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Research article

Prediction model and its application of helium extraction OPEX based on response surface methodology

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ABSTRACT

Focusing on the situation of the low helium content in natural gas resource in China and the high cost of helium extraction, the OPEX prediction model of helium extraction that based on the Response Surface Methodology (RSM) is proposed. This method applies ASPEN-HYSYS software to simulate the helium extraction process flow for a given product composition, pressure, and temperature; Applying the Design Expert module for Response Surface Methodology(RSM) parameter design, combined with OPEX of existing projects, determine the key influencing factors and upper and lower limits of OPEX, and obtaining the corresponding OPEX for different parameter values; Applying the Box Behnken Design (BBD) principle to optimize the helium extraction process parameters of RSM, based on fitting results and parameter significance verification of second-order regression function, the OPEX prediction model is built.This method is applied to a domestic helium extraction project, and the unit helium extraction cost is between 100 and 119.52 yuan/m^3, IRR is 13.37%. The result shows the project has economic benefit, and the method presents a good perspective application.

1. Introduction

As an indispensable rare strategic resource which has a major development in the area of Aviation and Medical and high-tech industry[1], helium plays an increasingly important role nowadays. China is short of helium resources, low helium content in natural gas fields, and the long-term external dependence is over 95% which lead to the high risk of the disruption of supply[2]. At present, industrial helium is mainly extracted from natural gas, so it is necessary to analyze the economic benefits of extracting helium. Helium extraction technology includes single helium extraction, combined natural gas extraction and co-production natural gas extraction. Single helium extraction technology includes low temperature method and non-low temperature method. The former is to purify helium by using cryogenic method, and the latter mainly includes pressure swing adsorption (PSA method), membrane separation method and solvent absorption method[3]. The mainstream method currently is cryogenic separation process that investment of equipment and material is relatively high. The emerging cascade membrane separation technology fuel power and other operating costs are the key to restrict the economic benefits of the project. Membrane separation method is a rapidly developing method in recent years[4], which has the advantages of low cost and high flexibility in processing. Optimizing membrane permeability, stage and membrane area can significantly reduce the cost, therefore the economic result of helium extraction can be improved. The combined

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method is to combine several extracting methods, therefore the recovery rate of helium can be improved. The co-production rule is a method that extracting helium, producing LNG, nitrogen removal and other units at the same time, obtaining helium while producing other by-products, to achieve the purpose of reducing unit extraction cost and increasing the whole value chain economic benefits [5,6].

Domestic and foreign scholars mainly study the economic benefits of helium extraction from several dimensions, such as helium resource characteristics, market development status, resource evaluation, exploration and development, and helium extraction technology. The price of helium is related to the cost of production. Zhiming Cai et al.et al. [7] used system dynamics modeling to predict the market price trend of helium, study helium supply patterns, evaluate the future development trend of helium, and predict the availability of helium resources. The results show that the depletion of helium resources will lead to the increase of production costs from two aspects: one is to inhibit investment and thus reduce production capacity; second, rising prices lead to reduced demand, which in turn leads to reduced production and higher costs. Scholes et al. [8]analyzed the economy of helium purification and determined the production cost of helium from two aspects: capital cost and operating cost. The results show that whether helium is produced directly from natural gas or purified using the nitrogen rejection unit (NRU) process, the economic sensitivity is mainly focused on the capital expenditure of the compressor[7–11]. Therefore, improving the efficiency of the compressor and reducing its capital expenditure are the most advantageous ways to reduce the price of helium production. Quader et al. [12,13] evaluated the potential of four mixed film-low temperature distillation processes using ASPEND HYSYS software simulation and techno economic analysis. It is concluded that the mixing process of producing 90% precision helium by HeRU distillation column and integrated with single stage film unit without feed compression is a low cost process design.

In terms of optimization of helium extraction process, Zhang Liping[14] and Hamedi H[15].et al. proposed the combination of natural gas liquefaction process and helium extraction, and used a thermodynamic equilibrium principle to calculate multi-component steam flow to conduct mathematical simulation and optimization of the process. Al-sobhi et al.[16] and Jiang Hong et al. [17] and Hamedi H[18] analyzed the process flow of extracting helium from LNG tail gas in a large helium liquefaction plant. Zheng Peijun et al. [4] studied the membrane separation method for helium extraction [8], analyzed the selection of separation membranes, explored the use of a two-stage gas-liquid membrane separation system, and optimized the helium extraction process from the perspective of energy consumption. Wang Jinbo et al.[17] and Quader M A et al.[12]designed the helium extraction process of two-stage low temperature distillation and nitrogen cycle refrigeration, and used BP neural network to optimize the low temperature helium extraction process. Rong Yangjia et al.[19] proposed self-produced refrigerant refrigeration, expansion refrigeration, integrated cooling box heat exchange and flash helium extraction co-production processes. Zhou Junet al.[5] combined the cryogenic separation process of natural gas for helium extraction with the membrane separation process to improve the volume fraction and recovery rate, and at the same time, combined with the natural gas ethane recovery process to maximize the utilization of cold energy, established the

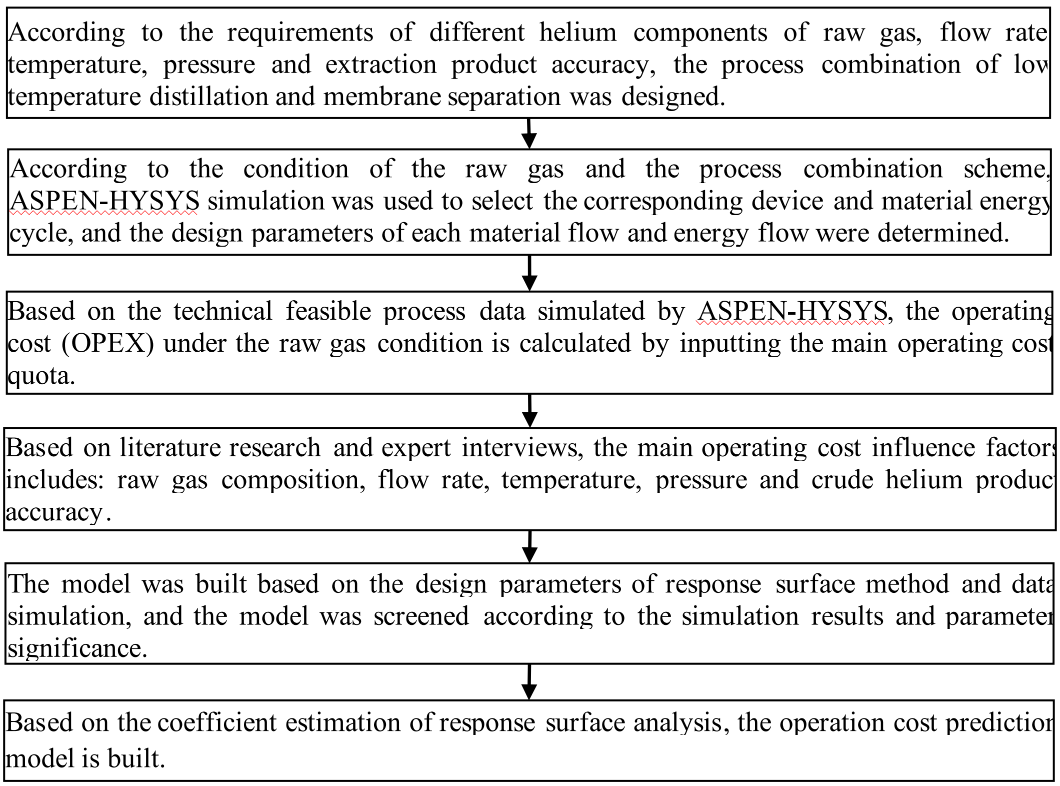

Fig. 1. Flow diagram of an OPEX prediction method for helium extraction combined process.

cryogen-membrane separation process of natural gas for helium extraction with co-production of ethane.

The investigation shows that there is no mature helium operating cost forecasting method at home and abroad, mainly in the following aspects: (1) there is a lack of unified methods and standards for helium extraction cost estimation at present, which makes it difficult to compare different research results. (2) Existing studies lack systematic research on the influencing factors and key drivers of operating costs, and the impact of different factors on operating costs cannot be comprehensively evaluated. (3) Existing studies lack systematic research on the influencing factors and key drivers of operating costs, and the impact of different factors on operating costs cannot be comprehensively evaluated. This paper focuses on the important technical requirements of low cost helium extraction, and discusses the operation cost prediction model based on response surface methodology and cost classification based on technological drivers, which improves the process reliability of helium projects and provides technical support for low-cost helium extraction technology.

2. Methodology

In view of the key parameters such as raw gas composition, helium concentration, helium extraction scale, natural gas production mode and sales market that affect the helium extraction process and efficiency, different helium extraction process design and parameter optimization, helium extraction plant investment method, operation cost prediction model, and incremental benefit evaluation method are studied (Fig. 1). Based on a combination of low temperature distillation and membrane separation,the operation cost prediction method for optimizing helium extraction process is proposed, which mainly includes: according to the extraction requirements of the different helium content of the raw gas and crude helium, the integrated process scheme for low temperature distillation and membrane separation is designed, thereby devices and the circulation of material flow and energy flow under different process combinations is determined; Based on the component content of raw gas, gas-liquid flow rate, process equipment and requirements of pressure and temperature, then the input quota of materials, labor and power in each process is determined. ASPEN-HYSYS software was used to simulate the combined process flow of low temperature distillation and membrane separation with given product composition, pressure and temperature, and the operating cost of the process flow was calculated. The response surface method was used to establish the nonlinear regression model of the optimization objective and the main process parameters to find the optimal process flow and parameters. Under the optimal process flow, the key influencing factors and the upper and lower limits of operating costs were determined based on literature research and production practice. The response surface parameters were designed by Design Expert software, and the operating costs corresponding to different parameter values were simulated by ASPEN-HYSYS software. The operating cost model was constructed based on the parameters designed by response surface analysis and the numerical simulation results. The model was screened according to the fitting results and parameter significance, and the operating cost prediction model was determined by the estimation of the response surface analysis coefficient. This method optimizes the helium extraction process, improves the prediction accuracy of the helium extraction operation cost, and accurately evaluates the economic value of helium projects in combination with feedstock gas conditions, process material flow and energy flow design, and product output, providing method support for the economical and effective acquisition of key mineral resources and the value-added of natural gas industry chain.

This method optimizes the helium extraction process and improves the prediction accuracy of helium extraction operation cost. Combined with the raw gas conditions, process material flow and energy flow design and product output, the economic value of helium projects can be accurately evaluated.

3. Application

3.1. Optimization of helium extraction process

According to the requirements of different raw gas helium components, flow rate, temperature, pressure and precision of crude helium extraction, the combined and integrated scheme of helium extraction process was determined. At present, the combination of low temperature distillation and membrane separation is the mainstream helium extraction process, The helium extraction unit is divided into four parts: primary concentration, secondary concentration, nitrogen cycle and membrane separation, using post-expansion and nitrogen cycle refrigeration, two-tower low temperature separation and membrane separation. However there is a large degree of freedom in the design of the mixing process, including the determination of the internal circulation flow of the membrane and distillation unit, the location of the side pumping of the distillation tower, and various options for thermal integration between the low temperature distillation unit and the membrane unit operating at close to the ambient temperature. Among them, the preset parameters of raw gas mainly include: raw gas composition, pressure (raw gas pressure), flow rate (raw gas flow rate), temperature (raw gas temperature degree) and extraction precision of crude helium products.

By comparing the helium co-production process of flash extraction[19], the cryogeny-membrane separation technology of natural gas co-production of ethane[5], the helium co-production process of natural gas co-production of LNG[20], the NGL recovery, nitrogen removal and the integrated helium extraction process[15] the direct heat transfer method (DHX) is used in the flash helium co-production process to reduce energy consumption. The cryogenic-membrane separation and helium extraction process of natural gas combined with the cryogenic-membrane separation and helium extraction process to reduce energy consumption; The process of helium extraction from natural gas and co-production of LNG is aimed at natural gas with low helium content (less than 0.5%), using low temperature and high pressure rectification and concentration, natural gas liquefaction, low temperature rectification and helium extraction integration to produce crude helium and LNG, and improve the industrial application value of helium extraction process.

The three processes of NGL recovery, nitrogen removal and helium extraction are integrated. The helium extraction device is embedded in the single column nitrogen removal process, and the natural gas and crude helium are simultaneously used in a single refrigeration cycle to reduce the number of equipment. Compared with the single cryogenic method, these co-production processes reduce the cost of helium extraction and greatly improve the economy. According to the requirements of raw gas composition and product gas in inland helium-poor gas fields in China, a combination scheme of mixed film and low temperature distillation process suitable for low helium-containing gas fields was proposed (Fig. 2). It mainly adopts expansion and nitrogen cycle refrigeration, two tower low temperature separation and membrane separation technology. The helium extraction unit is divided into four parts: primary concentration, secondary concentration, nitrogen cycle and membrane separation. According to the simulation model of ASPEN-HYSYS combined integration scheme(see Fig. 3), the process parameters of the combined integration scheme are determined, which mainly include the temperature of the primary concentrator, the feed pressure of the primary concentrator, the distribution ratio of the bottom of the primary concentrator and the reflux ratio of the secondary concentrator.

This process is applied to a gas field in China, where the helium content is 0.1078%, the proved geological reserves of helium are 45.49 million square meters, the predicted geological reserves of helium are 428 million square meters, the peak production of natural gas is 900 × 10^4Nm^3/d, the designed annual output of refined helium is 320 × 10^4m^3/a, the stable production is 8 years, and the evaluation period is 30 years. Terminal products include pipeline commercial gas, LNG and refined helium, refined helium purity of 99.999%, helium liquefied after shipping.

3.2. *Estimation of helium investment*

According to the feedstock gas condition and process combination scheme, the corresponding device and the material and energy cycle are selected through ASPEN-HYSYS simulation, and the design parameters of each material flow and energy flow are determined. The feedstock gas has been dehydrated and pretreated by deacidification and mercury removal. The feedstock gas is mainly divided into helium, nitrogen and methane. The selection of membrane materials is the key to the economy of helium extraction process. In order to determine the key driver affecting the operating cost, a polymer membrane with high selectivity and high permeability to helium in the raw gas methane and nitrogen was selected for commercial application in this example, and then put into different combinations of helium extraction process for simulation.

Based on the technically feasible process data simulated by Aspen-HYSYS, the operating cost (OPEX) under the feedstock gas condition is calculated by inputting the main operating cost quota. Output feasible simulation process scale data for each technology and calculate total capital cost (CAPEX) and operating cost (OPEX). Capital costs include:

Low-temperature distillation related investment. Low temperature distillation has design requirements for feed pressure and temperature, reflux ratio and feed ratio. This part of investment includes compressor investment, heat exchanger investment, condenser investment and rectification tower investment to meet the design requirements of low temperature distillation.

Investment related to film. The membrane unit investment is calculated according to the membrane area, including the cost of membrane frame, membrane material, connecting valve, supporting structure, instrumentation, and pipeline. The single-stage polymerized membrane can only purify the nitrogen stream containing 2–5% helium to 20–41%, so multiple membrane cascades are required to enhance the effect of purification. (2)Investment in film interstage compressor. It is related to the intermembrane pressure and temperature.

$$Mem_{CAPEX} = CC_{mm} + CC_{mf} = A_m C_m + \left(\frac{A_m}{2000}\right)^{0.7} C_{mf} \tag{1}$$

CCmm and CCmf are the capital cost of the membrane module and its framework. Am, Cm and Cmf are the membrane area (m^2), the unit price of the membrane module (\$/m^2) and the unit price of the membrane frame (M\$). For polymerized and silicon films,

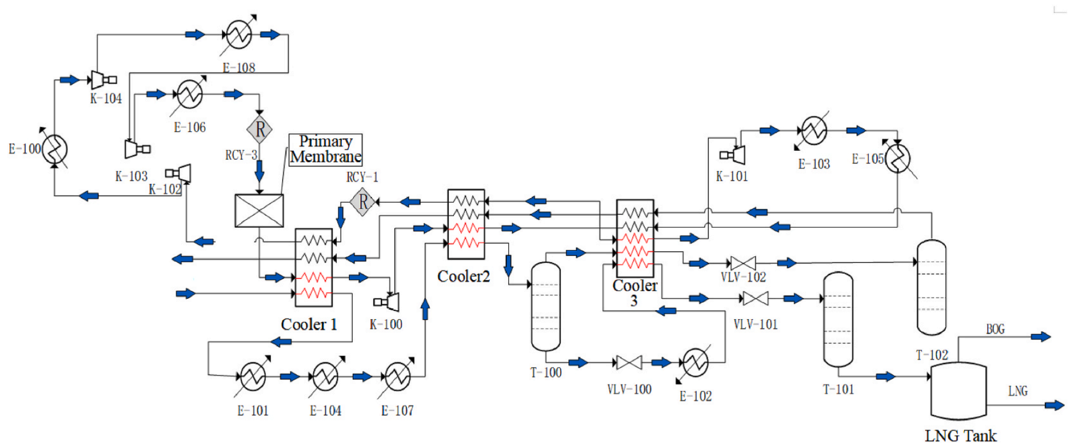

Fig. 2. Process flow chart of membrane separation and low temperature distillation combined production of LNG and helium extraction.

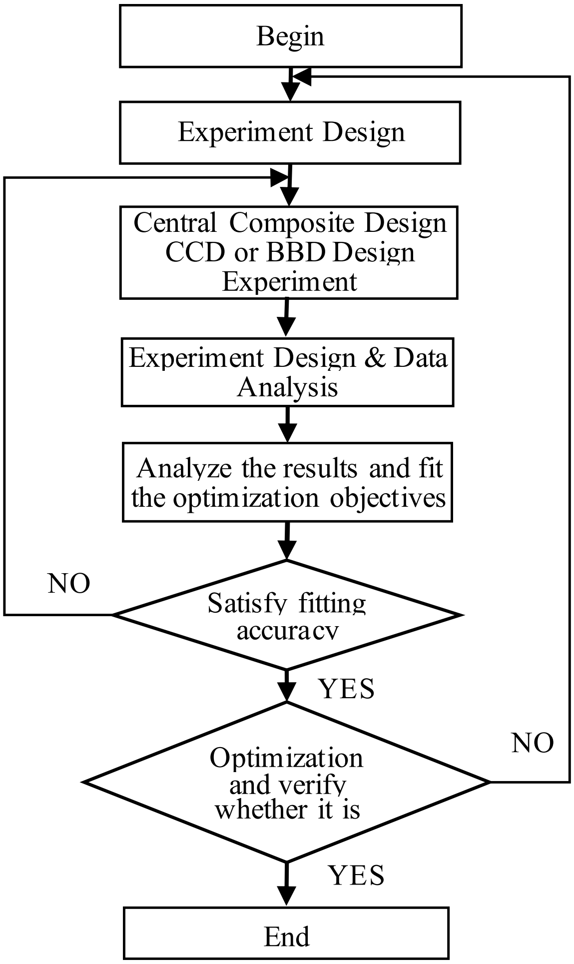

Fig. 3. Optimizing design process by RSM.

assume Cm of $\$50/m^2$ and $\$3000/m^2$, respectively. The Cmf is 0.238 M$.

Multi-stage film interstage compression, K-201, K-202 for the first and third stage centrifugal compressor, K-203 for the oil injection screw compressor. Given the total recovery rate, there is the following relationship between the recovery rates of the two stages:

$$\text{Recov}ery_{Mem-202} = \frac{1 - 1/\text{Recov}ery_{Mem-201}}{1 - 1/\text{Recov}ery_{total}} \tag{2}$$

$$\text{Recov}ery_{Mem-201} \geq \text{Recov}ery_{total} \tag{3}$$

in this command, RecoveryTotal, RecoveryMIM-201, and RecoveryMIM-202 indicate the total recovery amount, the recovery amount of primary and secondary membranes, respectively.

Low-temperature distillation related investment. The main equipment includes condenser, reboiler, distillation tower, and heat exchanger, cooler. According to intake air temperature, pressure and raw material composition of distillation column, plate number, reboiler, condenser load and reflux ratio are calculated. The capital cost is calculated from the number and unit price of the corresponding facilities selected from the temperature, pressure and flow rate of the treated gas during the simulation.

Investment related to storage and transportation. This part is mainly for liquid helium storage and transportation, LNG storage and transportation related investments, including LNG tank area and loading, refrigerant storage equipment, helium storage and loading facilities and empty nitrogen station investment.

Based on the simulation results, the actual cost of the same device of different scales is obtained, and the investment of each process device is estimated. The total investment of co-production LNG helium extraction process is 3.77 billion yuan, and the main investments include: (1) membrane related investment is 125 million yuan. The selection of the membrane is determined by the gas composition, the selectivity and permeability of each component. The economics of membrane separation can be achieved at different temperatures and pressures, and this part of the investment includes membrane facilities, compressors, and heat exchangers. (2) The decarburization dewatering plant is invested 247 million yuan. In this stage, it is mainly decarburized and dehydrated by MDEA solvent and molecular sieve. (3) Low-temperature distillation related investment of 605 million yuan. Low temperature distillation includes LNG liquefaction and demethanation. Low temperature distillation has design requirements for feed pressure and temperature, reflux ratio and feed ratio. This part of investment includes compressor investment, heat exchanger investment, condenser investment and rectification tower investment to meet the design requirements of low temperature distillation. Storage and transportation related investment of 1.955 billion yuan. Mainly the equipment investment involved in the storage and transportation of liquid helium, LNG and refrigerant.

3.3. Response interface design

The Response Surface Method (RSM) was first proposed by mathematicians Box and Wilson in 1951. It simulates the real limit state surface by fitting a response surface through a series of deterministic "experiments". Its basic idea is to assume an analytical expression between a limit state function containing some unknown parameters and the basic variables to replace the function that cannot be clearly expressed.This method is an optimization method that combines experimental design and mathematical modeling, which can effectively reduce the number of experiments and examine the interaction between influencing factors. Generally, Design Expert software is used for response surface methodology experimental design and analysis[21,22].

The input quota of materials, labor and power in each process is determined under the given value, and the input quota is taken as the preset operating cost quota, and then the preset operating cost quota is input into ASPEN-HYSYS, and the process operating cost of the combined integrated solution can be calculated, including: Coaxial compressor energy cost, exhaust compressor energy cost and nitrogen compressor energy cost.

Box-Behnken Design (BBD) response surface analysis method was used to optimize the process parameters. Response surface method (RSM) is an optimization method that integrates experimental design and mathematical modeling, which can effectively reduce the number of experiments and examine the interaction between influencing factors. It uses experimental design to obtain certain data, adopts data regression to fit the functional relationship between factors and response surface, and seeks the optimal process parameters through the analysis of regression equations to solve the multi-variable optimization problem (Table 1).

Aiming at the minimum investment and operating cost of each plant, a nonlinear regression model of optimization objective and main process parameters was established by response surface method to optimize the process flow and obtain the optimal plant design and process parameters. Response surface analysis method uses experimental design to obtain certain data, adopts data regression to fit the functional relationship between factors and response surface, and seeks the optimal process parameters through the analysis of regression equations to solve the multi-variable optimization problem (Table 1). Box-Behnken Design (BBD) response surface method was adopted. In this method, User-Defined design was applied, with the temperature of the primary concentrator (°C), the feed pressure of the primary concentrator (kPa), the logistics distribution ratio at the bottom of the primary concentrator and the reflux ratio of the secondary concentrator as independent variables, and the operating cost and molar ratio of crude helium including the energy consumption of the tower, the exhaust compressor and the nitrogen compressor as response values. A total of 29 test sites were designed, among which 6 groups of repeated tests were arranged to conduct misfit analysis of the expectation function, and optimize values and parameters were obtained (Table 2). Based on the selection of facilities, material flow design and energy flow design involved in the helium extraction process of low temperature distillation and membrane separation, it is concluded that the main factors affecting the operating cost are raw gas composition, flow rate, temperature, pressure and crude helium product accuracy.

3.4. Prediction model establishment

Based on response surface analysis design and different simulated and actual data of helium extraction plant, the upper and lower limits of feedstock gas composition, flow rate, temperature, pressure and crude helium product accuracy were determined. In order to determine the influence of single parameter interaction on plant energy consumption and helium extraction effect, the quantitative relationship between optimization target parameters and other process parameters was established. Data regression is used to fit the functional relationship between the factors and the response surface, and the optimal process parameters are sought by analyzing the regression equation to solve the multi-variable optimization problem. Affected by the preset parameters of feedstock gas, the conditional operating cost will also change with the change of the preset parameters of feedstock gas. Based on the optimal process parameters, the preset parameters of feedstock gas between the upper and lower bounds of each factor were input into the process simulation ASPEN-HYSYS, and the conditional operating costs corresponding to the preset parameters of feedstock gas were obtained.

According to the experimental data, the regression model with raw gas component, flow rate, temperature, pressure and crude helium product accuracy as the response values and considering the interaction between the response values was established, in which

Table 1
Upper and lower limits of response surface parameter design.

NO.	Name	Unit	Type	Min	Max	lower	Upper	Average	Standard variance
A	Helium component in raw gas	mol%	num	0.100	0.50	-1-0.10	+1–0.50	0.30	0.1193
B	Flow rate (processing scale)	10^4 m^3/d	num	10.00	50.00	-1-10.0	+1–50.00	30.00	11.93
C	Pressure	bar	num	10.00	80.00	-1-10.0	+1–80.00	45.00	20.87
D	Temperature	°C	num	30.00	40.00	-1-30.0	+1–40.00	35.00	2.98
E	Crude helium product accuracy	mol%	num	65.00	99.00	-1-65.0	+1–99.00	82.00	10.14

Table 2
Response surface analysis design data.

Std	Run	Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5	RS 1
		A: Helium component	B: Flow rate	C: Pressure	D: temperature	E: Crude helium product accuracy	OPEX
		mol%	10mcm/d	bar	°C	mol%	10 m$
30	1	0.1	30	10	35	82	250.58
17	2	0.3	30	45	30	65	253.769
19	3	0.3	30	45	30	99	253.77
44	4	0.3	30	45	35	82	253.763
40	5	0.3	50	45	40	82	265.735
18	6	0.3	30	45	40	65	253.769
35	7	0.1	30	45	35	99	250.585
22	8	0.3	50	10	35	82	265.735
45	9	0.3	30	45	35	82	253.763
14	10	0.5	30	10	35	82	255.303
20	11	0.3	30	45	40	99	253.77
10	12	0.3	50	45	35	65	265.741
3	13	0.1	50	45	35	82	260.672
23	14	0.3	10	80	35	82	241.107
8	15	0.3	30	80	40	82	253.763
2	16	0.5	10	45	35	82	241.658
6	17	0.3	30	80	30	82	253.763
43	18	0.3	30	45	35	82	253.763
16	19	0.5	30	80	35	82	255.304
34	20	0.5	30	45	35	65	255.303
30	21	0.3	30	80	35	65	253.769
31	22	0.3	30	10	35	99	253.77
1	23	0.1	10	45	35	82	239.9
41	24	0.3	30	45	35	82	253.763
12	25	0.3	50	45	35	99	265.742
7	26	0.3	30	10	40	82	253.763
37	27	0.3	10	45	30	82	241.107
46	28	0.3	30	45	35	82	253.763
29	29	0.3	30	10	35	65	253.769
24	30	0.3	50	80	35	82	265.735
4	31	0.5	50	45	35	82	269.371
25	32	0.1	30	45	30	82	250.58
21	33	0.3	10	10	35	82	241.107
15	34	0.1	30	80	35	82	250.58
42	35	0.3	30	45	35	82	253.763
5	36	0.3	30	10	30	82	253.763
9	37	0.3	10	45	35	65	241.113
26	38	0.5	30	45	30	82	255.31
32	39	0.3	30	80	35	99	253.77
28	40	0.5	30	45	40	82	255.31
38	41	0.3	50	45	30	82	265.735
36	42	0.5	30	45	35	99	255.311
27	43	0.1	30	45	40	82	248.506
33	44	0.1	30	45	35	65	250.585
11	45	0.3	10	45	35	99	241.114
39	46	0.3	10	45	40	82	241.107
36	42	0.5	30	45	35	99	255.311
27	43	0.1	30	45	40	82	248.506
33	44	0.1	30	45	35	65	250.585
11	45	0.3	10	45	35	99	241.114
39	46	0.3	10	45	40	82	241.107

raw gas component, flow rate, temperature, pressure and crude helium product accuracy were independent variables and operating cost was dependent variable [23]. Design-expert software was used to test the significance of linear function, 2FI model, second-order model and third-order model, and a suitable model was obtained by comparing the data of model significance test, missing item test

Table 3
Model parameter selection table.

Parameter	P-valued sequence	Adjusted R^2	Predicted R^2	Remark
Linearity	<0.0001	0.9896	0.9874	
2F1	0.0022	0.9939	0.9895	
Quadratic	<0.0001	0.9982	0.9959	Suggestion
cubic	0.3894	0.9984	0.9768	superposition

and correlation test (Table 3 and Table 4). Among them, temperature, pressure and crude helium product accuracy have no significant influence on operating cost. The fitting model formula (2.4) is as follows:

$$Y = Int + \beta_1 A + \beta_2 B + \beta_3 AB + \beta_4 AD + \beta_5 A^2 + \beta_6 B^2 \tag{2.4}$$

Y represents the annual operating cost, and the unit is $10,000; Int is the constant term, A is the helium component of the feedstock gas, the unit is mol%; B is the flow rate (processing scale), the unit is 10,000 square meters/day; C is the pressure, in bar; D is the temperature, the unit is °C; E is the crude helium product accuracy, in mol%.

According to the analysis of variance, the significance of constant terms, primary terms, quadratic terms (interaction terms) and square terms (surface effects) of the constructed second-order model was tested (Table 5 and Table 6).

The significance of the model coefficients was determined according to the P-value and F-value of ANOVA, and the coefficients of each parameter of the model were obtained (Formula (2.5)).

$$Y = 253.76 + 2.56A + 12.27B + 1.74AB + 0.5185AD - 0.8755A^2 - 0.2237B^2 \tag{2.5}$$

Y represents the annual operating cost, and the unit is $10,000; Int is the constant term, A is the helium component of the feedstock gas, the unit is mol%; B is the flow rate (processing scale), the unit is 10,000 square meters/day; C is the pressure, in bar; D is the temperature, the unit is °C; E is the crude helium product accuracy, in mol%.

The larger the F value and the smaller the P value, the more significant the correlation coefficient can be represented. The model by variance analysis can be considered significant if Prob > F value < 0.05, and extremely significant if Prob > F value < 0.01. The significance of the first-order terms A, B, C, interaction terms AB, AC, BC, quadratic terms A^2, B^2, C^2, and the Lack of Fit term is the same as the model significance.

In the analysis of variance table of the regression equation, it is required that the Prob > F value of the model<0.01, indicating that the response surface regression model has reached a highly significant level, indicating that the fitting accuracy is good and can be used to approximate the model for subsequent optimization design. The lack of fit term (Prob > F value > 0.05) is not significant.

The response surface method overcomes the disadvantage of orthogonal experiments that cannot provide intuitive images. Based on quadratic equations, three-dimensional response surfaces and contour maps of the interaction between experimental factors are created.Response surface analysis can examine the impact of the interaction of two other factors on operational costs when one factor is fixed at a constant central value (Fig. 4). The contour map (Fig. 5) and response surface (Fig. 6) can directly reflect the degree of influence of interaction on response value. The steeper the surface and the denser the contour lines, the more significant the influence, and the closer the contour line is to the ellipse, the stronger the interaction between the two factors.

In contour picture 4, when temperature, pressure and crude helium accuracy are at the center level, the operating cost gradually increases with the increase of flow rate of the same raw gas component. With the increase of raw gas component, the operating cost increases first and then decreases with the increase of flow rate. At the same flow rate, the operating cost increases first and then decreases with the increase of raw gas components.When the nonlinearity of the actual limit state function is not significant, the linear response surface has a high approximation accuracy.

In the operating cost of the helium extraction project obtained by RSM analysis, the power cost is 235 million yuan, the auxiliary material cost is 54 million yuan, the fuel cost is 45 million yuan, and the other indirect cost is 178 million yuan. It is basically consistent with the actual operational data of the project, with a compliance rate of 90.66%.

4. Discussions

The nonlinear grey Bernoulli model was used to predict the helium price [24], and the whale algorithm was used to obtain the optimal model parameters [25]. The helium price is predicted using the Nonlinear Grey Bernoulli Model (NGBM), which is the power form of the grey model. The grey prediction method can use small sample data to quantify its internal uncertainty. The traditional grey model is not suitable for series fitting with high volatility, and can only be used for series with exponential growth. The helium price and its growth rate show nonlinear characteristics, and the nonlinear grey Bernoulli model is used. The parameter values in NGBM model are determined by whale algorithm. The basic parameters are set as population size N = 40 and maximum number of iterations Max_Iter = 50. The nonlinear parameter r can be obtained by Matlab programming, and the parameters a and b can be further obtained. The predicted price value can be obtained by using these parameter values in the modeling process of NGBM model.

The raw material gas of this project is pipeline commercial gas, so the revenue and cost of pipeline commercial gas are not considered in the calculation of revenue and cost. LNG and refined helium production decreases with gas field production, and the total revenue of the project is estimated from the year-on-year decline in LNG and refined helium production and corresponding prices.

From a technical point of view, LNG investments such as demethane plants, helium refining plants, helium liquefaction plants, and helium storage and loading facilities are classified as helium extraction investments. Operating costs can be divided and estimated

Table 4
Model parameter selection table.

Std variance	0.3213	R^2	0.9990
Average	253.34	Adjusted R^2	0.9982
C.V.%	0.1268	Predicted R^2	0.9959
		Signal-to-noise ratio	136.5376

Table 5
Results of model significance fitting.

Source	Sum of Squares	df	Mean Square	F-value	P-value	
Model	2532.85	20	126.64	1226.69	<0.0001	significant
A-Helium Component of Feed gas	104.26	1	104.46	1011.81	<0.0001	
B-Flow Rate (processing scale)	2407.20	1	2407.20	23316.72	<0.0001	
C-Pressure	6.25E-08	1	6.25E-08	6.054E-07	0.9994	
D-Temperature	0.2688	1	0.2688	2.6	0.1191	
E-Crude Helium Accuracy	0.0000	1	0.0000	0.0001	0.9914	
AB	12.04	1	12.04	116.66	<0.0001	
AC	2.500E-07	1	2.500E-07	2.422E-06	0.9988	
AD	1.08	1	1.08	10.42	0.0035	
AE	0.0000	1	0.0000	0.0002	0.9902	
BC	0.0000	1	0.0000	0.0000	1.0000	
BD	0.0000	1	0.0000	0.0000	1.0000	
CD	0.0000	1	0.0000	0.0000	1.0000	
CE	0.0000	1	0.0000	0.0000	1.0000	
DE	0.0000	1	0.0000	0.0000	1.0000	
A2	6.69	1	6.69	64.80	<0.0001	
B2	0.4369	1	0.4369	4.23	0.0502	
C2	0.0029	1	0.0029	0.0276	0.8693	
D2	0.2061	1	0.2061	2.00	0.1700	
E2	0.0050	1	0.0050	0.0480	0.8283	
Residual	2.58	25	0.1032			
Lack of Fit	2.58	20	0.1290			
Pure Error	0.0000	5	0.000000			
Cor Toral	2535.43	43				

Table 6
Parameter estimation and significance analysis.

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	253.76	1	0.1312	253.49	254.03	
A-Helium component of feed gas	2.56	1	0.0803	2.39	2.72	1.0000
B-Flow rate (processing scale)	12.27	1	0.0803	12.10	12.43	1.0000
C-Pressure	0.0001	1	0.0803	−0.1654	0.1655	1.0000
D-Temperature	−0.1296	1	0.0803	−0.2951	0.0358	1.0000
E-Crude Helium Accuracy	0.0009	1	0.0803	−0.1646	0.1663	1.0000
AB	1.74	1	0.1607	1.40	2.07	1.0000
AC	0.0003	1	0.1607	−0.3306	0.3311	1.0000
AD	0.5185	1	0.1607	0.1876	0.8494	1.0000
AE	0.0020	1	0.1607	−0.3289	0.3329	1.0000
BC	0.0000	1	0.1607	−0.3329	0.3309	1.0000
BD	0.0000	1	0.1607	−0.3309	0.3309	1.0000
CD	0.0000	1	0.1607	−0.3309	0.3309	1.0000
CE	0.0000	1	0.1607	−0.3309	0.3309	1.0000
DE	0.0000	1	0.1607	−0.3309	0.3309	1.0000
A2	−0.8755	1	0.1088	−1.10	−0.6515	1.20
B2	−0.2237	1	0.1088	−0.4478	0.0003	1.20
C2	0.0181	1	0.1088	−0.2059	0.2421	1.20
D2	−0.1537	1	0.1088	−0.3777	0.0703	1.20
E2	0.0238	1	0.1088	−0.2002	0.2478	1.20

based on technical drivers, such as decarbonization scale, helium refining scale, decarbonization scale, total processing scale, natural gas liquefaction scale, income and investment drivers. The pressurization device and the ground supporting equipment are divided according to the proportion of the investment of helium extraction and LNG, and the electricity consumption, direct labor costs and operating costs are divided according to the proportion of helium extraction LNG consumption.

Cash inflow is revenue from sales of natural gas and revenue from sales of refined helium, and the sales price of natural gas is the net return price of the gas field, that is, the gate price of the target market less the transportation cost of the delivery point to the target market. Cash outflows include investment, operating costs and taxes, including value-added tax, city construction tax, education surcharge and income tax. Through the incremental evaluation method, it is estimated that the extraction of helium has better economic benefits in view of the multi-scenario analysis of LNG and refined helium as main by-products.

This technology has been used to complete the economic evaluation of helium extraction investment in 8 helium fields in 5 countries, including China, Tanzania, Kazakhstan, Russia and Algeria, and 3 economically recoverable helium fields are recommended, which is expected to achieve economic benefits of 1.222 billion yuan.

However, the RSM still has certain limitations, mainly due to insufficient and incomplete selection of factors, which will lead to

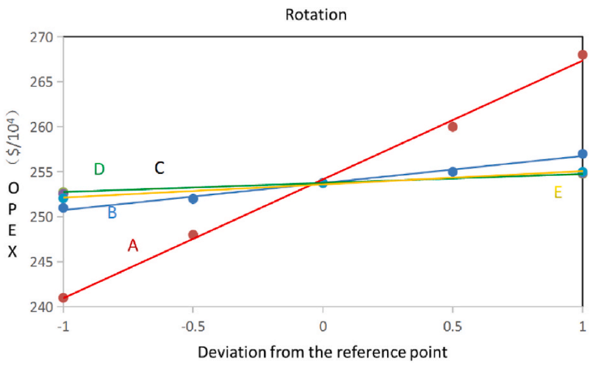

Fig. 4. Sensitivity analysis of OPEX.

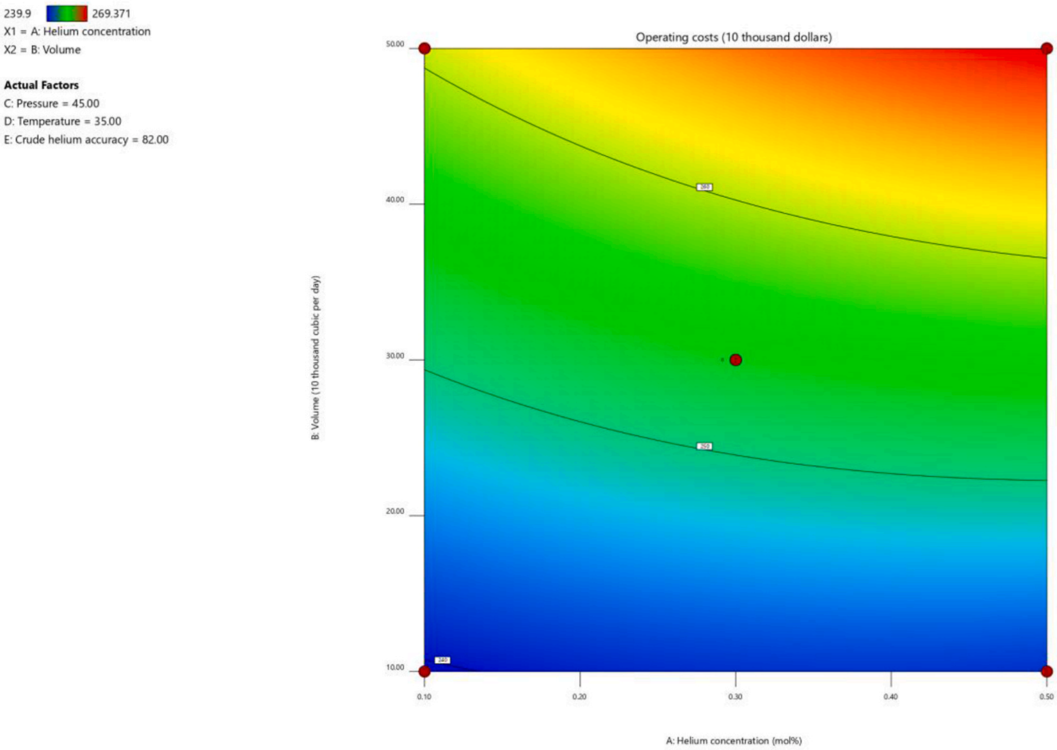

Fig. 5. Interactive effects of raw gas components and flow rate on operating costs.

significant deviation in the results. Secondly, regression results can only be used to evaluate such experiments, and regression data can only be predicted within the limited range of factors.

5. Conclusion

Based on the conditions of raw gas, process material flow, and energy flow, helium extraction process and product design are carried out. By RSM, key drivers of various operating costs in the helium extraction process can be identified, and a nonlinear regression model can be established to optimize the objectives of helium extraction and various main process parameters. It can effectively predict the operating costs of the helium extraction process. The RSM overcomes the horizontal values that can only be discretized in orthogonal design, optimizes the helium extraction process, accurately evaluates the economic value of helium projects. The predicted operating costs are highly consistent with the actual operation of helium extraction projects, it provides methodological support for economically and effectively obtaining key mineral resources and increasing the value of the natural gas industry chain.

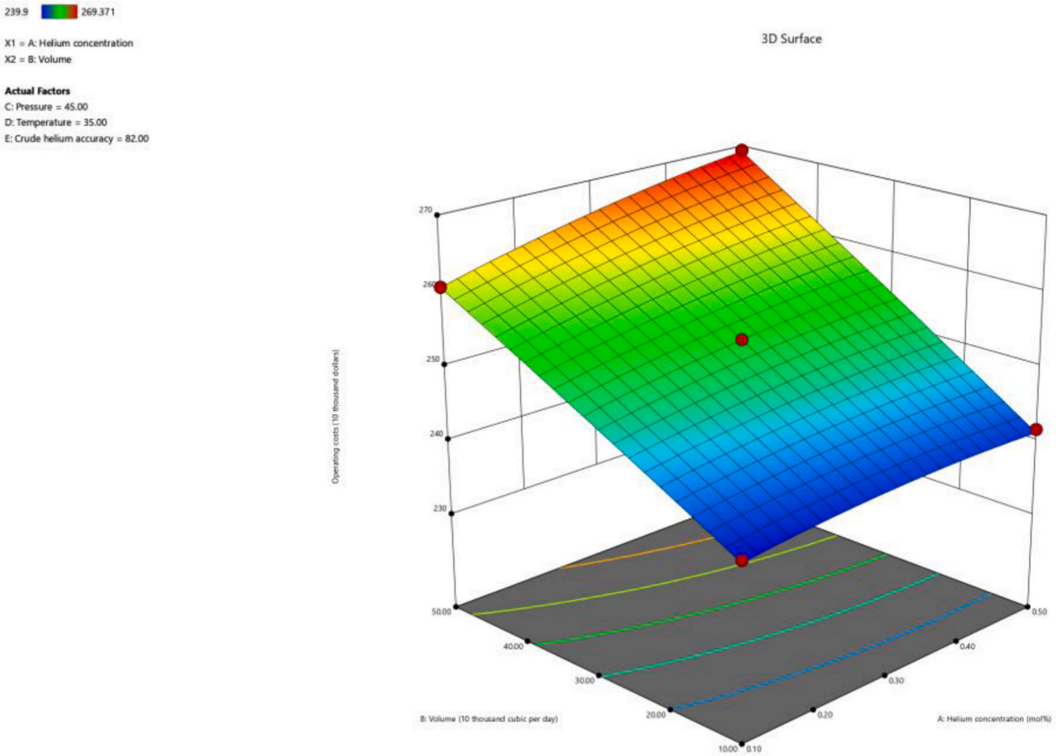

Fig. 6. 3D interactive effects of raw gas components and flow rate on operating costs.

6. Concluding remark

The research data in the paper are all from the actual data of domestic projects in China. Due to confidentiality reasons, the project name is not disclosed. This study is chartered by novel method, reliable data, careful process and reliable conclusion, and effectively guides the reduction of OPEX of helium extraction and provides the basis for formulating investment strategies of these assets.

CRediT authorship contribution statement

Wu Yiping: Formal analysis, Conceptualization. **Liu Shen'aoyi:** Investigation. **Wang Qing:** Data curation. **Chen Rong:** Software, Resources. **He Yuanyuan:** Validation. **Fu Li:** Investigation. **Li Wanting:** Writing – review & editing. **Yang Ruiyi:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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