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Exergoeconomic analysis for crude oil gathering and transportation system in matrix pattern

Qinglin Cheng[1] | Zhidong Li[1] | Chunguang Yu[1] | Hao Wu[2] | Lili Lv[2] | Hongjun Xie[2] | Guoyu Ma[3]

[1]Key Lab of Ministry of Education for Enhancing the Oil and Gas Recovery Ratio, Northeast Petroleum University, Daqing, China

[2]PetroChina Planning & Engineering Institute (CPPEI), Beijing, China

[3]Beijing Oil and Gas Control Center of PetroChina Co Ltd, Beijing, China

Correspondence
Qinglin Cheng, Key Lab of Ministry of Education for Enhancing the Oil and Gas Recovery Ratio, Northeast Petroleum University, Daqing, China.
Email: chengqinglin517@163.com

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Abstract

Based on exergoeconomic theory, the energy consumption situation for a typical oil transfer station in eastern China is evaluated. According to the analysis of the distribution for logistics and exergy flow, the crude oil gathering and transportation system is divided into two subsystems: pipe network and oil transfer station. The unit exergoeconomic costs for each component exergy flow are calculated by computing method in matrix pattern, of which the pressure exergy and thermal exergy at the end of the process are 812.58 yuan/GJ and 1575.24 yuan/GJ, respectively. Simultaneously, exergoeconomic evaluation indicators such as exergy cost growth coefficient, relative cost difference, and exergoeconomic coefficient are calculated, which can conclude the weak link of technical system is heating furnace equipment. The growth value of its exergy cost growth coefficient is 14.988, the relative cost difference is 94.503, and the exergoeconomic coefficient is 9.046, so it has great potential for energy saving. Exergoeconomic analysis method can provide a scientific and effective method or basis during the energy-saving reconstruction for oil gathering and transportation system.

KEYWORDS

crude oil gathering and transportation system, exergoeconomic coefficient, exergoeconomic in matrix pattern, exergy cost growth coefficient, relative cost difference

1 | INTRODUCTION

In 1932, American scientists first mentioned the concept of exergy cost. It was emphasized that the calculation of energy consumption cost should be based on effective energy rather than energy traditionally. Exergoeconomic really came into being in the 1960s, Tribus et al.[1] carried out a study on the exergy cost of seawater desalination device, and exergoeconomic was first defined. Through the unremitting research and exploration of many experts and scholars, it has become a more rigorous and mature discipline.[2,3] The application scope of exergoeconomic is very wide, which can be applied to the treatment of municipal solid waste and can also help to better understand what energy conversion system is.[4,5] At the same time, researchers have made some achievements in the research of energy utilization for sustainable development.[6-8]

During the development process of exergoeconomic, new patterns and methods are constantly emerging. At present, exergoeconomic exists in several relative mature methods: accounting pattern, optimization pattern, structural coefficient pattern, matrix pattern, and exergy technology–economic pattern. With the efforts of scholars at home and abroad for

many years, the study of exergoeconomic has been constantly advancing. Norouzi et al.[9] carried on optimization for heat recovery steam generator (HRSG) design under structural coefficient pattern, in which the optimization objective was the minimum exergy economic cost under fixed volume. Xu et al.[10] analyzed irreversible regenerative ferromagnetic Ericsson refrigeration cycle by means of accounting pattern. Then, regenerator efficiency, heat capacity rate, and corresponding cooling rate of cryogenic regenerator were obtained, which had a certain theoretical guidance for the optimization of cycle design. Hadi et al.[11] made exergoeconomic analysis about a complex system containing refrigeration, heating, power generation, and air purification processes by genetic algorithm. The result showed that the system optimal efficiency was 94.84%. Through the summarization of accounting pattern and algebraic pattern methods, a Spanish scholar, Valero et al.[12] proposed exergoeconomic method in matrix pattern, in which the cost of economics concept and economic theory analysis were better combined with the second law of thermodynamics. At the same time, it provided a solid theoretical basis for the exergoeconomic development.

Most of the previous studies on gathering and transportation system were from the perspective of energy analysis and exergy analysis, in which only energy saving was considered rather than cost saving.[13-15] In this paper, a gathering and transportation system is analyzed combined with exergoeconomics. Not only energy saving is considered, but also the saving of cost investment analysis is taken into consideration, which is also an innovation in the gathering and transportation system. The crude oil gathering and transportation system refers to the mutual transformation of mechanical energy, thermal energy, and electrical energy.[16] Enthalpy analysis method based on the first law of thermodynamics is commonly adopted to analyze energy application situation of engineering system. With the development of thermodynamics theory, entropy analysis method and exergy analysis method on the basis of the second law of thermodynamics are gradually promoted in engineering practice. When thermodynamics analysis fails to meet the requirement of energy saving, it is better to integrate thermodynamics and economics; that is, more comprehensive analysis and evaluation are carried out by the exergoeconomic analysis method.[17] This paper analyzes an oil field gathering and transportation system in eastern China,[18] in which exergoeconomics in matrix pattern is applied.

2 | EXERGOECONOMIC SYSTEM DIVISION IN OIL GATHERING AND TRANSPORTATION SYSTEM

Based on exergoeconomic principle in matrix pattern, an exergoeconomic model of crude oil gathering and transportation system is made after determining energy flow and destroyed exergy pricing methods.[19,20] Taking an oil transfer station as an example, in which the dual-pipe water mixing oil gathering process is adopted. The dual-pipe water mixing oil gathering process chart is shown in Figure 1. And the "three-in-one" process including separation, buffer, and settlement is used in the station as well. Therefore, the interstation production process can be divided into oil system process, natural gas system process, and water mixing system process. That is to say, the fluid in metering plant is separated into three phases of oil, gas, and water through the "three-in-one" device. After being pressurized through the efflux pump, oil in the system can be transported to the combined station. The natural gas system

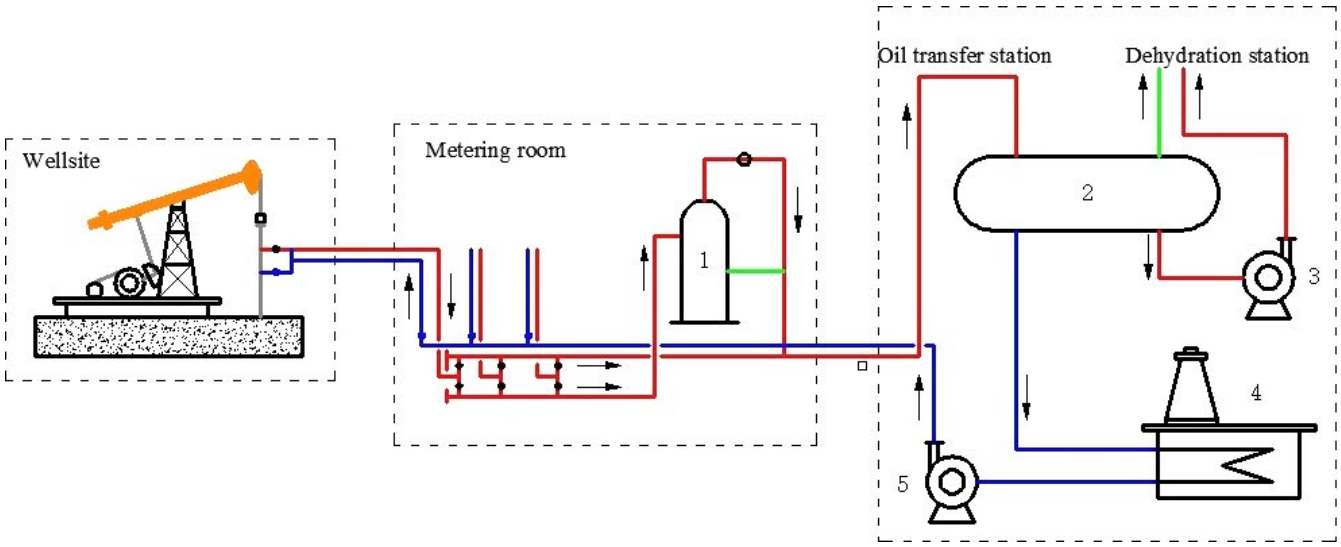

FIGURE 1 The dual-pipe water mixing oil gathering process chart. (1) Metering separator; (2)"Three-in-one" device; (3) Efflux pump; (4) "Two-in-one" device; (5)Water mixing pump

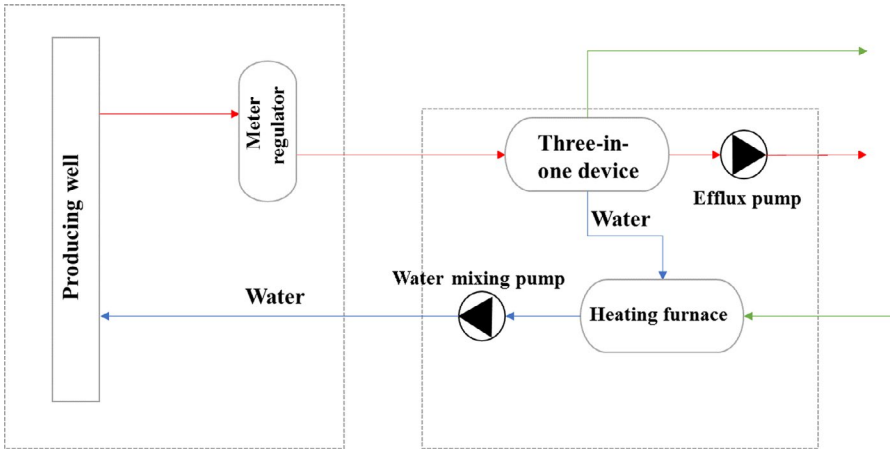

FIGURE 2 The schematic diagram of division of crude oil gathering and transportation subsystem

transmits gas outside to the combined station or heating furnace for its own use. The water is heated and pressurized by the "two-in-one" device and then transported to water mixing valve group in metering plant.

At present, heating furnace, water mixing pump, and efflux pump used in oil field need natural gas or electricity supplied from external to operate. Pipeline operation does not require external energy supply. In order to make the analysis convenient, the equipment which requires external energy from two-in-one heating buffer device, outflow pump, or water mixing pump are grouped into one subsystem, called oil transfer station subsystem. Conversely, those equipment without external energy is grouped into another subsystem, named pipe network subsystem, which mainly includes two sections, from wellhead to metering room and from metering room to oil transfer station. The schematic diagram of division of crude oil gathering and transportation subsystem is shown in Figure 2.

3 | ESTABLISHMENT OF EXERGOECONOMIC MODEL IN MATRIX PATTERN

3.1 | Exergoeconomic analysis model

In terms of the logistics model, the exergoeconomic analysis model chart is shown in Figure 3.

In the model, besides the inlet, outlet exergy flow, and supply exergy, the destroyed exergy of efflux pump, heating furnace, water-mixing pump, and pipelines are included. The internal destroyed exergy is represented by dashed lines, and the others are expressed by solid lines.

3.2 | Establishment of transfer station subsystem matrix

In terms of the transfer station subsystem physical model in oil gathering and transportation system, a gray box model is established. Simultaneously, the system is divided into several subsystems. The exergy analysis model of transfer station is shown in Figure 4.

Where E_{xm1} is physical exergy input from "three-in-one" device, MJ/h, E_{xg} is physical exergy of gas separated by "three-in-one" device, MJ/h, E_{xe1} is electricity exergy supplied to oil pump unit, MJ/h, E_{xl1} is the total destroyed exergy of oil pump unit, MJ/h, E_{xm2} is output physical exergy of oil pump unit, MJ/h, E_{xf} is fuel exergy supplied to "two-in-one" device, MJ/h, E_{xl2} is the total destroyed exergy of "two-in-one" device, MJ/h, E_{xe2} is electricity exergy supplied to water mixing pump unit, MJ/h, E_{xl3} is the total destroyed exergy of water mixing pump unit, and MJ/h, E_{xw} is output hot water exergy of water mixing pump, MJ/h.

In general, a mixture of oil, gas, and water from each metering plant is input to the subsystem. By contrast, water cut crude oil, natural gas, and hot water reinfused in the metering room are output. Supply exergy of system is fuel (natural gas) exergy and electricity exergy. The major energy consumption equipment in transfer station is heating furnace (two in one), efflux pump, and water mixing pump. And the separator (three in one) only isolates liquid from the metering room, with little change in pressure and temperature. Energy consumption is low, and there are only the inflow and outflow of exergy flow. Accordingly, the separator is not mainly analyzed in establishing the transfer station analysis model. In contrast, equipment with high energy consumption is taken into significant consideration[21].

According to Figure 4, there are four devices in transfer station, which are composed of thirteen exergy flow. The event matrix is shown as follows:

$$A=\begin{pmatrix} 1 & -1 & -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \end{pmatrix}$$

In thermoeconomic analysis, the logistics and energy flow in the system are usually classified into "fuel" and "product"[22]. For each subsystem, there can be several fuels, but

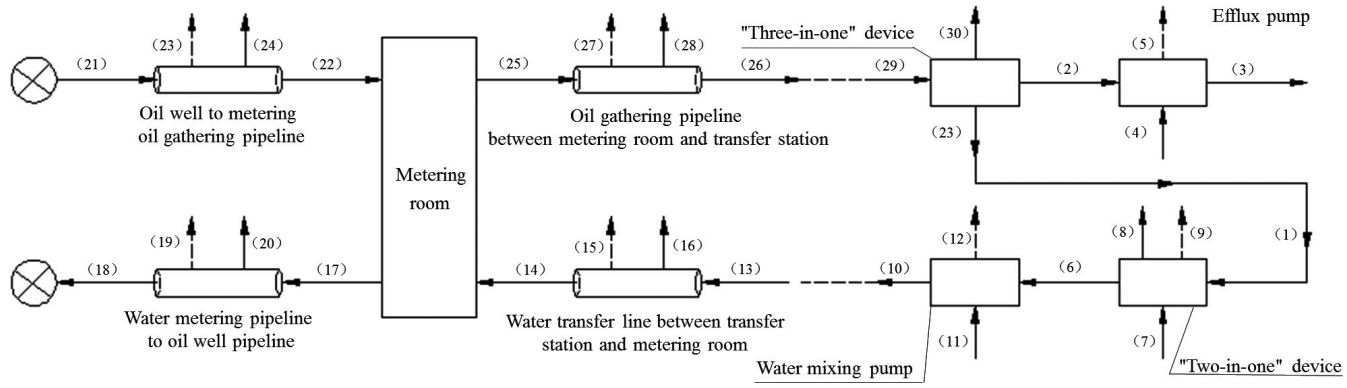

FIGURE 3 Exergoeconomic analysis model chart

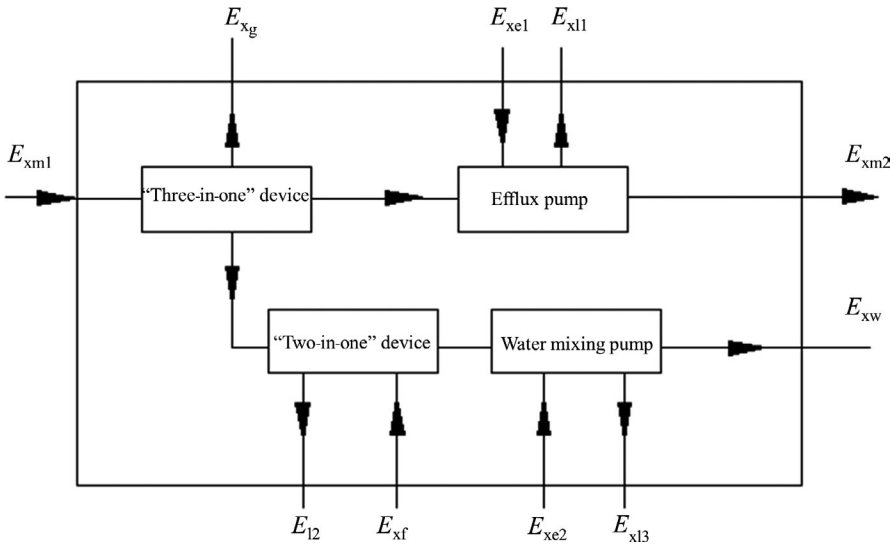

FIGURE 4 Exergy analysis model of transfer station

only one product. Therefore, in this system, fuel–product of transfer station subsystem is shown in Table 1, in which B_i indicates the exergy value of the ith logistics.

Based on the number of exergy flow and subsystems in the system, nine supplementary equations are needed to constitute the exergy cost vector. Among them, the exergy prices of exergy flow E_{xm1}, E_{xg}, E_{xf}, E_{xe1}, E_{xe2} are known; thus, five auxiliary equations can be established in the form of:

$$\alpha_i \times E_D \times C^* = W_i \tag{1}$$

where

$$\alpha_i = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

$$W_i = \begin{pmatrix} C_1 M_1 \\ C_2 M_2 \\ C_3 M_3 \\ C_8 M_8 \\ C_{10} M_{10} \end{pmatrix}$$

where α_i is input exergy flow matrix with 1 as its element, W_i is cost vector of exergy flow, E_D is $(n \times n)$ diagonal matrix of exergy vector, n is the number of exergy flow, $C*$is $(n \times 1)$ cost vector of unit thermal economics.

3.3 | Establishment of pipe network subsystem matrix

The main energy consumption units are composed of four parts: interwell oil gathering pipeline and water mixing pipeline; interstation oil gathering pipeline and water mixing pipeline[23]. Both interwell pipeline and interstation pipeline are dual pipes, and logistics flows in opposite direction. There are only input exergy, output exergy, and destroyed exergy in the pipe network subsystem exergy flow, without supply exergy. In virtue of the high energy consumption of the pipe network subsystem, it is analyzed with the gray box model. The gray box analysis model of pipeline network subsystem is shown in Figure 5.

$$E_{xm1} + E_{xw1} = E_{xm2} + E_{xw2} + E_{xlinm} + E_{xlinw} + E_{xloutm} + E_{xloutw} \tag{2}$$

TABLE 1 Fuel–Product of transfer station subsystem

Devices	Fuel	Product
1	0	0
2	B_4	$B_6+B_5-B_3$
3	B_9	$B_{10}+B_8-B_7$
4	B_{11}	$B_{13}+B_{12}-B_{10}$

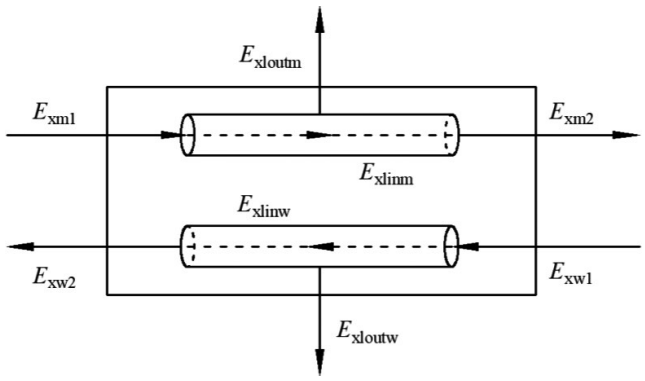

FIGURE 5 Gray box analysis model of pipeline network subsystem

where E_{xm1},E_{xm2} are physical exergy for mixed flow of oil, gas, and water input and output of the pipeline, respectively, MJ/h, E_{xw1},E_{xw2} are hot water exergy input and output of the pipeline, MJ/h, E_{xlinm},E_{xloutm} are internal and external destroyed exergy of mixed flow pipeline, MJ/h, E_{xlinw},E_{xloutw} are internal and external destroyed exergy of hot water pipeline, MJ/h.

The exergy flow and destroyed exergy, in and out the pipeline model, have the same type and quantity, but only the transmission media and its parameters are different. The number of oil wells, metering rooms, and pipelines in the system is excessive. Consequently, during pipeline cost composition analysis and exergoeconomic model establishment, only a single well or a single metering room is taken as an example.

For instance, an economics model is established through the water mixing pipeline from oil well to metering room and from metering room to oil transfer station. As can be seen from the figure, the transfer station is composed of six exergy flow, and the event matrix is shown as follows:

$$A=\begin{pmatrix}1 & -1 & -1 & 0 & 0 & 0\\ 0 & 0 & 1 & -1 & 0 & 0\\ 0 & 0 & 0 & 1 & -1 & -1\end{pmatrix}$$

According to the number of exergy flow and subsystems, three supplementary equations are required to get the exergy cost vector, in which the unit price of exergy flow E_{xm1} is known. And one auxiliary equation can be established as follows:

$$\alpha_i \times E_D \times C^* = W_i \tag{3}$$

where

$$\alpha_i = (1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0)$$

4 | EXERGOECONOMIC COST DETERMINATION

For a single product system, the product cost can be calculated directly with the cost equation.[24] In oil gathering and transportation system,[25] the products are usually more than two. Therefore, it should be solved by reasonable cost allocation principles and methods. Currently, the common methods are as follows: extraction method, equivalent method, by-product method, and energy-level method.

Oil gathering and transportation system usually outputs many required products and consumes different costs of fuel, and the extraction method and energy-level method are more suitable. The extraction method fails to distinguish energy quality influence on its cost; on the contrary, the energy-level method can differentiate the change of energy quality and distribute the price.[26] As a result, the calculation results in energy-level method are more accurate and reasonable. And the auxiliary equation is introduced by energy-level method in this paper.

4.1 | The introduction of auxiliary equation with energy-level method

4.1.1 | The introduction of auxiliary equation in the station subsystem

By introducing energy-level coefficients, auxiliary equations are established with the energy-level method. Electric and mechanical energy have high grade and can be converted into work in energy conversion process. The energy-level coefficient λ is 1. The other forms of energy-level coefficients need to be calculated with formula 4.

$$\lambda = \frac{E}{H} \tag{4}$$

where H is the value of energy, kJ. The economics cost of each unit should be proportional to its energy-level coefficient, namely:

$$\frac{c_2}{\lambda_2} = \frac{c_3}{\lambda_3} \tag{5}$$

The energy-level coefficient is dimensionless and can represent the quality of energy. The energy quality increases with the higher energy-level coefficient. Conversely, it decreases with the lower exergy proportion.

The auxiliary equations established by energy-level method are shown in formulas 6-9:

$$\frac{1}{E_3}\times E_3\times C_3-\frac{1}{E_7}\times E_7\times C_7=0 \tag{6}$$

$$\frac{1}{E_6}\times E_6\times C_6-\frac{1}{E_5}\times E_5\times C_5=0 \tag{7}$$

$$\frac{1}{E_{10}}\times E_{10}\times C_{10}-\frac{1}{E_8}\times E_8\times C_8=0 \tag{8}$$

$$\frac{1}{E_{13}}\times E_{13}\times C_{13}-\frac{1}{E_{12}}\times E_{12}\times C_{12}=0 \tag{9}$$

The extended event matrix and the extended non–energy cost vector can be obtained through the energy-level method:

$$\overline{\mathrm{A}}=\begin{pmatrix}
1 & -1 & -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1\\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0\\
0 & 0 & \frac{1}{E_3} & 0 & 0 & 0 & -\frac{\lambda_3}{E_7\lambda_7} & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & -\frac{1}{E_5} & -\frac{\lambda_6}{E_5\lambda_5} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{\lambda_{10}}{E_8\lambda_8} & 0 & \frac{1}{E_{10}} & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{\lambda_{13}}{E_{12}\lambda_{12}} & \frac{1}{E_{13}}
\end{pmatrix}$$

$$\overline{Z}=\begin{pmatrix}
Z_1\\ Z_2\\ Z_3\\ Z_4\\ -W_1\\ -W_2\\ -W_3\\ -W_8\\ -W_{10}\\ 0\\ 0\\ 0\\ 0
\end{pmatrix}$$

4.1.2 | The introduction of auxiliary equation in the pipe network subsystem

Based on the exergoeconomic requirements of matrix model and the application of cost allocation energy-level method, the auxiliary equations of pipe network subsystem are shown in formulas 10 and 11:

$$\frac{1}{E_3}\times E_3\times C_3-\frac{\lambda_2}{E_2\lambda_3}\times E_2\times C_2=0 \tag{10}$$

$$\frac{1}{E_5}\times E_5\times C_5-\frac{\lambda_5}{E_4\lambda_4}\times E_4\times C_4=0 \tag{11}$$

The extended event matrix and the extended non–energy cost vector can be obtained through the energy-level method:

$$\overline{\mathrm{A}}=\begin{pmatrix}
1 & -1 & -1 & 0 & 0 & 0\\
0 & 0 & 1 & -1 & 0 & 0\\
0 & 0 & 0 & 1 & -1 & -1\\
1 & 0 & 0 & 0 & 0 & 0\\
0 & -\frac{\lambda_2}{E_2\lambda_3} & \frac{1}{E_3} & 0 & 0 & 0\\
0 & 0 & 0 & 0 & -\frac{\lambda_6}{E_5\lambda_5} & \frac{1}{E_6}
\end{pmatrix}$$

$$\overline{Z}=\begin{pmatrix}
Z_1\\ Z_2\\ -W_1\\ 0\\ 0
\end{pmatrix}$$

4.2 | Non–energy cost determination

The nonenergy cost is mainly divided into two parts[27]: fixed investment and product cost. The calculation method is as follows.

4.2.1 | Fixed investment

Fixed investment in equipment is mainly grouped into equipment fixed assets investment, building and structure investment, and other cost investment. The equipment fixed assets investment includes equipment factory price and transportation and installation cost, which is as follows:

$$I_{\mathrm{e}}=\sum_{i=1}^{n}Q_i p_i(1+\xi_i) \tag{12}$$

where Q_{in}, p_{in} are the number and factory prices of equipment, respectively, ξ_i is equipment transportation and installation cost coefficient (machinery equipment generally takes 0.43), n is the number of equipment types.

The building and structure investment can be estimated empirically according to equipment investment proportion, namely:

$$I_b = \xi_b I_e \tag{13}$$

where ξ_b is empirical coefficient, for indoor engineering, it is 0.6-1.

Other costs are calculated by multiplying equipment investment by empirical coefficient, namely:

$$I_r = \xi_r I_e \tag{14}$$

where ξ_r is empirical coefficient, which stands for the proportion of other expenses in equipment investment, fixed investment is as follows when formulas 12-14 are synthesized.

$$C_a = I_e + I_b + I_r \tag{15}$$

4.2.2 | Product cost

When the analysis of energy system product cost in oil transfer station is ongoing, the main components are raw materials costs, fuel and power costs, depreciation, and maintenance costs. The raw materials, and fuel and power costs are calculated by the following formula:

$$C_a = \sum (W_i p_i) + C_{fp} \tag{16}$$

where W_i is annual material consumption, p_i is unit price of material, and C_{fp} is annual consumption cost of fuel and power.

There are many depreciation methods[28,29], but no matter which method is used, it is related to the service life of fixed assets. It is extremely significant to estimate the economics life of equipment because it is an important basis for determining equipment depreciation cost. There are two methods for calculating depreciation cost: uniform depreciation method and heating depreciation method, of which the former is commonly applied. The depreciation cost can be expressed as:

$$Z = \frac{I_0 - I_L}{L} \tag{17}$$

where I_0 is equipment initial investment, L is equipment economic life, I_L is the salvage value after using L years.

Equipment maintenance should be divided into overhaul and routine maintenance in terms of maintenance purpose, scope, duration, and cost[30]. Due to the high cost of overhaul, its fund is usually drawn termly by year or month, which is represented as follows:

$$C_r = C_x + C_{xr} \tag{18}$$

where C_x is the cost of annual overhaul fund and C_{xr} is equipment once investment. Product cost is as follows when formulas 17 and 18 are synthesized.

$$C_b = Z_i + C_r \tag{19}$$

Based on the relevant basic cost data and formulas 12-19, the non–energy cost calculation results are shown in Table 2.

4.3 | Exergoeconomic cost determination

Before determining the exergoeconomic cost, the calculation of each exergy flow value should be completed first, which can be computed in light of the following formula.

$$E = (h - h_0) - T_0 (s - s_0) \tag{20}$$

where h is exergy flow enthalpy, s is exergy flow entropy, T_0 is environmental temperature, K.

In transfer station system operation process, the fluid flow needs to consider both pressure exergy and thermal exergy. Therefore, the formula 20 can be simplified as follows:

$$E = T_0 \int_{p_0}^{p} \frac{1}{\rho T} \mathrm{d}p + \int_{T}^{T_0} mc_p \left(1 - \frac{T_0}{T}\right) \mathrm{d}T \tag{21}$$

where ρ is the fluid density, kg/m^3, p_0 is environmental pressure, kPa, c_p is its heat capacity at constant pressure, J/(kg·°).

In which, the pressure exergy $E_{x,\Delta p}$ can be calculated by the following formula:

$$E_{x,\Delta p} = T_0 \int_{p_0}^{p} \frac{1}{\rho T} dp \tag{22}$$

The thermal exergy $E_{x,h}$ can be computed by the following formula:

$$E_{x,h} = \int_{T}^{T_0} mc_p \left(1 - \frac{T_0}{T}\right) \mathrm{d}T \tag{23}$$

Exergy values calculation results are shown in Table 3.

Based on the exergy values calculation results in Table 3, and auxiliary equations are combined with the non–energy cost calculation results, then the exergoeconomic cost of oil

TABLE 2 Non–energy cost calculation results

Equipment	Fixed investment cost		Operation and maintenance costs		
	Direct equipment investment (10 000 yuan)	Total investment cost (10 000 yuan)	Depreciation expense (10 000 yuan/year)	Maintenance cost (10 000 yuan/year)	Nonenergy cost (10 000 yuan/year)
Heating furnace	557.7	892.32	29.74	26.77	56.51
Efflux pump	38.47	61.55	3.08	1.85	4.92
Water mixing pump	33.61	53.78	2.69	1.61	4.30
Interwell oil gathering pipeline	481.61		16.05	4.82	20.87
Interwell water mixing pipeline	389.99		13.00	3.90	16.90
Interstation oil gathering pipeline	375.28		12.51	3.75	16.26
Interstation water mixing pipeline	376.87		12.56	3.76	16.33

TABLE 3 Exergy values calculation results

Number	Pressure exergy value E_P (kJ/h)	Thermal exergy value E_T (kJ/h)	Number	Pressure exergy value E_P (kJ/h))	Thermal exergy value E_T (kJ/h)
1	13280.53	232519.35	15	1312.50	13356.96
2	14688.87	314610.22	16	—	6334.70
3	55589.15	314610.22	17	1596.13	26391.91
4	76153.85		18	1254.36	21695.7
5	35253.57	—	19	341.64	3185.45
6	13280.53	518046.02	20	—	1510.57
7	2685201.60		21	981.26	22923.42
8	—	157027.5	22	496.07	18687.43
9	—	2298419.80	23	485.19	2610.13
10	107326.12	518046.02	24	—	1625.86
11	185418.01		25	4509.75	207638.18
12	129792.61	—	26	2775.23	189043.33
13	14612.50	220849.05	27	1734.517	11457.79
14	13300.00	201157.41	28	—	7137.10

gathering and transportation system can be obtained through solving the matrix. After that, the calculation results of exergoeconomic cost are calculated as shown in Figure 6.

In order to show the relationship of exergy flows among components more clearly, a Grassman diagram is drawn to more vividly show the flow path of exergy in the system. The Grassman diagram is shown in Figure 7.

The Grassmann diagram shows that in this gathering and transportation system, the transfer rule of exergy flow among components is determined quantitatively, which makes the subsequent research and analysis more convenient and accurate. In the energy-level method[31], the unit exergoeconomic costs of backmixing water pressure exergy and thermal exergy in initial stage of water mixing process are 579.11 yuan/GJ and 1243.39 yuan/GJ, respectively, which increase to 812.58 yuan/GJ and 1575.24 yuan/GJ, respectively, at the end of the process. In initial stage of oil gathering process, the values are 163.44 yuan/GJ and 1181.33 yuan/GJ respectively, which increase to 330.60 yuan/GJ and 1243.39 yuan/GJ, respectively, in the end. And the costs are continuously rising until backmixing water is confluent with produced fluid at wellhead, and then, the costs will drop sharply. This is because logistics temperature and pressure will decrease after being mixed, which need to be re-valued. When the logistics enters the oil gathering pipeline network, the costs will keep rising. In addition, the unit exergoeconomic cost of pressure exergy

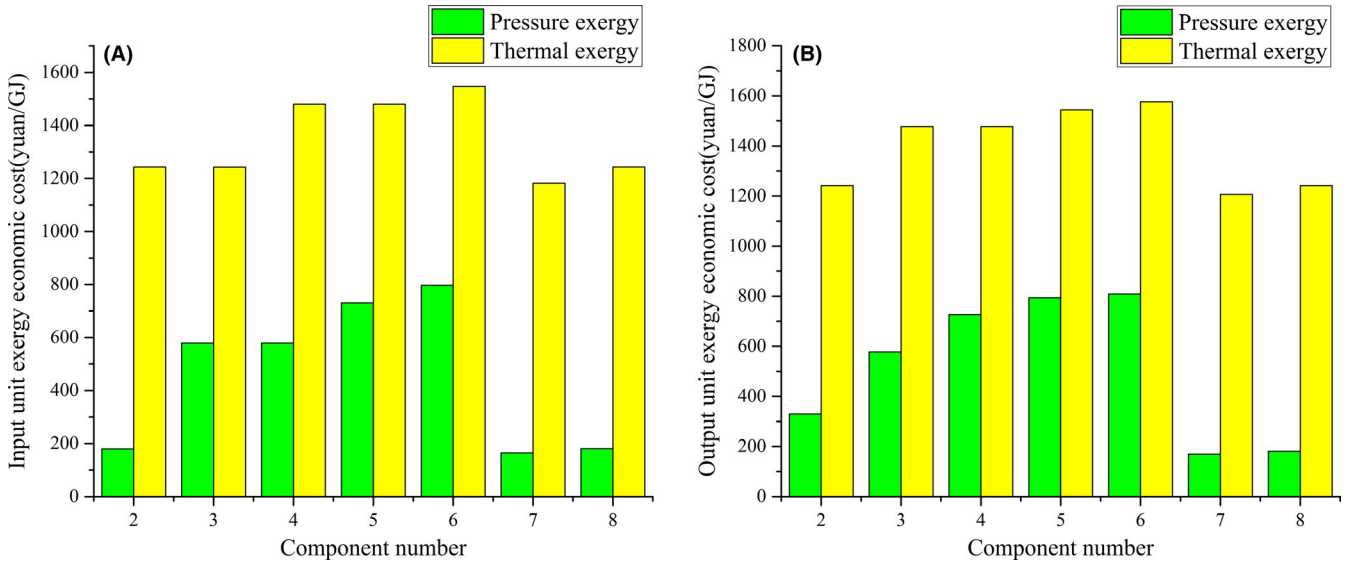

FIGURE 6 The calculation results of exergoeconomic cost. 1. efflux pump, 2. heating furnace, 3. water mixing pump, 4. interstation water mixing pipeline, 5. interwell water mixing pipeline, 6. interwell gathering pipeline, 7. interstation gathering pipeline

is far less than that of thermal exergy flow in and out of each component, which is shown that the "cost" to increasing or maintaining normal production temperature in the system is higher than increasing pressure.

5 | CALCULATION AND ANALYSIS OF EXERGOECONOMIC EVALUATION INDEX

5.1 | Exergy cost growth coefficient

The value of exergy is not equivalent in different positions and stages of the system[32]. Energy and nonenergy costs are continuously accumulating at every link of the exergy flow[33]. The "cost" of output products exergy is different. The closer the product is to the end of the process, the higher the "cost" will be. The exergy cost growth coefficient describes the inequivalence of exergy on the economy in the whole process. The unit exergy cost growth coefficient of subsystem K is as follows:

$$\beta_k = \frac{c_k}{c_{\text{in}}} = \frac{1 + \sum_{i=1}^{k} C_{\text{capi}}/(c_{\text{in}}E_{\text{in}})}{\prod_{i=1}^{k} \eta_i} \tag{24}$$

where β_k is the unit exergy cost growth coefficient of the subsystem K, $c_{\text{in}}E_{\text{in}}$ is the exergy flow price of exergy brought in the system, C_{capi} is nonenergy cost of the ith subsystem, and η_i is exergy efficiency of the ith subsystem. The calculation results of exergy cost growth coefficient are shown in Figure 8.

As shown in Figure 8, the exergy cost growth coefficients of interwell and interstation oil gathering pipelines are smaller, which are 1.132 and 1.457, respectively and

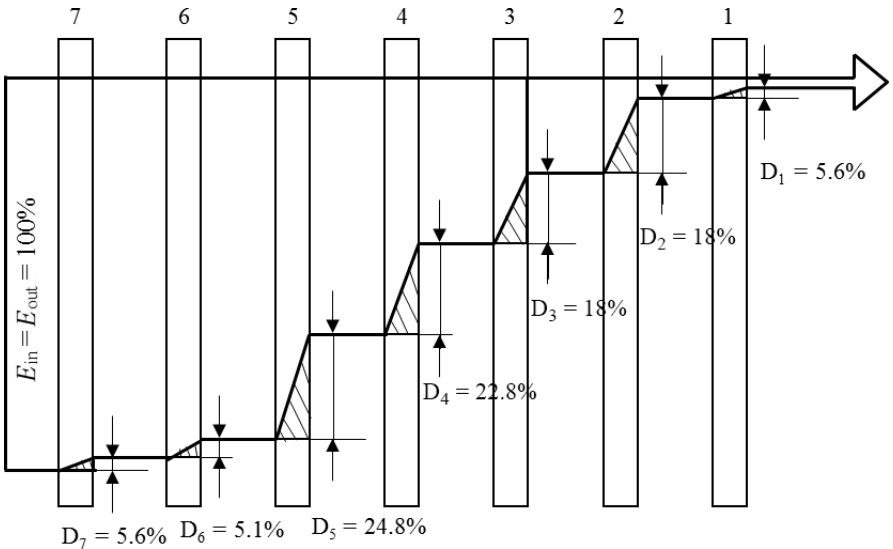

FIGURE 7 The Grassman diagram of exergy flow among components

that of the efflux pump at the end of the process is the highest, which is 2.789. The coefficients of each equipment and unit in oil gathering process are much smaller than water mixing process, which is mainly because of the cost growth caused by the destroyed exergy of heating furnace and water mixing pump or the large nonenergy cost in water mixing process.

The cost growth coefficients show that exergy costs are not the same in different parts of the system; that is, the exergy is not economically equivalent[34]. Along the direction of production, the exergy cost growth coefficient of each component increases progressively. When it closes to the end of the process, the energy consumption is great. By contrast, it closes to the initial point, and the energy consumption is small. This result corresponds to the production relationship of each component in the exergy economic analysis model.

5.2 | Relative cost difference

Relative cost difference refers to the proportional relationship between the unit exergy economic cost of fuel exergy and the increase of the cost caused by irreversible process, emissions, wearing, and nonenergy costs of system components[35,36]. However, when relative cost difference is calculated in traditional methods, only component improvement potential is judged. It is not considered from the whole system, which makes the exergy economic analysis results inconsistent with the fact. Researchers introduce weight coefficient into evaluation indexes of the relative cost difference in order that the analysis and evaluation results are more accurate. The expression is as follows:

$$\gamma_i = m_i \frac{c_{P,i} - c_{F,i}}{c_{F,i}} \tag{25}$$

where γ_i is the relative cost difference of the component i, $c_{P,i}$ is unit exergy economic cost of product exergy for component i, yuan/GJ, $c_{F,i}$is unit exergy economic cost of fuel exergy for component i, yuan/GJ, $m_i$is weight coefficient of the component i, which can be calculated by the following formula:

$$m_i = \frac{C_i}{\sum_{j=1}^{n} C_j} \tag{26}$$

where n is the component number in system, C_i is investment cost of the component i, yuan.

The exergy cost growth coefficient mainly describes the inequivalence of exergy on the economy[37]. The analysis of exergy cost growth coefficient increase in the process can provide a reference for evaluating the performance of the equipment, but it cannot entirely illuminate the performance of the equipment or unit. But the relative cost difference can reflect the equipment or unit with larger increase directly. Since the relative cost difference is proposed for equipment evaluation indexes, for the sake of a convenient analysis, the components in oil gathering and transportation system are divided into equipment and pipeline, which are calculated and analyzed, respectively. The relative cost difference of equipment and pipeline is calculated by introducing a weight coefficient. The calculation results of relative cost difference are shown in Figure 9.

It is shown in Figure **9** that the relative cost difference of efflux pump is smaller, which is 2.695%, the water mixing pump is 7.985%, the heating furnace is the highest, which is 94.503% and far higher than that of pumps. The results show that heating furnace has the highest "cost" for the exergy of output "product"; that is, the cost growth caused by irreversibility or investment is large, so the heating furnace has the largest energy-saving potential in the equipment.

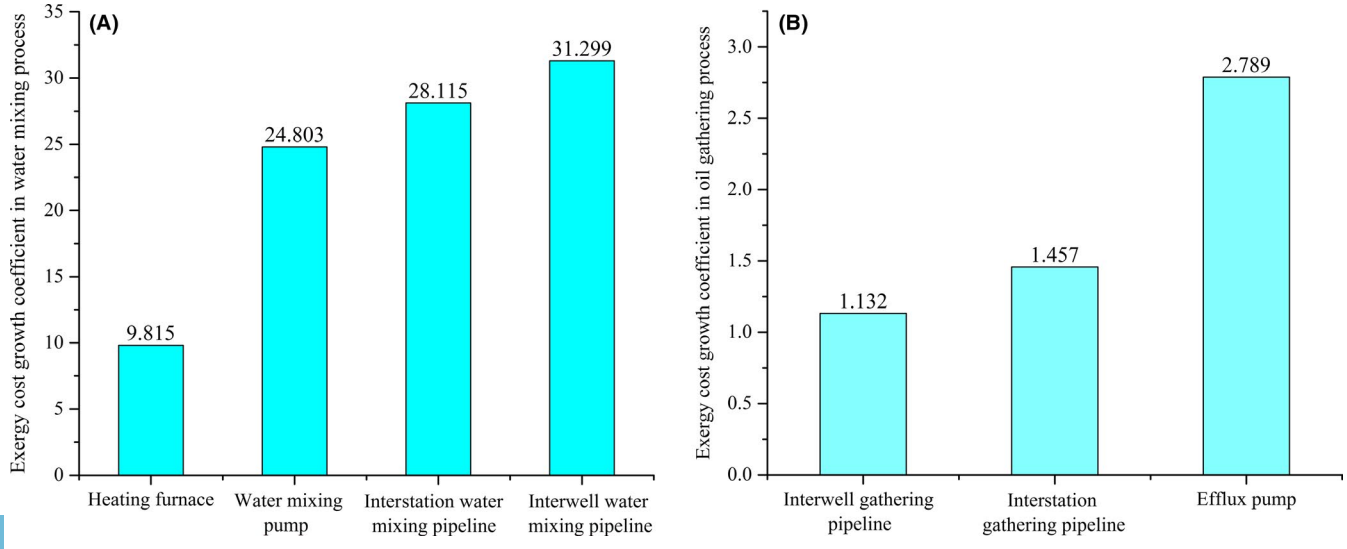

FIGURE 8 The calculation results of exergy cost growth coefficient

After a comprehensive comparison between the calculation results of relative cost difference of the equipment and pipelines, the equipment relative cost difference is higher, especially heating furnace is 94.503%, but that of pipelines is lower, the maximum value is only 0.696%. It can be seen that the higher the irreversible loss or nonenergy cost of equipment is, the greater the energy-saving potential is. It is necessary to focus on the analysis of heating furnace and pump equipment in further optimization.[38]

5.3 | Exergoeconomic coefficient

The system performance mainly depends on destroyed exergy cost and nonenergy cost. The former cost can reflect the thermodynamic performance of the system, and the latter one can reflect the economy of the system. These two costs are not independent with each other. When one item is reduced, the other may increase. Hence, there is a certain proportion relationship between the two costs. In the cause of describing and reflecting the relationship, the exergoeconomic coefficient can be used. The mathematical expression can be written as follows:

$$f_{ex} = \frac{Z}{c_{ir} \sum I_r + Z} \tag{27}$$

where Z is annual depreciation cost of equipment, yuan, $\sum I_r$ is annual destroyed exergy of system, GJ, c_{ir} is unit price of destroyed exergy, yuan/GJ.

The exergoeconomic coefficient can reflect the proportion of nonenergy cost to the total consumption of the whole system, of which the expression form is simple.[39] However, if the specific value of the coefficient is required, not only the destroyed exergy and its cost need be computed, but also the nonenergy cost demands calculating term by term.

Although the relative cost difference can show the components performance in the production process, it fails to directly reflect the reasons for the large increase in cost. Based on exergoeconomic coefficient analysis, it is available to find out the main reasons for each component cost increase amplitude. Meanwhile, the rationality and economy of the energy consumption are improved, so as to meet the purpose of scheme decision.[40]

It is not ideal with an exergoeconomic coefficient too large or small. When the destroyed exergy cost and nonenergy cost reach the appropriate value, the system achieves the double benefits of thermodynamic and economic concurrently. Generally speaking, when the exergoeconomic coefficient deviates from 50% seriously, it is said that the equipment operation effect is unsatisfactory and needs to be improved. Based on the non–energy cost calculation results and the unit exergy economic cost of each component, the exergoeconomic coefficients are calculated with formula 27, and the exergoeconomic coefficients are shown in Figure 10.

It can be seen from Figure 10, the exergoeconomic coefficient of heating furnace is the lowest, only 9.046%, of which the exergy efficiency is 8.71%. It shows that the destroyed exergy of heating furnace is too large and has great energy-saving value. It is necessary to take effective measures to reduce the destroyed exergy of heating furnace and improve the exergy efficiency. For pumping equipment, the exergoeconomic coefficient of the efflux pump is 43.491%, of which the exergy efficiency is 65.00% and the exergoeconomic coefficient is close to 50%. It shows that the pump has better thermal economy, relatively perfect thermal performance and small energy-saving potential under large initial investment condition. However, the

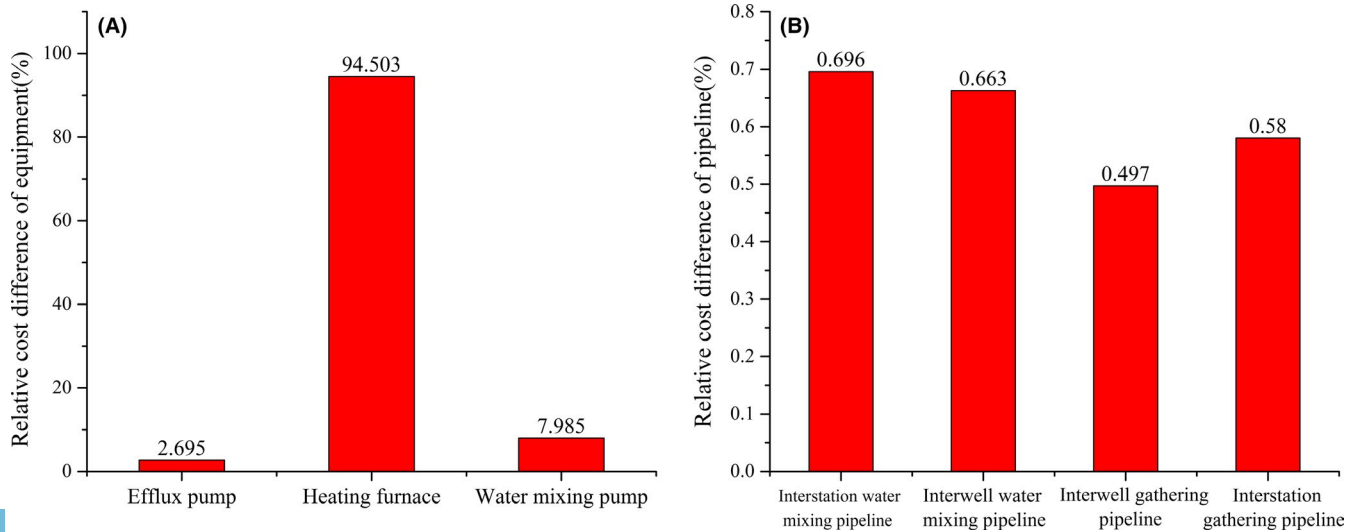

FIGURE 9 The calculation results of relative cost difference

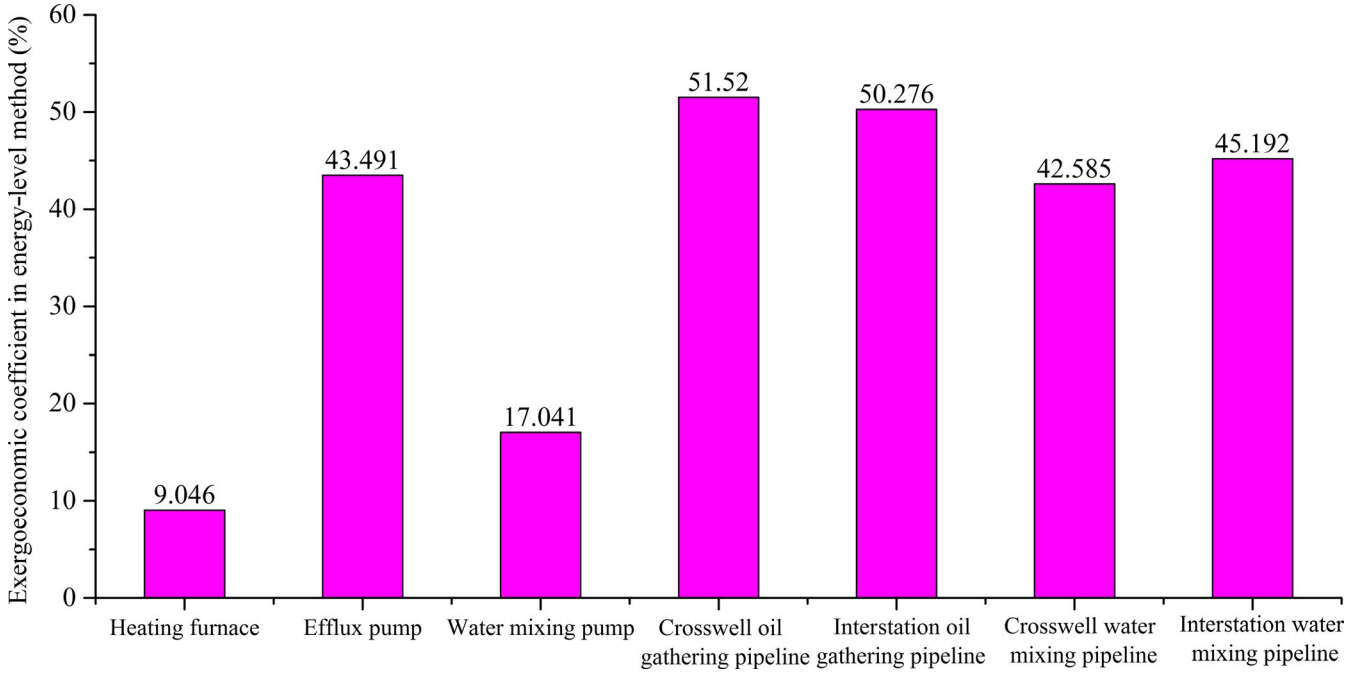

FIGURE 10 Exergoeconomic coefficient

exergoeconomic coefficient of mixing water pump is 17.041%, the exergy efficiency is 30.43%, and the destroyed exergy is relatively high, which has a certain energy-saving potential. For the pipeline unit, the exergoeconomic coefficient is between 42% and 52%, and the exergy efficiency is over 80%. It shows that the pipeline overall energy consumption is reasonable and the economy is favorable. Especially for interstation oil gathering pipelines, the exergoeconomic coefficient is 50.276, which is the closest to 50%, and the exergy economy is the best. The exergy economy of other pipelines from high to low is successively interwell oil gathering pipeline, interstation water mixing pipeline and interwell water mixing pipeline. While pipeline unit initial investment is small, the thermal economy is fine, and the exergy economy will not improve too much if the investment is increased again, and at the same time, the energy saving value is small.

5.4 | Sensitivity analysis

According to the analysis of formula 24-27, the nonenergy cost should be a fixed value when the equipment is not changed. The main variation parameter of the exergy cost growth coefficient is the bring-in exergy price of equipment. In the relative cost difference, the main variation parameter is the unit exergy economic cost of each component fuel and product, and of the exergoeconomic coefficient, it is unit exergy economic cost of exergy loss in equipment. The major effect parameters on the unit exergy economic cost of each equipment are input and output temperature, pressure and flow through the medium. In this gathering and transportation system, the variable effect parameters are mainly the temperature of backmixing water, the flow rate of backmixing water, the inlet temperature of oil transfer station, and the pressure of backmixing water. Under the condition of changing the effect parameters, the sensitivity analysis of calculation result for each evaluation indicator on the equipment with weak energy consumption is as follows.

5.4.1 | Exergy cost growth coefficient

According to formula 24, the variation results for exergy cost growth coefficient of heating furnace under the condition of changing the parameters are as follows (Figure 11).

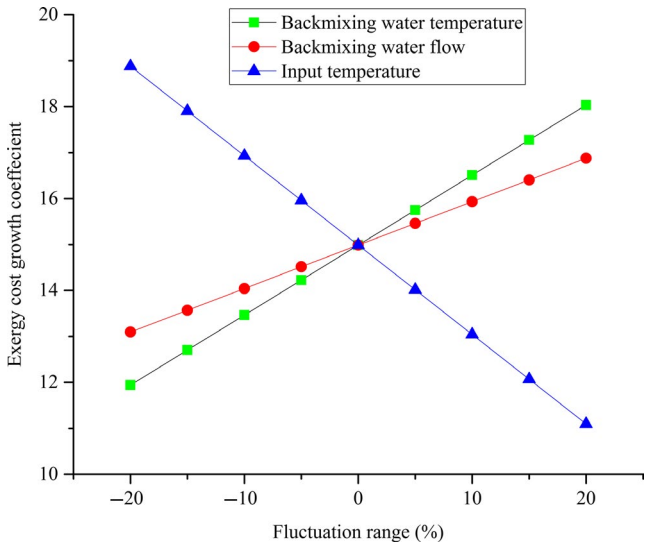

FIGURE 11 Sensitivity analysis of exergy cost growth coefficient

In terms of the calculation results, the unit exergy economic cost of heating furnace entrance rises due to the increase of input temperature, of which the exergy cost growth coefficient decreases, while the temperature of mixing water and the flow of backmixing water are inversely proportional to the exergy cost growth coefficient. The order of change amount on the exergy cost growth coefficient when effect factor values fluctuate by 5% is as follows: input temperature (-6.49%) > backmixing water temperature (3.15%) > backmixing water flow (5.08%).

5.4.2 | Relative cost difference

According to formula 25 and 26, the variation results for relative cost difference of heating furnace under the condition of changing the parameters are as follows (Figure 12).

Based on the calculation results, the temperature of backmixing water, the flow rate of backmixing water, and the temperature of input station are all proportional to the relative cost difference. This is because the unit exergy economic cost of output products rises with the increase of three parameters, and the unit exergy economic cost of fuel exergy keeps invariant. Therefore, the relative cost difference increases, and the relative cost difference increases with the fluctuation of the influencing factor value of 5% per fluctuation. The order of change amount on the relative cost difference when effect factor values fluctuate by 5% is as follows: backmixing water temperature (0.97%) > backmixing water flow (0.63%) > input temperature (0.58%).

5.4.3 | Exergoeconomic coefficient

According to formula 27, the variation results for exergoeconomic coefficient of heating furnace under the condition of changing the parameters are as follows (Figure 13).

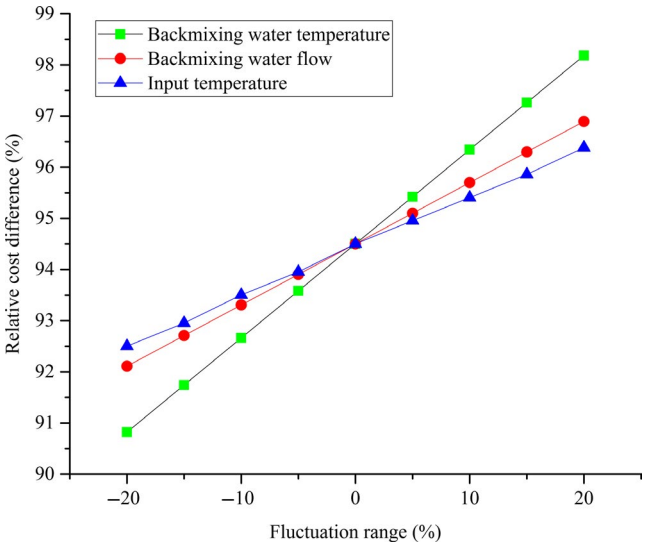

FIGURE 12 Sensitivity analysis of exergy cost growth coefficient

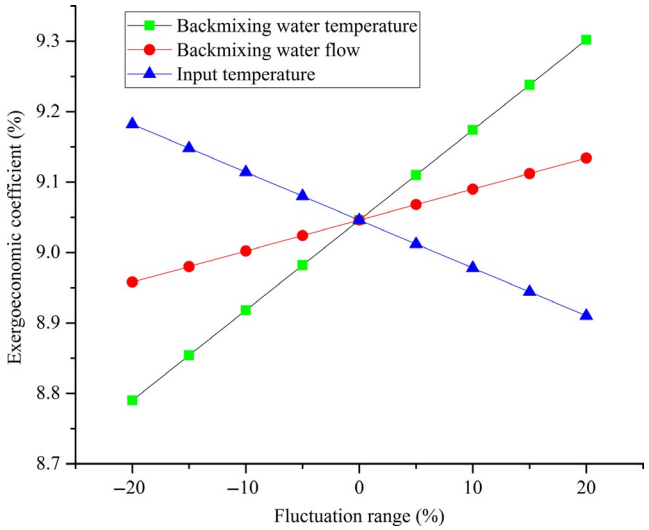

FIGURE 13 Sensitivity analysis of exergoeconomic coefficient

Because the unit exergy economic cost of heating furnace equipment is determined by fuel exergy, the unit exergy economic cost keeps invariant under the condition of a constant gas price, and the fluctuation of its exergoeconomic coefficient is mainly affected by the equipment exergy loss. On the basis of the calculation results, the exergy loss value of heating furnace decreases with the increase of input temperature, and the exergoeconomic coefficient decreases, the temperature and the flow rate of backmixing water are inversely proportional to the exergoeconomic coefficient. The order of change amount on the exergoeconomic coefficient when effect factor values fluctuate by 5% is as follows: backmixing water temperature (0.71%) > input temperature (-0.37%) > backmixing water flow (0.24%).

6 | CONCLUSIONS

1. The exergoeconomic theory in matrix pattern is applied to an oil transfer station energy system in this paper. The distribution of exergy flow is analyzed, and an exergy economic analysis model is established. The auxiliary equations are introduced in the energy-level method to calculate the unit exergy economic cost of each exergy flow. Accordingly, exergy economic evaluation indexes are confirmed to analyze the thermodynamic performance and economy of every system link, which can provide a direction for further optimization and excogitation.
2. Based on the calculation results of exergy economic analysis model, the unit exergoeconomic costs of pressure exergy and thermal exergy in the process initial stage are 579.11 yuan/GJ and 1243.39 yuan/GJ, respectively, which increase to 812.58 yuan/GJ and 1575.24 yuan/GJ, respectively, at the end of the process. The unit exergoeconomic cost of pressure exergy is less than that of thermal exergy,

which is shown that the "cost" to increasing or maintaining system normal production temperature is higher than increasing pressure.

3. The minimum exergy cost growth coefficient of heating furnace is 9.887, and the maximum of interwell mixing water pipeline is 31.299. Along the direction of production, the exergy cost growth coefficient increases progressively. The exergy cost growth coefficients of each equipment and unit in oil gathering process are much smaller than those in water mixing process. The main reasons are the loss of heating furnace or water mixing pump and the cost increase amplitude of the larger nonenergy cost. The relative cost difference of heating furnace comes up to 94.503%. While the pipeline relative cost difference is lower, the highest value is only 0.696%. It is necessary to analyze heating furnace and pump in exergy economic optimization. The exergoeconomic coefficient of efflux pump is close to 50%, which shows that the pump has commendable exergoeconomic performance under large initial investment condition. The exergoeconomic coefficient of heating furnace is 9.046%, and the mixing water pump is 17.041%. The destroyed exergy is relatively high, so it has great potential for energy saving.
4. Based on the traditional energy and exergy analysis, the gathering and transportation system can only be analyzed from the perspective of energy. By using exergy economic analysis method to calculate indicators such as unit exergy economic cost, relative cost difference, and exergoeconomic coefficient, we can elect equipment with unreasonable ratio of energy consumption and economic cost. On the basis of this, the optimization of exergy economics operation for gathering and transportation system can be studied. Taking the total operation exergy cost and unit exergy economic cost as objective functions, the exergy economic analysis and optimization of poor equipment can provide a theoretical basis for energy saving and consumption reduction of gathering and transportation system and optimal operation of equipment.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Qinglin Cheng https://orcid.org/0000-0002-0768-6688

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