IOP Conf. Series: Materials Science and Engineering **171** (2017) 012022 doi:10.1088/1757-899X/171/1/012022

Multi-objective Optimization on Helium Liquefier Using Genetic Algorithm

H R Wang[1,2],L Y Xiong[1,3,4],N Peng[1,3,4],Y R Meng[1,2],L Q Liu[1,3,4]

[1]Technical Institute of Physics and Chemistry, CAS, Beijing, 100190, China

[2] University of Chinese Academy of Science, Beijing, 100190, China

[3]Key Laboratory of TIPC, CAS, 100190, China

[4]State Key Laboratory of Technologies in Space Cryogenic Propellants, 100190, China

*corresponding author's email: Lianyou Xiong@mail.ipc.ac.cn

Abstract. Research on optimization of helium liquefier is limited at home and abroad, and most of the optimization is single-objective based on Collins cycle. In this paper, a multi-objective optimization is conducted using genetic algorithm (GA) on the 40 L/h helium liquefier developed by Technical Institute of Physics and Chemistry of the Chinese Academy of Science (TIPC,CAS), steady solutions are obtained in the end. In addition, the exergy loss of the optimized system is studied in the case of with and without liquid nitrogen pre-cooling. The results have guiding significance for the future design of large helium liquefier.

1.Introduction

It's known that for a refrigeration cycle, the power needed increases sharply with lowering of the refrigeration temperature. Ideally, 70.43 W power is needed to be done on the refrigeration system to get 1W cooling capacity at 4.2 K. Certainly more power is expected to get liquid helium, so an optimization design means a lot for reducing energy consumption. Some optimization studies have already been carried out on helium liquefier and most of them are in theory. Rijo Jacob Thomas et al[1] have conducted an exergy analysis on Collins cycle, results show that the first and the last heat exchanger should be taken seriously for their low exergy efficiency. In addition, the optimal mass flow into expanders is found to be 80% of the total mass flow. Rijo Jacob Thomas et al [2] also analyzed the effect of the number of the Brayton cooling stage in a helium liquefier. It is found that the optimal number of Brayton cooling stage is four to achieve the highest exergy efficiency. There is no obvious increase in exergy efficiency when adding more cooling stages. M.D.Atrey[3] found that the optimal mass fraction into expander is 80% to realize the maximum liquefaction rate as well as the minimum power consumption by developing a computer program, this is one of the few multi-objective optimization studies on helium liquefier. G.Cammarata et al [4] conducted optimization on thermodynamic parameters using genetic algorithm to get the lowest specific power consumption for helium liquefier where two expanders are connected in series. However, there is no discussion about the financial cost when area of heat exchangers increase.

Aiming at the shortcomings of the previous studies, a multi-objective optimization is carried out by genetic algorithm (GA) in this paper. It is known that adding area of heat exchangers leads to reducing of temperature difference when the heat load is certain, the exergy loss will decrease in the end. However, increasing area of heat exchangers means financial cost increases at the same time. The dilemma is well solved by GA method, which performs excellently in multi-objective optimization. Mass fraction and temperatures into expanders, intermediate pressure between two expanders are variables to be optimized. The calculation converges after several generations and steady solution is reached. The exergy efficiency is also calculated and it is improved compared to the original data.

2.Optimization method

The scheme of helium liquefier focused on is presented in Fig.1. It is considered as no liquid nitrogen pre-cooling case when mass flow of liquid nitrogen equals zero. The original characteristic parameters are displayed in table 1 for the purpose of comparison.

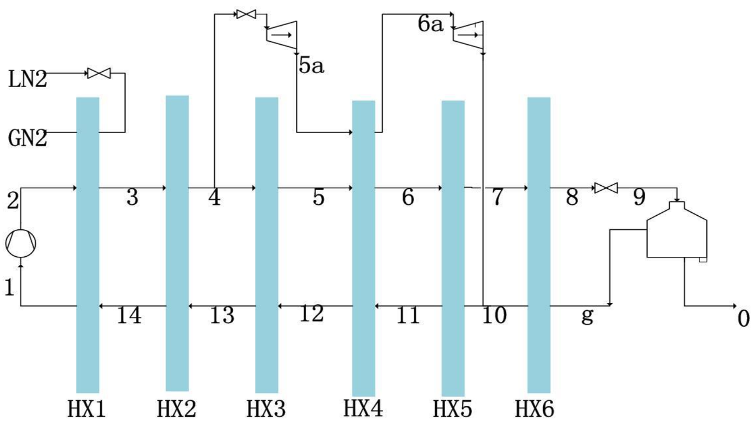

Figure 1. Flow chart of the helium liquefier

Table 1. Original characteristic parameters

	UA(kW/K)	y	FOM	T4/K	T6a/K	me	P5a/kPa
With LN2	376.4	0.0568	1.516e-4	45	14.37	0.74	610
Without LN2	292.4	0.0184	0.629e-4	57	16.24	0.81	725

2.1 Assumptions

The following assumptions are made to simplify calculation model:

(1) The mass flow to compressor is assumed to be 1 kg/s.

(2) The system is working at steady state.

(3) Dependency of variation in pressure, temperature and mass flow on the efficiency of compressors and expanders has been considered negligible [2].

(4) The efficiency of two turbines are assumed to be 69% and 66% respectively.

(5) The heat leak and other ir-reversibility are ignored.

(6) The low and high pressures are set 105 kPa and 1290 kPa. Prssure drops of the hot side and cold side of heat exchangers are 1 kPa and 2 kPa respectively.

2.2 Method of optimization

GA is a very useful method in multi-objective optimization. It converges as long as the object function and the genetic factors are well chosen. The mass fraction (me) and temperatures (T4, T6a), intermediate pressure (P5a) are variables to be optimized to obtain maximum liquefaction rate as well as minimum heat exchanger area. A computer program is developed to realize thermodynamic calculations and evolutionary process. The conservation law and the second law of thermodynamics, speed of turbine which shouldn't be higher than 250 m/s are constrains in the optimization. The detailed genetic factors are shown in table 2.

Table 2. The main factors of GA

parameters	Selection probability （Ps）	Cross probability （Pc）	Mutation Probability (Pm)	Individual number	Chromosome length	Evolutionary generation
value	0.89	0.82	default	1000	30	60

The system's economic performance has been considered as an evaluation index, which is:

$$FOM = \frac{y}{UA} = \frac{m_f / m_c}{\sum \frac{Q_i}{\ln T_i}} \quad (1)$$

Where, y is the liquefaction rate which is defined as the ratio of liquid helium mass flow to compressor mass flow. UA means the sum of the product of overall heat transfer coefficient and heat transfer surface area of all the heat exchangers.

3. Results and discussion

3.1 The optimal solution

The evolutionary processes of these two cases are shown in Fig.1 and Fig.2 respectively. The variation of the population mean value and the optimal solution in every generation are plotted at the same time. y is the liquefaction rate which is defined as the ratio of liquid helium mass flow to the total mass flow into compressor. UA is the product of overall heat transfer coefficient (W/m2.K) and heat transfer surface area (m2) [5]. Obviously, stable solutions are reached when generation reaches 60. Table 2 gives the optimal solutions and object function values in detail.

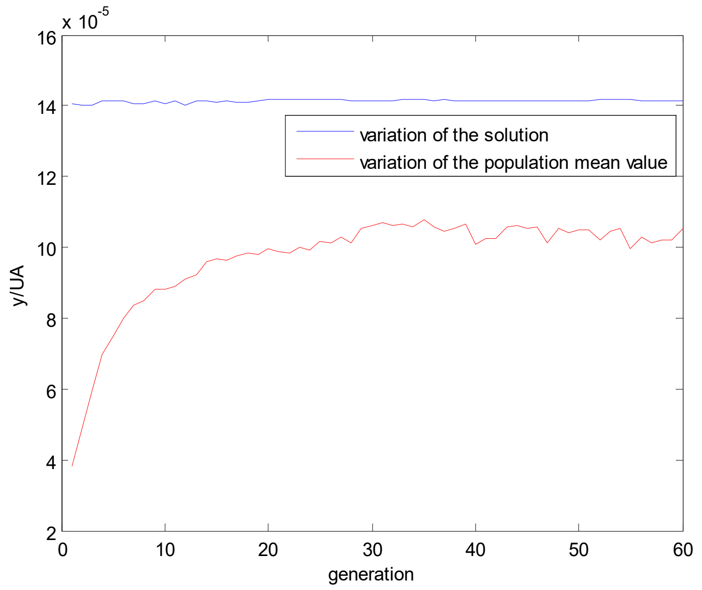

Figure 2. The evolutionary process in the case of without nitrogen pre-cooling

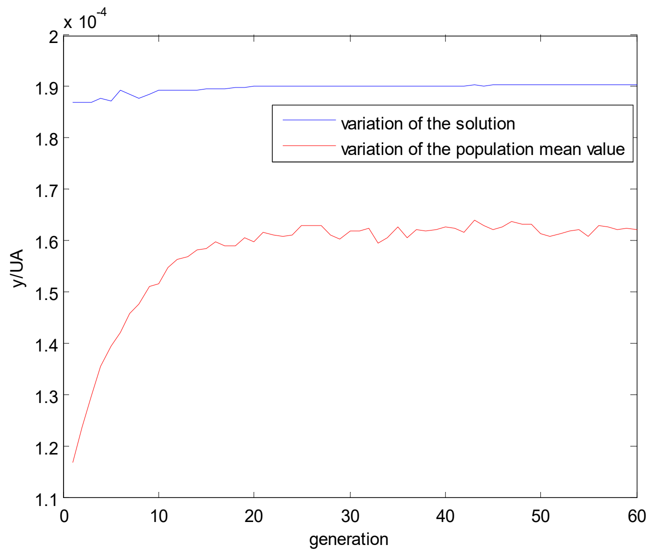

Figure 3. The evolutionary process in the case of with nitrogen pre-cooling

Table 3. Detailed optimal solutions

	UA(kW/K)	y	FOM	T4/K	T6a/K	me	P5a/kpa
With LN2	323.9153	0.0616	1.90e-04	48.08	14.50	0.77	500.01
Without LN2	213.8296	0.0303	1.42e-04	66.55	16.21	0.86	572.08

From table 3 we can see the optimal parameters and two optimal object function solutions. UA is larger when helium liquefier is pre-cooled by liquid nitrogen and liquefaction rate is almost two times of that without nitrogen pre-cooling. It can be compared by FOM which indicates the economic performance to decide the performance of the system. Obviously, the system performs better when liquid nitrogen pre-cooling is added. In addition, compared with the case of with nitrogen pre-cooling, the inlet temperatures and mass fraction of expanders are higher to produce more cooling ability when nitrogen pre-cooling isn't attached.

Compared with the reference value presented in table 1, FOM increases greatly in the optimal condition. Liquefaction rate increases and UA decreases at the same time when parameters are set to be the optimal ones achieved by GA.

3.2 exergy analysis of the optimized system

The liquefaction cycle performs at higher economic efficiency after optimization. Except for the economic effectiveness, a further explore on the exergy loss is conducted and the flow charts of exergy are shown in figure 4 and figure 5.

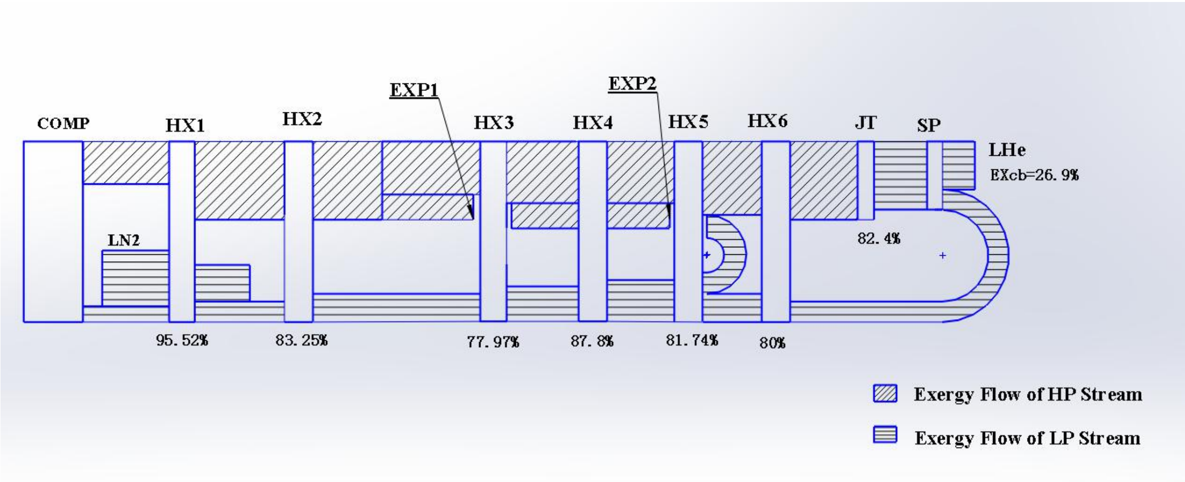

Figure 4. The exergy flow chart with nitrogen pre-cooling

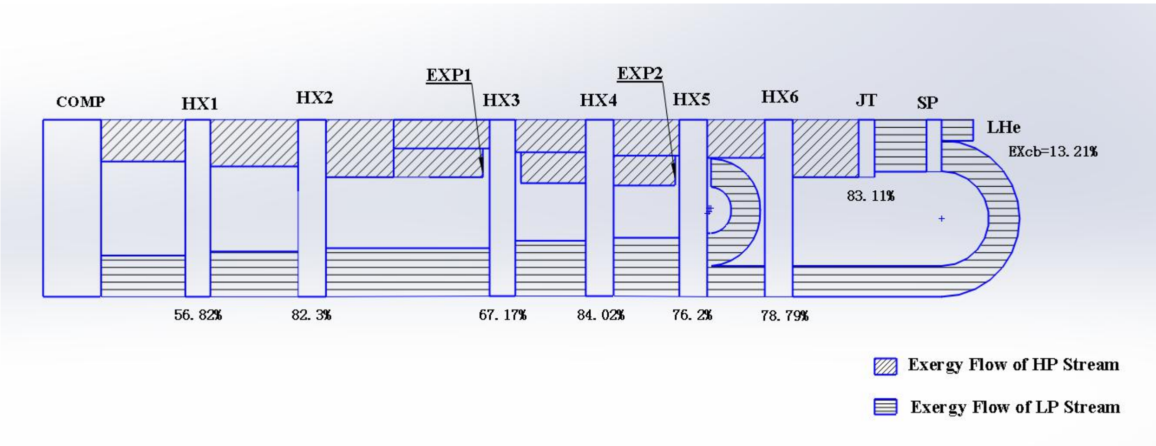

Figure 5. The exergy flow chart without nitrogen pre-cooling

The exergy efficiency is attached below the corresponding component. The exergy efficiency of cold box is 26.9% when pre-cooled by liquid nitrogen, which is almost two times of that without nitrogen pre-cooling. The mainly reason is that nitrogen pre-cooling enhance the exergy efficiency of HX1 greatly and there is slightly increase of exergy efficiency for HX2, HX3, HX4 and HX5.

4. Conclusion

A multi-objective optimization has been conducted on an existing helium liquefier, the results show a great improvement in economic performance. An exergy analysis is also performed to show the detail of exergy flow, the following conclusions can be drawn:

(1)The optimal solutions are reached by genetic algorithm in two case, it shows great improvement compared with the reference values. The liquefaction rate increases and UA decreases at the same time.

(2)When liquid nitrogen pre-cooling is added, the liquefaction rate is almost two times of that in no nitrogen pre-cooling condition.

(3)When liquid nitrogen pre-cooling is added, the exergy efficiency of cold box is almost two times of that in no pre-cooling condition, which coincidences with the trend of liquefaction rate.

(4)Exergy analysis shows that the main reason for improved efficiency of cold box is the nitrogen pre-cooling.

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