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ENERGY CONSUMPTION AND REFRIGERANT COMPOSITION OPTIMIZATION FOR SMALL-SCALE SKID-MOUNTED C3-MR LIQUEFACTION PLANT

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ABSTRACT

The small-scale skid-mounted natural gas liquefaction plant can recover natural gas economically and conveniently without pipeline transportation. The mixed refrigerant liquefaction process is widely used in small plants currently. However, the liquefaction process is very energy–intensive. In this paper, We simulated the propane precooled mixed refrigerant liquefaction process and found that increasing the pressure and lowering the feed gas temperature can reduce the liquefaction energy consumption. Moreover, parameters such as refrigerant composition, flow rate, and heat exchangers outlet temperature are also related to energy consumption. The genetic algorithm (GA) was used to optimize the process, and the minimum specific energy consumption of liquefaction process S_{Total} was 0.3821kW·h/kg, which was 37.9% lower than the base case. In addition, the results also suggest that when the C_4H_{10} mass fraction exceeds 35%, the compressor inlet has liquid phase component. When the CH_4 and N_2 components are less than 20%, the cryogenic heat exchanger has insufficient heat exchange capacity.

Keywords: small-scale skid-mounted liquefaction plant, propane pre-cooling liquefaction, mixed refrigerant, genetic algorithm, specific energy consumption

NONMENCLATURE

Abbreviations	
LNG	Liquefied natural gas
GA	Genetic algorithm
MR	Mixed refrigerant liquefaction
SMR	Single-stage mixed refrigerant cycle
C3-MR	Pre-cooled mixed refrigerant cycle
Symbols	
S_{Total}	Specific energy consumption
W	Compression power consumption
$\dot{m}$	Mass flow rate
ω	Mass fraction
T	Temperature
w	Unit mass power consumption

1. INTRODUCTION

With the global demand for lower emissions, natural gas is used in more and more fields with good cleanliness, so the demand is also greatly increased [1]. There are many gas fields with small reserves in the mountainous areas of western China. Compared with the natural gas produced by laying pipelines, it is more economical to use a small-scale skid-mounted liquefaction equipment to liquefy gas phase natural gas to 101kPa, 113K liquefied natural gas (LNG), and then transport it to a large natural gas distribution center through LNG tank trucks. In addition, because the skid-mounted liquefaction equipment is assembled from several working packages, the liquefaction equipment can be transported by truck to other gas fields after the completion of a gas field, which will greatly reduce the mining and transportation costs.

The small-scale skid-mounted LNG plant mainly uses mixed refrigerant liquefaction process (MR) currently [2], which is divided into single-stage mixed refrigerant cycle (SMR) and propane pre-cooled mixed refrigerant cycle (C3-MR) [3]. According to statistics, the cost of liquefaction refrigeration accounts for 42% of the total cost of LNG projects [4]. In order to reduce liquefaction energy consumption and improve energy efficiency, it is necessary to optimize the liquefaction process. Many researchers have conducted thermodynamic analysis of the liquefaction process and optimized it using mathematical algorithm models. Mehrpooya and Ansarinasab [5] conducted a thermodynamic and economic analysis of SMR and found that investment costs can be controlled by reducing compressor exergy losses and heat exchanger costs. Aspelund et al. [6] used the Tabu search and the Nelder-Mead Dowhill Simplex method to optimize the mixed refrigerant composition, flow rate and other factors of the PRICO process in Aspen HYSYS and Visual Basic for Applications. They found that the joint optimization of Tabu search and NMDS methods get the optimal solution faster than Tabu search. Alabdulkarem et al. [7] applied GA model to optimize the propane pre-cooling cycle and the MR cryogenic cycle respectively, and the optimized energy consumption was 100.78MW, which was 13.28% higher than the baseline. He et al. [8] also used the GA to optimize SMR process and the nitrogen expansion liquefaction process, and the optimized specific energy consumption was 0.411kW·h/kg and 0.618kW·h/kg respectively. By analyzing exergy efficiency, process investment, SMR is considered more suitable for small-scale skid-mounted liquefaction equipment. Song et al. [9] proposed an exergy destruction reduction algorithm to optimize the C3-MR process. This method can increase exergy destruction rate by 2.9% than sequence quadratic programming algorithm.

This paper firstly simulates C3-MR liquefaction process by HYSYS, and analyzes the influence of feed gas parameters, mixed refrigerant parameters and heat exchangers outlet temperature on energy consumption. Then HYSYS and MATLAB are connected through ActiveX, and the genetic algorithm is used to obtain optimization results in MATLAB environment. Finally, by studying the optimized refrigerant ratio and the thermodynamic properties of the mixed refrigerant, the rules for the distribution of refrigerant components in the liquefaction process is summarized.

2. PROCESS DESIGN AND PARAMETER ANALYSIS

2.1 C3-MR process design

Fig.1 shows the C3-MR process, which consists of a purification skid, a compression skid, and a liquefied skid. The liquefied skid is divided into a propane pre-cooling liquefaction process and a main liquefaction process. The purified natural gas is pre-cooled by 1HX heat exchanger and then enters separator S-2 to separate the liquid heavy hydrocarbon component with temperature below 233k. The separated natural gas NG2 enters 2HX and 3HX to continue liquefaction, and then is depressurized to 150kPa through the expansion valve V-4 to obtain a liquid phase LNG product of 113K. The mixed refrigerant with a pressure of 150kPa is first pressurized to 3500kPa by two-stage compression intermediate cooling, as is shown in the Compression Section of Fig.2. After passing through S-1, the mixed refrigerant MR Cold is divided into two flow paths to enter the 1HX, and the stream 3 enters S-3 and is divided into a gas phase stream 4 and a liquid phase stream 5 to exchange heat in the 2HX. The stream 6 enters the 3HX and flows through V-3 to provide cooling capacity for 3HX. The heat-exchanged stream 11 merges with the throttled stream 8 to form a stream 13 which provides cooling capacity for the 2HX heat exchanger, then merges with the stream 15 to provide cooling capacity for 1HX and returns to the compressor inlet. The propane pre-cooling cycle is shown in the Propane Precooling Section of Figure 2. The

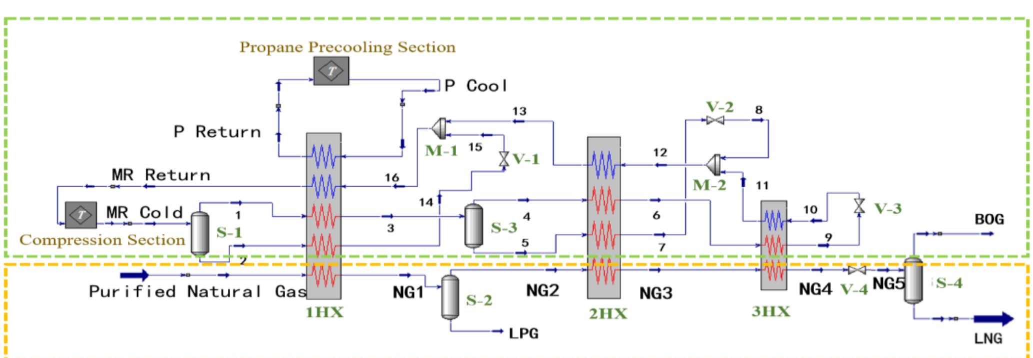

Fig 1 C3-MR liquefaction process

propane is compressed and throttled into 1HX to pre-cool the feed gas and mixed refrigerant to 233K. According to the literature [8-9] and equipment operation experience, the main parameters in this process are listed in Table 1.

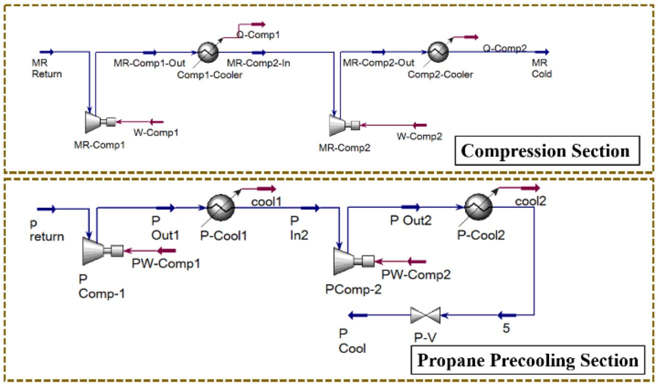

Fig.2. Mixed refrigerant compression section and propane pre-cooling section

Table 1 Process assumption parameter

Parameter	Value
Cold fluid pressure drop in heat exchanger	30kPa
Thermal fluid pressure drop in heat exchanger	200kPa
Pinch temperature	3K
Compressor isentropic efficiency	0.8
Cooling temperature after compression	313K
Pressure and temperature of LNG	150kPa、113K
Thermodynamic property package	Peng-Robinson

2.2 Parameter analysis

2.2.1 *Influences of feed gas parameters*

Natural gas is purified first and enters the liquefied process after it is mined. The purified feed gas mass fraction is listed in Table 2.

Table 2 Purified feed gas component

Component	Mass fraction（%）
Methane（CH_4）	92.06
Ethane（C_2H_6）	3.03
Propane（C_3H_8）	1.43
n-butane（n-C_4H_{10}）	1.26
i-butane（i-C_4H_{10}）	0.32
n-pentane（n-C_5H_{12}）	0.55
i-pentane（i-C_5H_{12}）	0.43
Hexane（C_6H_{14}）	0.21
Nitrogen（N_2）	0.71
Total	100.0

Due to the complicated working conditions of the small gas field, the feed gas pressure ranges from1.0 MPa to 4.5MPa, the temperature range is 5°C to 25°C, and the liquefaction equipment treatment flow rate is required to between 3×10^{4}Sm^3/d and 5×10^{4}Sm^3/d. In this C3-MR process, the compression is the most energy-intensive. The pressure, temperature and flow fluctuation of the feed gas affect the power consumption of the system. The total power consumption of the process is equal to the mixed refrigerant compression power consumption W_{Comp1} , W_{Comp2} and the propane pre-cooling compression power consumption$W_{P-Comp1}$ $W_{P-Comp2}$, as Eq.(1). The feed gas flow rate is positively correlated with the system power consumption. Therefore, the energy consumption per unit mass of natural gas liquefaction is used to evaluate the influence of the feed gas temperature and pressure on the process as Eq.(2).

$$W_{Total} = W_{Comp1} + W_{Comp2} + W_{P-Comp1} + W_{P-Comp2} \quad (1)$$

$$S_{Total} = \frac{W_{Total}}{m_{NG}} \quad (2)$$

The C3-MR model can be created by Aspen HYSYS V9.0. It is found that when the feed gas inlet temperature is constant, S_{Total} reduces as the feed gas pressure increases under the condition of flow rate of 5×10^{4}Sm^3/d. When the feed gas inlet pressure is constant, S_{Total} decreases as the feed gas temperature rises. The above results are shown in Fig.3. As the feed gas parameters change, the refrigerant flow rate increases when the cooling capacity required for liquefaction increases. Therefore， the tendency of refrigerant flow rate is similar with the variation curve of S_{Total} in different inlet temperatures and pressures of feed gas.

2.2.2 *Influences of mixed refrigerant parameter*

Mixed refrigerant is the source of cooling capacity for the liquefaction process, which boosts pressure through the compressor. When the mixed refrigerant flow increases, the power consumption increases. Compressibility factor is a major factor resulting in difference in unit power consumption of the refrigerant since it is different for each refrigerant component under the same working conditions. Therefore, the mixing ratio will have a great influence on the power consumption to ensure that sufficient cooling capacity.

2.2.3 *Influences of heat exchangers outlet temperature*

Three heat exchangers are set in this process, and the temperature range is from 298K to 113K. 1HX inlet temperature and 3HX outlet temperature are fixed, while 1HX outlet temperature and 2HX outlet temperature need to be set. 1HX outlet temperature is determined to have an effect on the separation of heavy hydrocarbon components, so it cannot be higher than 243K. Different outlet temperatures determine the heat exchange capacity of the heat exchanger. Since the heat exchange load requires the matching of the cooling capacity provided by the refrigerant, it has an impact on the power consumption. Therefore, we need to get the optimum value of the outlet temperature of the heat exchanger.

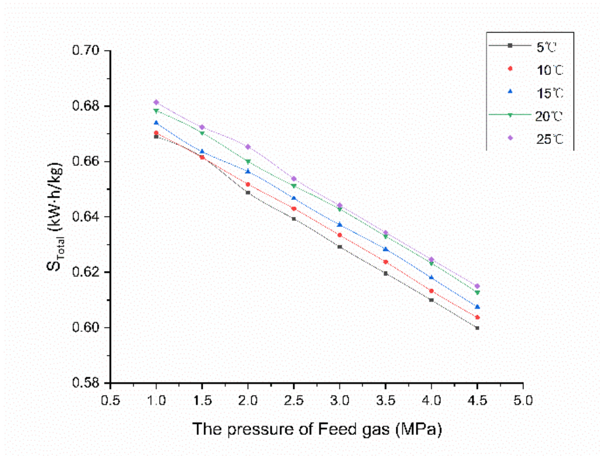

Fig.3 Variation curve of S_{Total} in different inlet temperatures and pressures of feed gas

3. OPTIMIZATION RESULTS AND DISCUSSION

3.1 Optimization approach

The natural gas liquefaction process is complex and involves many parameters, which is a multi-factor optimization problem. The genetic algorithm encodes multiple variables similar to biological genetic DNA, and obtains the optimal solution by global parallel search. Therefore, the algorithm is suitable for optimizing this process. In order to get the lowest energy consumption of the process, the optimization objective function is:

$$f = \min\{S_{Total}\} \quad (3)$$

The function variables are mixed refrigerant flow $\dot{m}_{MR}$, propane pre-cooling cycle flow $\dot{m}_{C_3}$, 1HX outlet temperature $T_{1outlet}$, 2HX outlet temperature $T_{2outlet}$, and $CH_4/C_2H_6/C_3H_8/i\text{-}C_4H_{10}/N_2$ mass fraction $\omega_{CH_4}/\omega_{C_2H_6}/\omega_{C_3H_8}/\omega_{i-C_4H_{10}}/\omega_{N_2}$. The value range of each variable is shown in Table 3.

Table 3 Function variable range

Variables	Ranges
$\dot{m}_{MR}$ (kg/h)	[3000,12000]
$\dot{m}_{C_3}$ (kg/h)	[1000,5000]
$T_{1outlet}$ (K)	[213,253]
$T_{2outlet}$ (K)	[143,183]
Mass fractions($CH_4/C_2H_6/C_3H_8/i\text{-}C_4H_{10}/N_2$)	[0,1]

In the process of using GA optimization, the constraints of the liquefaction process need to be guaranteed. The process constraints are:

1. The pinch temperatures of heat exchangers, i.e. 1HX, 2HX, and 3HX, are all higher than 3K. This constraint condition penalizes the results that do not satisfy the above conditions by the penalty function method.
2. When setting the value of each component of the mixed refrigerant, it is necessary to ensure
$$\omega_{CH_4} + \omega_{C_2H_6} + \omega_{C_3H_8} + \omega_{i\text{-}C_4H_{10}} + \omega_{N_2} = 1 \quad (4)$$
3. Compressor inlet material gas fraction is 1.

Figure 4 shows the logic of GA optimization. By connecting MATLAB with Aspen HYSYS through ActiveX, the HYSYS simulation is written and read in the MATLAB environment. Because MATLAB has good computing power, variables can be assigned to the HYSYS process, and the results obtained by HYSYS simulation are passed to MATLAB to search for the best results. The tuning parameters optimized by GA are listed in Table 4.

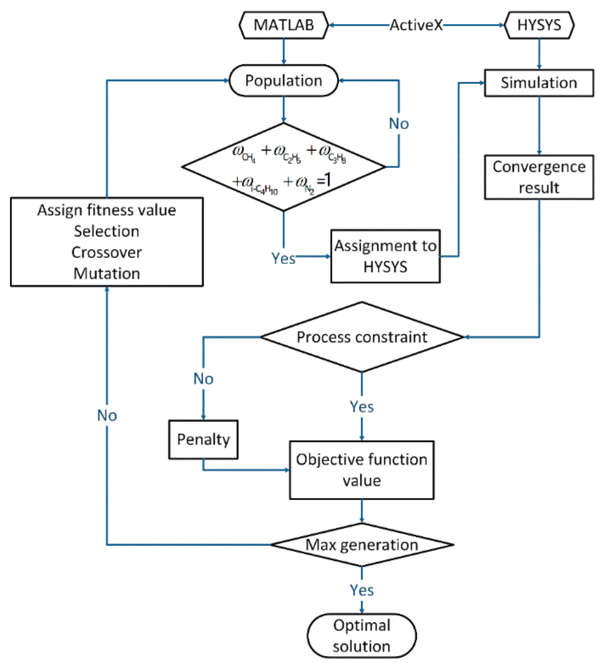

Fig.4 GA optimization logic diagram

Table 4 GA tuning parameter

Parameter	Value
Population size	200
Maximum generations	20
Generation gap	0.9
Crossover fraction	0.7
Selection method	stochastic universal sampling

3.2 Optimization Results

The feed gas temperature of 25°C and pressure of 4500kPa was set for optimization. After 20 generations of genetic iteration, the optimal result appeared in the 17th generation. Compared with baseline case under the same assumptions, the optimal result S_{Total} is 0.3821kW·h/kg, which is 37.9% lower than the specific energy consumption 0.615kW·h/kg before optimization. The optimization results and baseline case results are listed in Table 5.

Table 5 Optimization results and baseline case rusults

Variables	Value	Baseline case
$\dot{m}_{MR}$ (kg/h)	4830	6980
$\dot{m}_{C_3}$ (kg/h)	2000	2756
$T_{1outlet}$ (K)	226.3	235
$T_{1outlet}$ (K)	151.5	175
Mass fractions (CH_4/C_2H_6/ C_3H_8/i-C_4H_{10}/ N_2)	0.2338/0.3405/ 0.0597/0.3163/ 0.0497	0.1763/0.3361/ 0.1223/0.3076/ 0.0577
S_{Total} (kW·h/kg)	0.3821	0.615

The pinch temperatures of the optimized heat exchangers 1HX, 2HX, and 3HX are 5.0K, 3.1K, and 4.9K, respectively. The hot composite curve and cold composite curve match very well. Figure 5 shows the cold and hot composite curve for heat exchanger 2HX.

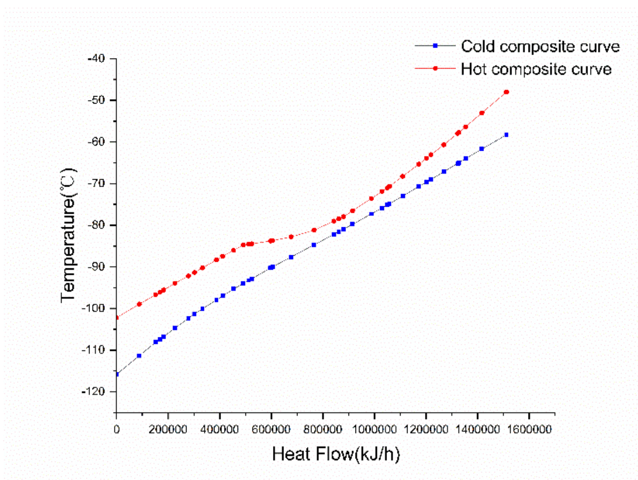

Fig.5 Cold and hot composite curve for heat exchanger 2HX

3.3 Discussion on Mixed Refrigerant Components

The unit mass single component refrigerant compression power consumption w_i can be calculated by HYSYS under the same compression conditions. According to the optimized compression refrigerant ratio, multiplied by the corresponding compression power consumption w_i and then summed, the result W_{Ri} is 0.0968kW·h/kg, as Eq. (5).

$$W_{Ri} = \sum w_i \omega_i \qquad (5)$$

Although the thermal properties of the mixed refrigerant will change due to mixing, W_{Ri} is similar to the unit mass mixed refrigerant compression power consumption W_{MR} 0.0963kW·h/kg, and the relative error is 0.52%. Therefore, the compression power consumption of single refrigerant can be referenced. The latent heat of vaporization of several refrigerants and the compression power consumption per unit mass of single refrigerant are shown in Table 6.

Table 6 Unit mass compression power consumption and latent heat of vaporization of refrigerant

Refrigerant	CH_4	C_2H_6	C_3H_8	i-C_4H_{10}	N_2
w_i (kW·h/kg)	0.193	0.093	0.056	0.041	0.117
Latent heat of vaporization (kJ/kmol)	8294	14787	18804	21206	5595

Due to the large temperature span of these heat exchanges, different refrigerants undertake heat exchange in different temperature ranges. C_3H_8 and i-C_4H_{10} provide cooling capacity at temperatures around 233K. Although the process sets a propane pre-cooling cycle at 1HX, the thermal load of the 1HX heat exchanger is the highest of the three heat exchangers, so the $\omega_{C_3H_8}$ and $\omega_{i-C_4H_{10}}$ account for more than 37%. The values of $w_{C_3H_8}$ and $w_{i\text{-}C_4H_{10}}$ listed in Table 6 are relatively lower than that of the other refrigerants, so the higher mass fraction of these two components will have a certain effect on the total power consumption reduction. However, there are 206 groups of $\omega_{i-C_4H_{10}}$ higher than 35%, 186 groups of mixed refrigerants contained liquid phase at the compressor inlet by comparing the 3800 different mixture ratios in the genetic algorithm program. This is because i-C_4H_{10} has relatively high boiling point. If the mass fraction is too high, $\omega_{i-C_4H_{10}}$ in the mixed refrigerant will be in liquid phase when entering compressor. So $\omega_{i-C_4H_{10}}$ should be controlled below 35%.

C_2H_6 mainly provides cooling capacity in the temperature range of heat exchanger 2HX, which has large unit mass power consumption and high latent heat of vaporization relatively. If its proportion is great, the power consumption will be large. It is necessary to divide the temperature range reasonably, when the 2HX heat exchanger is designed. CH_4 and N_2 are the main refrigerants in Cryogenic heat exchanger. Due to N2 has low boiling point, it can cover the natural gas liquefaction zone. Nevertheless, the vaporization latent heat of N2 is the lowest in the five mixed refrigerants. The unit mass of N2 brings less cooling capacity and consumes more power, so ω_{CH_4} is more than ω_{N_2}. In the algorithm results, 103 groups in which the pinch temperature of the 3HX heat exchanger is less than the constraint, and 93 of them are the sum of ω_{CH_4} and ω_{N_2} less than 20%. Therefore, in order to ensure the effective operation of the cryogenic heat exchanger, it is necessary to specify the sum of ω_{CH_4} and ω_{N_2} greater than 20% in this process.

4. CONCLUSIONS

The specific energy consumption and refrigerant composition optimization of the propane precooled mixed refrigerant liquefaction cycle were studied in this paper. The genetic algorithm is used to optimize the process by analyzing the effects of different variables in the process. The conclusions are as follows:

1. When the feed gas flow rate is constant, specific energy consumption S_{Total} decreases as the feed gas pressure increases if the feed gas inlet temperature does not change. When the feed gas inlet pressure does not change, S_{Total} decreases as the feed gas temperature decreases. In addition, the refrigerant and heat exchanger outlet temperature are important variables affecting process power consumption.
2. The optimal result S_{Total} is 0.3821kW·h/kg, which is 37.9% lower than the base case. The mixed refrigerant flow rate is 4830kg/h. And the hot composite curve and cold composite curve match very well while pinch temperature meets the requirements.
3. Properly increasing C_4H_{10} mass fraction $\omega_{i-C_4H_{10}}$ is beneficial to reduce power consumption, but if $\omega_{i-C_4H_{10}}$ exceeds 35%, it will cause liquid phase in the compressor inlet. In addition, when ω_{CH_4} and ω_{N_2} are less than 20%, the cryogenic heat exchanger capacity will be insufficient.

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