2022). The subscript in and out refer to input and output.

Equation 11: The exergy balance equation.

$$\sum \mathrm{Ex_{in}} + \sum W_{\mathrm{in}} = \sum \mathrm{Ex_{out}} + \sum W_{\mathrm{out}} + \sum \mathrm{L}$$

where:

- W = work (kJ)
- L = exergy loss due to irreversible processes and environmental depletion (kJ)

The total exergy efficiency is defined as the ratio of the exergy output to the exergy input (Pan et al., 2022). For the CAS-ORC-GCS-DE-LNG system proposed in this article, the total exergy efficiency is shown in equation 12 to 14. The superscript Net is net, LN is liquid nitrogen, LA is liquid air, DT is distillation tower. The subscript q can be taken as 1, 2, 3, 4, representing low temperature pump, working fluid pump, circulating pump 1, and circulating pump 2 respectively; j can be taken as 1 and 2, representing compressor 1 and compressor 2 respectively; k can be taken as 1, 2, and 3, respectively representing the expander, turbine 1, and turbine 2. Others see previous equations.

Equation 93: The total exergy efficiency.

$$\eta^{\mathrm{Ex}} = \frac{\mathrm{Ex}^{\mathrm{Net}}_{\mathrm{out}}}{\mathrm{Ex}^{\mathrm{Net}}_{\mathrm{in}}}$$

Equation 94: The exergy input of the proposed system.

$$\mathrm{Ex}^{\mathrm{Net}}_{\mathrm{in}} = \mathrm{Ex}^{\mathrm{LNG}}_{\mathrm{in}} + \mathrm{Ex}^{\mathrm{AIR}}_{\mathrm{in}} + \sum \dot{W}^{\mathrm{p}}_{\mathrm{q}} + \sum \dot{W}^{\mathrm{com}}_{\mathrm{j}}$$

Equation 95: The exergy output of the proposed system.

$$\mathrm{Ex}^{\mathrm{Net}}_{\mathrm{out}} = \mathrm{Ex}^{\mathrm{LNG}}_{\mathrm{out}} + \mathrm{Ex}^{\mathrm{LN}}_{\mathrm{out}} + \mathrm{Ex}^{\mathrm{LA}}_{\mathrm{out}} + \sum \dot{W}^{\mathrm{exp}}_{\mathrm{k}} + \mathrm{E}x^{GCS} + \mathrm{E}x^{DT}$$

2.4. Optimization method

The optimization objective for the CAS-ORC-GCS-DE-LNG system is to maximize the exergy efficiency of the proposed system. Given that the pressure ratios in each stage are the same, the exergy produced by the LNG expander and the air expander is fixed. Additionally, the cold storage temperatures are pre-designed, so the cold output exergy is also fixed. Therefore, the exergy output is primarily influenced by the air separation process and the ORC. The objective function is the ratio of net output exergy to net input exergy, which can be described by equation 15, the ratio of the exergy output to the exergy input. Additionally, in MATLAB, a particle swarm optimization algorithm is used to achieve a simulation-based optimization method. The optimization process is illustrated in Figure 2. The parameters of the particle swarm algorithm used in this study are listed in Table 5. During the optimization process, constraints are used to prevent infeasible searches of decision variables. In this study, the following constraints are proposed to ensure the system operates under practical engineering conditions:

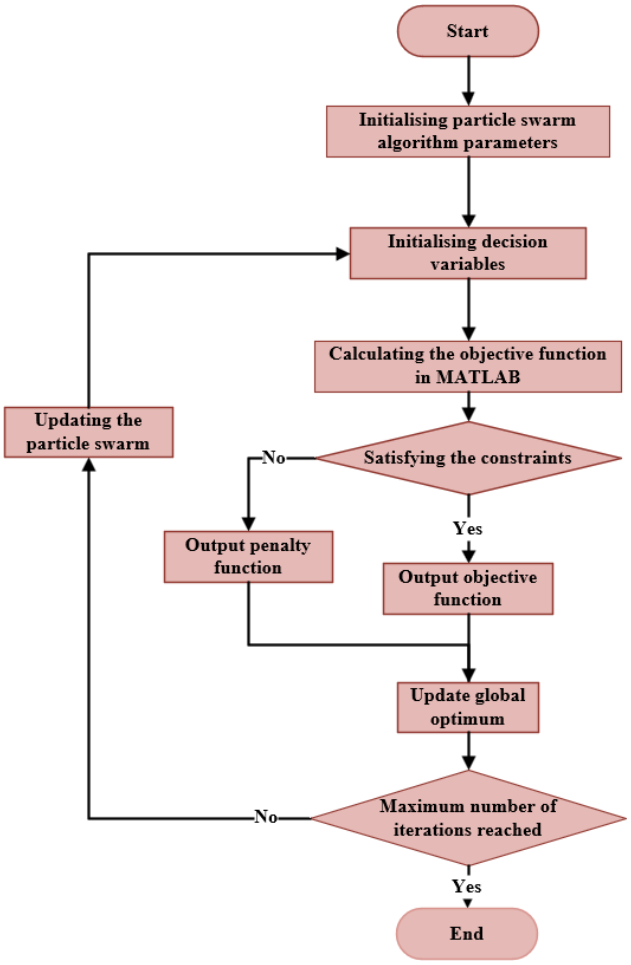

Figure 2: Optimization process flowchart

Table 5: Parameter settings of particle swarm optimization algorithm

Parameter	Value
Number of particles	50
Maximum number of iterations	100
Coupling function	@fmincon
Function tolerance	10^{-6}
Individual learning factor	1.49
Social learning factor	1.49
Minimum Neighbor Number	0.25

To improve optimization accuracy and reduce optimization time, the upper and lower limits of the decision variables were set based on the probability of the system operating correctly. Narrowing the range of values for these variables helps achieve more precise optimization. The ranges for each variable are listed in Table 6.

Table 6: Ranges of decision variables

Variable Name	Symbolization	Lower Bound	Upper Bound
Flow AIR quality flow	$\dot{m}_{AIR}$	0.73 kg/s	0.8 kg/s
Flow L2 temperature	T_{L2}	-152 ℃	-142 ℃
Flow L3 temperature	T_{L3}	-146 ℃	-128 ℃
Flow L5 temperature	T_{L5}	-94 ℃	-84 ℃
Flow F1 temperature	T_{F1}	16 ℃	21 ℃
Flow F1 pressure	P_{F1}	900 kPa	1400 kPa

The minimum temperature difference in the heat exchangers must be greater than or equal to 3°C. The mathematical expression for this constraint is shown in equation 15.

Equation 96: the constraint of the minimum temperature difference

$$\Delta T_{\mathrm{HEX-i}} \geq 3\,, i = 1,2\ldots,13$$

To prevent liquid from entering the expanders and causing damage to the blades, the gas fraction for streams A9, F1, and L9 should be equal to 1. The mathematical expression for this constraint is shown in equation 16.

Equation 97: Preventing liquid from entering the expanders.

$$\mathrm{GF}_m = 1, m = \mathrm{A9, F1, L9}$$

where:

- GF = gas fraction
- A9, F1, L9 = stream A9, stream F1, stream L9

To prevent any water vapor from entering the pumps, the gas fraction for the LNG, F4, PG1, EG1, and SW streams should be equal to 0. The mathematical expression for this constraint is shown in equation 17.

Equation 98: Preventing water vapor from entering the pumps.

$$\mathrm{GF_n} = 0, \mathrm{n} = \mathrm{LNG, F4, PG1, EG1, SW}$$

where:

- LNG, F4, PG1, EG1, SW = stream LNG, stream F4, stream PG1, stream EG1, stream SW

If any of the constraints are violated, a penalty function is introduced to replace the objective function during the optimization process. Typically, the penalty function is designed to be the opposite of the objective function. Since the goal of this study is to maximize net power output, a penalty function with a very small value is set to penalize violations. The penalty function is shown in equation 18 (He et al., 2020).

Equation 99: The penalty function.

$$p(X) = 10^{-9}|f(X)|$$

where:

- $p(X)$ = the penalty function
- $|f(X)|$ = the absolute value of the objective function

3. RESULTS AND DISCUSSION

In the air separation process, the pressure is approximately 0.5-1 MPa. Additionally, under suitable conditions, the air turbine machinery operates with a compression ratio range of 2.2-2.6 and an expansion ratio range of 0.24-0.3 (Lu et al., 2023). Therefore, in this system, the air compressor compression ratio was set to 2.6, and the expander expansion ratio was set to 0.3.

The results of the particle swarm optimization are listed in Table 7. The system exergy efficienc y is 79.55 %, the air mass flow rate is 0.752 kg/s, and the temperatures of the streams L2, L3, and L5 are -152°C, -138.8°C, and -87.5°C, respectively. The temperature and pressure of stream F1 are 20°C and 1390 kPa.

The performance parameter results of the optimized CAS-ORC-GCS-DE-LNG system are shown in Table 8. It can be observed that the distillation column requires a significant amount of cooling, needing 166.34 kW of cooling power. The expansion devices, including the expander, Turbine 1, and Turbine 2, generate 12.85 kW, 29.12 kW, and 78.95 kW of power, respectively, totalling 120.92 kW of power generation for the proposed CAS -ORC-GCS-DE-LNG system. The power consumption of the circulating pump is minimal, as it is only used to overcome the circulation pressure drop. The LNG pump has higher power consumption due to the large pressure changes in the LNG.

Table 7: Optimal results

Parameter Name	Parameter Value
η^{Ex}	79.55 %
$\dot{m}_{AIR}$	0.752 kg/s
T_{L2}	-152.0 ℃
T_{L3}	-138.8 ℃
T_{L5}	-87.5 ℃
T_{F1}	20.0 ℃
P_{F1}	1390 kPa

Table 8: Performance parameters of the optimized system

Parameter Name	Parameter Value
$\dot{W}_1^p$	57.76 kW
$\dot{W}_2^p$	0.02 kW
$\dot{W}_3^p$	0.03 kW
$\dot{W}_4^p$	0.84 kW
$\dot{W}_1^{com}$	39.89 kW
$\dot{W}_2^{com}$	35.00 kW
$\dot{W}_1^{exp}$	12.85 kW
$\dot{W}_2^{exp}$	29.12 kW
$\dot{W}_3^{exp}$	78.95 kW
Q_{DT}	166.34 kW
Q_{G1}	103.55 kW
Q_{G2}	83.85 kW

3.1. Energetic analysis

Under the optimized system conditions, the total amount of cold energy provided by the liquefied natural gas (LNG) is 860.90 kW, with a total of 708.07 kW utilized by the process, accounting for 82.24% of the total cold energy. The total cold energy provided by the liquefied natural gas (LNG) is 860.90 kW, with 708.07 kW of this cold energy utilized by the process, accounting for 82.24% of the total cold energy. Among this, the CAS system utilizes approximately 261.56 kW of LNG cold energy in the low temperature range (-162 to -87°C), accounting for 30.38% of the total cold energy. However, the heat transfer curve between the liquefied natural gas and the air is not well-matched, leading to a waste of cold energy. In the intermediate temperature range (-87 to -48.3°C) and during the heating process before entering the NG pipeline, the ORC utilizes 259.06 kW of cold energy, accounting for 30.09% of the total cold energy. Subsequently, the staged cold storage absorbs approximately 187.45 kW of cold energy in the mid-to-high temperature range (-48.3 to 2°C), with a cold energy utilization efficiency of 21.77%. The remaining cold energy is discharged into seawater, accounting for 17.76% of the total cold energy. The efficiency of cold energy utilization for each process is listed in Table 9.

Table 9: Efficiency of cold energy utilization for each subsystem

System Name	Cooling capacity	Efficiency
CAS	261.56 kW	30.38 %
ORC	259.06 kW	30.09 %
GCS	187.45 kW	21.77 %
Total	708.07 kW	82.24 %

Figure 3 illustrates the T-Q curve of the CAS-ORC-GCS-DE-LNG system. It is evident that the distance between the curves for the mixed working fluid, cold storage refrigerants, and LNG is significantly smaller compared to the distance between the air and LNG curves, indicating more efficient cold energy utilization. Furthermore, the heat transfer process with mixed working fluids involves phase changes, which results in inflection points on the transfer curves.

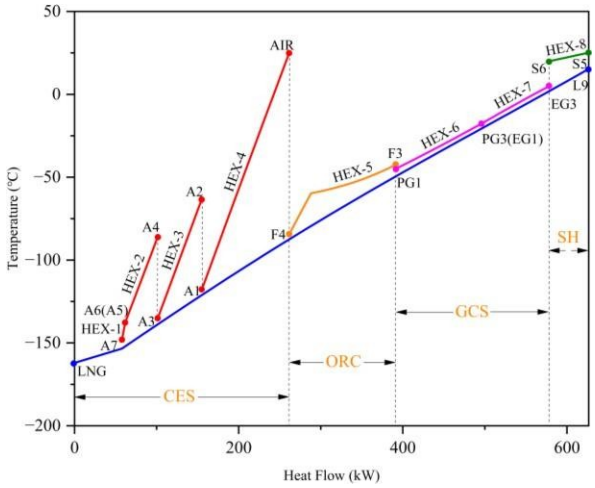

Figure 3: T-Q curve

3.2. Exergy analysis

After optimizing using the particle swarm algorithm, the exergy efficiency of the CAS-ORC-GCS-DE-LNG system is 79.55% and the total exergy loss is 385.67 kW. Figure 4 displays the exergy loss percentage radar chart. From the perspec tive of subsystems, the CES subsystem has an exergy loss of 229.25 kW, accounting for 59.44% of the total. This high loss is due to the relatively low heat transfer efficiency of the heat exchangers. The ORC subsystem has an exergy loss of 62.71 kW, representing 16.26% of the total. The DE subsystem has an exergy loss of 29.14 kW, which is 8.73% of the total. The GCS subsystem, considering only the exergy loss related to LNG heat exchange, has a very small exergy loss of 3.14 kW, accounting for 0.82% of the total. The exergy loss values for each subsystem are listed in Table 10.

Table 10: Exergy losses of each subsystem

System Name	Exergy loss	Proportion
CAS	229.252 kW	59.44 %
ORC	62.709 kW	16.26 %
GCS	3.143 kW	0.82 %
DE	29.14 kW	8.73 %

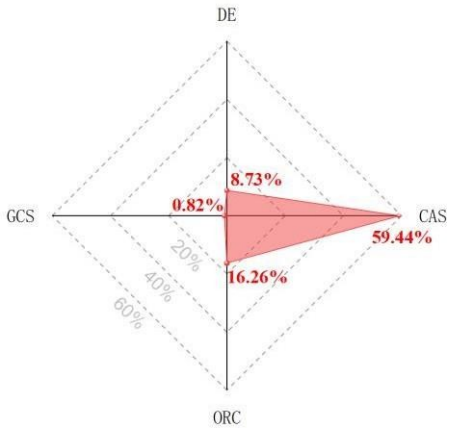

Figure 4: Distributions of the exergy loss of the CAS-ORC-GCS-DE-LNG system

4. CONCLUSION

In this article, the author proposed a novel LNG cold energy cascade utilization system, which integrated cryogenic air separation (CAS), organic Rankine cycle (ORC), graded cold storage (GCS), and direct expansion (DE). The proposed system recovered LNG cold energy through appropriate processes across various temperature ranges, achieving high cold energy utilization efficiency and exergy efficiency. A static analysis model, including energy and exergy calculation models, was developed to analyse the cold energy utilization efficiency of the system. A simulation model was built and combined with MATLAB software; the exergy efficiency of the proposed system was targeted for global optimization usingparticle swarm optimization. The main conclusions of the study are as follows:

(1) Under the optimized system conditions, the total cold energy provided by LNG is 860.90 kW, of which 708.07 kW is

utilized by the process, accounting for 82.24% of the total cold energy. The CAS, ORC, and GCS subsystems utilize 21.23%, 21.34%, and 30.87% of the LNG cold energy in different temperature ranges, respectively. The distance between the mixed working fluid, refrigeration fluid, and LNG curves is significantly smaller than that between air and LNG, indicatinghigher cold energy utilization efficiency.

(2) After optimization with particle swarm algorithm, the CAS-ORC-GCS-DE-LNG system's exergy efficiency is 79.55%, and the total exergy loss is 385.67 kW. The values of the decision variables are as follows: Flow AIR quality flow is 0.752kg/s. Flow L2 temperature is -152℃. Flow L3 temperature is -138.8℃. Flow L5 temperature is -87.5℃. Flow F1 temperature is 20℃. Flow F1 pressure is 1390kPa. The total simulated power generation of the CAS-ORC-GCS-DE-LNGsystem is 120.92 kW, and the three expansion devices, the expander, Turbine 1 and Turbine 2, generate 12.85 kW, 29.12 kW, and 78.95 kW each.

(3) From the perspective of subsystems, the exergy losses for CES, ORC, DE, and GCS are 59.44%, 16.26%, 8.73%, and 0.82%, respectively. It is recommended that further improvements in the process focus on modifications to the CAS subsystem process configuration.

5. ACKNOWLEDGEMENT

The authors would like to appreciate the funding support of the Science and Technology Support Program of Jiangsu Province (No. BA2023103) and the National Natural Science Foundation of China (No. 92271111).

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